GRADUATE TEXTS IN PHYSICS

Claus Grupen

Introduction to Radiation Protection

Practical Knowledge for Handling Radioactive Sources

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Practical Knowledge for Handling Radioactive Sources

Collaborators: Ulrich Werthenbach and Tilo Stroh

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Professor Dr. Claus Grupen
University of Siegen, Department of Physics
Walter-Flex-Str. 3, 57068 Siegen, Germany
E-mail: grupen@hep.physik.uni-siegen.de

Collaborators:
Dr. Tilo Stroh
Dr. Ulrich Werthenbach
University of Siegen, Department of Physics
Walter-Flex-Str. 3, 57068 Siegen, Germany
E-mail: stroh@sirs02.physik.uni-siegen.de
werthenbach@deph.physik.uni-siegen.de

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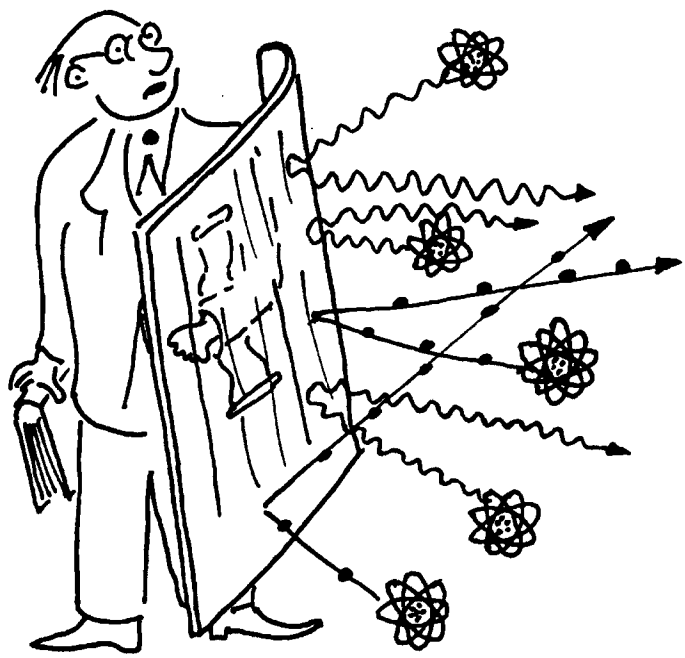
This book provides an overview of radiation physics and radiation-protection regulations. It is essentially meant for students and professionals concerned with problems of radiation aspects. We have tried to keep the information correct and up-to-date. However, any reliance on such information is strictly at your own risk. This refers to the availability of the shown commercial products and also to those places where web sites are given. Web addresses can change quite rapidly, but we have made sure that the sites given in the text are available at the time of printing of this book. The referred web sites are not under our control. We have also tried to get written permissions for all products on radiation detection and radiation instruments and other material which is shown in this book. Not in all cases did the companies providing such instruments or information respond to our request for permission to show their products. If material is being described which is not properly or incompletely referred to, we would be grateful to be informed so that we can consider this for future editions of the book.

Claus Grupen



"Radiation Protection"

Preface

Radiation is everywhere. In this book, we are concerned with ionizing radiation, i.e. radiation that can ionize ordinary atoms. Translated into energies this corresponds to α, β, or γ rays with energies larger than, say, 30 eV. Almost everything is radioactive. Radiation emerges from the soil, it is in the air, and our planet is constantly bombarded with energetic cosmic radiation. Even the human body is radioactive: about 9000 decays of unstable nuclei occur per second in the human body. In the early days of the Earth, when our planet was formed from the debris of the proto-solar system, the radiation level was even higher. One can assume that the origin and development of life might have been positively influenced by ionizing radiation.

Since the beginning of the twentieth century, mankind has been able to artificially create radioactive nuclei, in particular, since the discovery of nuclear fission in the late 1930s. As early as 1905, Pierre Curie remarked that radium in the hands of criminals could be a disaster. Also, Louis de Broglie noted in his Nobel lecture in 1927 that he did not know whether science in the hands of humans is a good or a bad thing. The bombing of Hiroshima and Nagasaki in 1945 with nuclear weapons clearly demonstrated the disastrous effect of ionizing radiation. The Nobel laureate for medicine, Sir Maurice Hugh Frederick Wilkins, said contemplatively: "We have now reached the point where it is an open question as to whether doing more science is a good thing". The nuclear accidents near Harrisburg at the Three-Mile-Island reactor (1979), in Chernobyl (1986), and Tokaimura (1999) clearly demonstrated that nuclear fission requires high-quality safety systems.

It is in the nature of humans to try to further the understanding of the world around us. No law will stop people undertaking research which might carry them into new domains and which carries the risk of misusing the new technology. Therefore, it is important to understand the results of research and to explain the benefits and possible risks to everybody who is interested. The benefits of nuclear energy and ionizing radiation are already clearly visible in medical diagnosis and therapy. Successful tumor treatment with particle beams is an example of a remarkable achievement. Also nuclear fusion – the energy source of the stars – will very likely solve the energy problem of mankind in less than a century.

Since one cannot 'see' or 'smell' ionizing radiation, one needs measurement devices which can detect it, and also a scale on which to judge on its possible dangerous effects. This leads to the definition of units for the activity of radioactive nuclei and quantifications for

the effect on humans in terms of absorbed energy and biological effectiveness of different types of radiation.

This book originated from a series of lectures that I gave over a period of more than thirty years. The main body of the text was first published in German by Vieweg and in updated later editions by Springer. It included mainly chapters on the units of radiation protection, the necessary ingredients from nuclear and quantum physics, and the interaction of ionizing radiation with matter and radiation detectors. Also environmental radioactivity, X rays, and the biological effects of radiation and radiation accidents were described. The German versions contained chapters on the legal aspects and regulations for safe handling of radioactive material. Since these sections concerning national laws of one country are not of common interest, I have replaced these regulations by describing the European and American perspectives on the legal aspects of the handling of radioactive sources, and on radiation protection at accelerators and in nuclear medicine. Also the main outlines of radiation-protection regulations from some other countries are included. I have added two chapters on nuclear power plants and radiation sources, not present in the original German version. Since all of us are living in electromagnetic radiation fields from all kinds of sources, I have also added a short chapter on the effects of nonionizing radiation.

Radiation protection concerns, among others, physicists, engineers, lawyers, and health-care professionals. The phenomena of radioactivity and their effects on matter are most elegantly described by the language of mathematics. I have added, therefore, a small mathematical appendix for those who want to refresh their knowledge of basic calculus, logarithms, and exponentials.

This work was only possible with the help of colleagues who contributed to the completion of the book. Ms. Ute Smolik typed the first version of this translation from my tape recordings. My ‘Germanic’ English benefitted significantly from the linguistic improvement and polishing by the native speakers Mark Rodgers, M. Sci., and Dr. Matthew Beckingham who worked in our group in Siegen. Dr. Ulrich Werthenbach made valuable contributions to the description of the detection of radioactivity and practical measurement devices, and Dr. Tilo Stroh proofread everything and took over the very important job of typesetting the text in LaTeX and optimizing the figure layout. He also checked all the problems and the appendices, and he created the table of isotopes. In particular we would like to thank the Project Manager Asher Ebenezer of the Integra Software Services in Puducherry, India for their excellent work and cooperation during the production of the book. Thank you all!

Claus Grupen, Siegen, January 2010

Contents

1 Introduction

"All problems are finally scientific problems."

G. B. Shaw 1856–1950

Life on Earth has developed under permanent exposure to radiation. In addition to ionizing radiation from natural sources a multitude of exposures from artificial sources produced by mankind came into play in the twentieth century. These radioactive sources have been introduced and used in the course of the rapid development of medical diagnostics and therapy and natural science and technology.

Humans have no senses for ionizing radiation. Therefore, possible risks related to ionizing radiation were often underestimated. Even today it happens quite frequently that strong radioactive sources, which had been used in medicine or technology and disposed off illegally as scrap metal are 'found', for example, by children. Since no particular danger appears to originate from such sources, they are sometimes handled by the children and even stored in their homes. Considering the strength of radioactive sources used in medicine and technology, the irradiation from these sources over a period of several days can easily lead to radiation sickness and even death.

To judge correctly the potential danger caused by radioactive sources, one has to develop a feeling for the biological effects of ionizing radiation. It is impossible to eliminate radiation exposure altogether. This relates to the fact that one cannot possibly avoid natural radioactivity from the environment. Therefore, additional exposures have to be compared and judged with respect to the natural radiation exposure. To estimate the potential risk from radiation from the environment and from other sources, a minimum knowledge about physics, chemistry, and biology is required which will replace in some sense the missing senses for radioactivity.

Radioactivity was discovered by Henri Antoine Becquerel in 1896, when he realized that radiation emerging from uranium ores could blacken photosensitive paper. Originally it was believed that this was due to some fluorescence radiation from uranium salts. However, the photosensitive paper was also blackened without previous exposure of the uranium ore to light. The radiation spontaneously emerging from uranium was not visible to the human

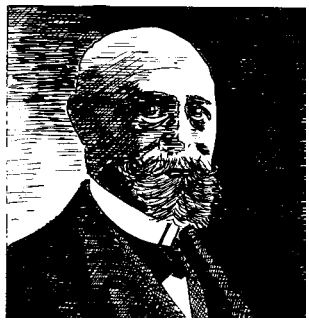


Figure 1.1
Portrait of
Henri Antoine Becquerel
(Drawing: C. Grupen)

Figure 1.2
Portrait of
Wilhelm Conrad Röntgen
(Drawing: C. Grupen)

1896
discovery of radioactivity by Henri Antoine Becquerel

C. Grupen, *Introduction to Radiation Protection*,
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eye. Therefore, it was clear that one was dealing with a new phenomenon.

1895
discovery of X rays by Wilhelm Conrad Röntgen

In the context of radiation protection also the discovery of X rays by Wilhelm Conrad Röntgen has to be mentioned. This radiation emerged from materials after bombardment with energetic electrons. Actually the discovery by Röntgen in December 1895 had been a factor of stimulating Becquerel to investigate fluorescence radiation from uranium salts.

discovery of polonium and radium

The new research field of radioactivity became particularly important when Marie and Pierre Curie in 1898 succeeded in isolating new radioactive elements (polonium and radium) from pitchblende. Marie Curie was awarded with two Nobel Prizes for her research (1903 Henri Becquerel, Pierre Curie, Marie Curie: Physics Nobel Prize for the discovery and research on radioactivity; 1911 Marie Curie: Nobel Prize for Chemistry for the discovery of the elements polonium and radium by chemical separation techniques from pitchblende).

α, β, γ rays

At the turn of the century (1899–1902) the investigation by Ernest Rutherford clearly demonstrated that there are different types of ionizing radiation. Since initially it was impossible to identify these different types, they were named after the first letters of the Greek alphabet α, β, and γ rays. It could be shown that α and β rays could be deflected by magnetic fields, in contrast to γ rays.

artificial radioactivity
nuclear fission

This radioactivity was a phenomenon of the natural environment. Nobody was able to turn inactive materials into radioactive sources by chemical techniques. Not until 1934 Frederic Joliot and Irène Curie managed to produce new radioactive materials artificially using nuclear physics methods. Only a few years later Otto Hahn and Fritz Straßmann (1938/39) succeeded in inducing fission of uranium nuclei. The intention of Hahn and Straßmann was to produce elements beyond this heaviest naturally occurring element by neutron bombardment. The particular importance of fission was recognized by Lise Meitner and Otto Frisch.

transuranic elements

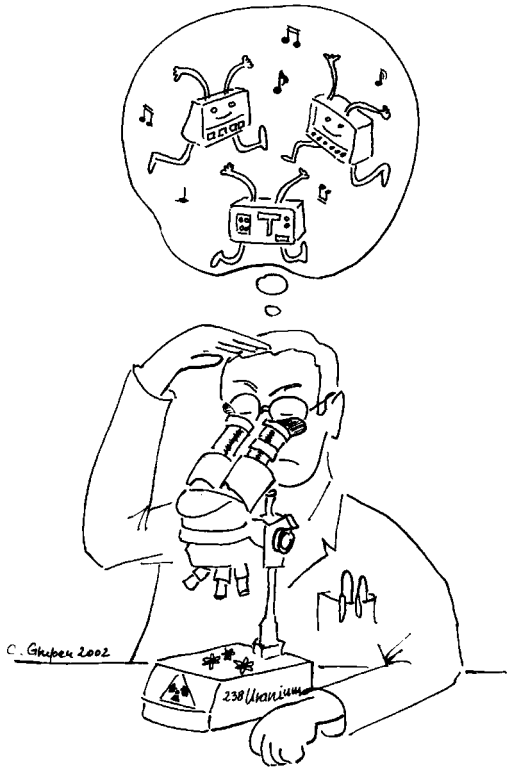
Since then physicists have been trying to produce artificially superheavy elements beyond uranium ('transuranic elements') which do not occur in nature. Most of these elements are highly radioactive. This group also includes the chemically toxic plutonium and americium. Up to now 26 elements which do not occur in the natural environment have been artificially synthesized.

effects of ionizing radiation

The importance of radioactivity and of radiation protection for mankind and the environment is quite substantial. The judgment on the effects of ionizing radiation on humans should not be left only to so-called experts. Everybody who is prepared to get involved in these problems should be in a position to come to his own judgment.

It is highly desirable that, for example, discussions on the benefits and risks of nuclear power are not dominated by emotional antipathy or blind support, but rather by solid facts about radiation and radiation-related effects.

The intention of this book is to introduce the reader into the physical, technical, medical, and legal aspects of radiation. At the same time this book will hopefully contribute to the readers' understanding of the necessary scientific issues, allowing, for example, discussions on nuclear energy with higher objectivity.



Dr. Linkenstein was baffled when he found 'radio-activity' had a literal meaning.

2 Units of Radiation Protection

"All composed things tend to decay."

Buddha 563–483 B. C.

A large number of units has been proposed and used in the course of historical development and research in the field of radioactivity. Only those which have survived to today shall be used and defined here. I will introduce the modern units which are recommended by the International Commission on Radiological Protection (ICRP). In addition, I will also mention those units which are still in use in countries like in the USA, and give the relations to the ICRP-recommended units used in Europe and elsewhere.

1 becquerel (Bq) = 1 decay per second

1 curie (Ci) = 3.7 × 10^{10} Bq

The unit of activity is becquerel (Bq). 1 Bq is one decay per second. The old unit curie (Ci) corresponds to the activity of 1 g of radium-226:[1]

$$1\,\mathrm{Ci} = 3.7 \times 10^{10}\,\mathrm{Bq}\ ,$$
$$1\,\mathrm{Bq} = 27 \times 10^{-12}\,\mathrm{Ci} = 27\,\mathrm{pCi}\ . \qquad (2.1)$$

In radioactive decays the number of decaying nuclei ΔN is proportional to the number of existing nuclei N and the observation time Δt. The number of nuclei decreases by decay. This fact gives the negative sign for ΔN. Therefore, one has

$$\Delta N \sim -N\ \Delta t\ . \qquad (2.2)$$

Since the decay rate changes in time it makes sense to use very small, indeed infinitesimal times $\mathrm{d}t$ and numbers $\mathrm{d}N$ (see Appendix Q),

$$\mathrm{d}N \sim -N\ \mathrm{d}t\ . \qquad (2.3)$$

decay constant

Starting from this relation one obtains the equation by introducing a constant of proportionality, namely, the decay constant λ,

[1] Because of the frequently occurring very large and very small numbers I will use throughout the notation using powers, e.g. $10^6 = 1\,000\,000$ and $10^{-6} = 0.000\,001$. A word of caution is in order here: A billion is in most parts of the world 10^9 while in some parts, e.g. in Germany, a billion is 10^{12}.

C. Grupen, *Introduction to Radiation Protection*,
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$$\mathrm{d}N = -\lambda\, N\, \mathrm{d}t \ . \tag{2.4}$$

Such a differential equation can be solved generally by the so-called exponential function (see Appendix Q):

$$N = N_0\, \mathrm{e}^{-\lambda\, t} \ . \tag{2.5}$$

N_0 characterizes the number of nuclei existing at time $t = 0$, i.e. the number of originally existing atomic nuclei. The number $\mathrm{e} = 2.718\,28\ldots$ is the basis of the natural logarithm (see Appendix Q). Since the exponent of the exponential function has to be without dimension, the physical unit of the decay constant is second^{-1}. The decay constant λ is related to the *lifetime* of the radioactive source as

lifetime

$$\lambda = \frac{1}{\tau} \ . \tag{2.6}$$

One has to distinguish the half-life $T_{1/2}$ from the lifetime. The half-life is the time after which a half of the initially existing atomic nuclei has decayed. After another half-life a half of the remaining nuclei will have decayed, so that one is left with only one quarter of the original nuclei. That means, say, after 10 half-lives, there is still a fraction of 2^{-10} nuclei which has not decayed. Because of

half-life

$$N(t = T_{1/2}) = \frac{N_0}{2} = N_0\, \mathrm{e}^{-T_{1/2}/\tau} \ , \tag{2.7}$$

we will get, applying the rules of exponential functions and natural logarithms as explained in Appendix Q,[2]

$$\begin{aligned} \frac{1}{2} &= \mathrm{e}^{-T_{1/2}/\tau} \ , \\ \mathrm{e}^{T_{1/2}/\tau} &= 2 \ , \\ T_{1/2}/\tau &= \ln 2 \\ \text{or} \quad T_{1/2} &= \tau\ \ln 2 \ . \end{aligned} \tag{2.8}$$

The decay constant λ of an unstable radioactive nucleus is obtained as

$$\lambda = \frac{1}{\tau} = \frac{\ln 2}{T_{1/2}} \ . \tag{2.9}$$

The activity A of a radioactive source characterizes the number of decays per second. Therefore, the activity A is equal to the change

activity

[2] The exponential function e^x and the natural logarithm $\ln x$ are operations which are available on most, even simple, non-scientific pocket calculators.

rate ΔN of existing atomic nuclei in the time Δt. Because a decreasing number of atomic nuclei represents a positive activity, one defines

$$A = -\frac{\Delta N}{\Delta t} \ . \tag{2.10}$$

For infinitesimal time intervals $\mathrm{d}t$ one has

$$A = -\frac{\mathrm{d}N}{\mathrm{d}t} \ . \tag{2.11}$$

With the help of Eq. (2.5) and the rules of calculus as presented in Appendix Q one obtains:

$$A = -\frac{\mathrm{d}}{\mathrm{d}t}(N_0 \, \mathrm{e}^{-\lambda t}) = \lambda \, N_0 \, \mathrm{e}^{-\lambda t} = \lambda \, N = \frac{1}{\tau} N \ . \tag{2.12}$$

Radioactive sources with a large lifetime τ (or, equivalently, half-life $T_{1/2}$) naturally have lower activities if a given number of nuclei is considered.

The activity in Bq does not say very much about possible biological effects. These are related to the deposited energy by the radioactive source in matter. The energy dose D (absorbed energy

energy dose

"I rather stick to the old activity unit.
'Micro-curie' sounds so much better
than 'mega-becquerel'!"

ΔW per mass unit Δm),

$$D = \frac{\Delta W}{\Delta m} = \frac{1}{\rho}\frac{\Delta W}{\Delta V} \tag{2.13}$$

(ρ – density, ΔV – volume element[3]), is measured in gray:

gray

$$1 \text{ gray (Gy)} = 1 \text{ joule (J)} \;/\; 1 \text{ kilogram (kg)} \;. \tag{2.14}$$

Gray is related to the old unit rad (radiation absorbed dose, 1 rad = 100 erg/g; still in use in the US) according to:[4]

1 Gy = 1 J/1 kg
1 Gy = 100 rad

$$1\,\text{Gy} = 100\,\text{rad} \;. \tag{2.15}$$

For indirectly ionizing radiation (i.e. photons and neutrons, but not electrons and other charged particles) a further quantity characterizing the energy dose, the 'kerma', is defined. Kerma is an abbreviation for "kinetic energy released per unit mass".[5] The kerma k is defined as the sum of the initial energies of all charged particles, ΔE, liberated in a volume element ΔV by indirectly ionizing radiation divided by the mass Δm of this volume element:

kerma

$$k = \frac{\Delta E}{\Delta m} = \frac{1}{\rho}\frac{\Delta E}{\Delta V} \;, \tag{2.16}$$

where ρ is the density of the absorbing material.

We see that kerma relates only to the energy transferred to the charged particles: it does not depend on which fraction of the energies of the charged particles is transported out of the volume by particle motion or by bremsstrahlung. Therefore, kerma is sometimes also called dose unit of the first interaction step. The unit of kerma is also gray (Gy).

dose unit of the first interaction step

Gray and rad describe the pure physical energy absorption. These units cannot easily be translated into the biological effect of radiation. Electrons, for example, ionize relatively weakly while, in contrast, α rays are characterized by a high ionization density. Therefore, biological repair mechanisms cannot be very effective in the latter case. The relative biological effectiveness (RBE) depends on the type of radiation, the radiation energy, the temporal distribution of the dose, and other quantities. The relative biological effectiveness is a factor by which we have to multiply the energy dose D

relative biological effectiveness

[3] A volume element, sometimes also called 'unit volume', is the differential element ΔV whose volume integral over some range in a given coordinate system gives the total volume V.

[4] 1 joule (J) = 1 watt second (W s) = $1\,\frac{\text{kg m}^2}{\text{s}^2} = 10^7\,\frac{\text{g cm}^2}{\text{s}^2} = 10^7$ erg

[5] Occasionally one also finds "kinetic energy released in matter (or: in material)".

of our chosen type of radiation giving the energy dose D_γ of X rays or γ rays which would have the same biological effect,

$$\mathrm{RBE} = D_\gamma / D \ . \tag{2.17}$$

Since it is not always known in radiation protection which biological effects one has to refer to in a specific case, instead of the complicated energy-, radiation-, and dose-rate-dependent RBE factors one uses the so-called quality factor Q to assess the effect of a physical energy deposition. This leads to the dose equivalent H,

dose equivalent

$$H = Q \ f \ D \ . \tag{2.18}$$

sievert

H is measured in sievert (Sv). The factor f considers further radiation-relevant factors such as the dose-rate dependence or reduced biological effects by a periodic irradiation. Such a technique of intermittent radiation is used in cancer therapy: if a patient should receive, say, a dose of 2 Sv to destroy a tumor, this dose is applied e.g. in ten separate fractions of 0.2 Sv, because in the intervals between these fractions the healthy tissue will recover more easily in contrast to the tumor tissue. A typical interval between subsequent fractions of irradiations is a day. All in all the product of the quality factor Q and the modifying factor f assesses the biological radiation effect of an absorbed dose D. Therefore, this product $q = Q \ f$ is called the weighting factor. Since both the quality factor Q and the correction factor f are dimensionless, so is the weighting factor q, and the unit of the equivalent dose is also J/kg.[6] The old unit rem (roentgen equivalent man), still in use in the United States, is related to sievert according to

weighting factor

1 Sv = 100 rem

$$1\,\mathrm{Sv} = 100\,\mathrm{rem} \ . \tag{2.19}$$

Nowadays the weighting factors q are called radiation weighting factors following a recommendation by the International Commission on Radiological Protection. These radiation weighting factors w_R depend on the type of radiation and for neutrons also on their energy. The most recent definition of radiation weighting factors following the recommendation of the International Commission on Radiological Protection is given in Table 2.1.

radiation weighting factors

For the radiation field R one gets the dose equivalent H_R from the energy dose D_R according to

[6] The energy dose D is measured in Gy and the equivalent dose H in Sv, therefore, the weighting factor q in principle has the unit Sv/Gy. However, both Gy and Sv have the same physical unit J/kg, where Gy only considers the physical effect while Sv also takes the biological effect into account.

"Atomic progress is quite educating!"

after Jupp Wolter

Table 2.1
Radiation weighting factors w_R[7]

type of radiation and energy range	**radiation weighting factor w_R**
photons, all energies	1
electrons and muons[8], all energies	1
neutrons $E_n < 10\,\mathrm{keV}$	5
neutrons $10\,\mathrm{keV} \le E_n \le 100\,\mathrm{keV}$	10
neutrons $100\,\mathrm{keV} < E_n \le 2\,\mathrm{MeV}$	20
neutrons $2\,\mathrm{MeV} < E_n \le 20\,\mathrm{MeV}$	10
neutrons with $E_n > 20\,\mathrm{MeV}$	5
protons, except recoil protons, $E > 2\,\mathrm{MeV}$	5
α particles, fission fragments, heavy nuclei	20

$$H_R = w_R\, D_R \ . \tag{2.20}$$

Figure 2.1 shows photographic records taken with a diffusion cloud chamber in normal air. They clearly demonstrate the strong ionizing effect of α particles from the radon decay chain (left). At the same time the weakly ionizing effect of decay electrons is visible. Their tracks in the diffusion cloud chamber are characterized by multiple scattering and large bending angles (right image).

Apart from these units another quantity is used for the amount of created charge, the roentgen (R). One roentgen is that radiation dose of X rays and γ rays, which liberates one electrostatic charge unit

roentgen

[7] The energy-dependent radiation weighting factor for neutrons can be approximated by the function $w_R = 5 + 17\,\mathrm{e}^{-\frac{1}{6}(\ln(2\,E_n))^2}$, where the neutron energy E_n is measured in MeV.

[8] Muons are short-lived elementary particles which are produced predominantly in cosmic radiation (see also Sect. 11.1).

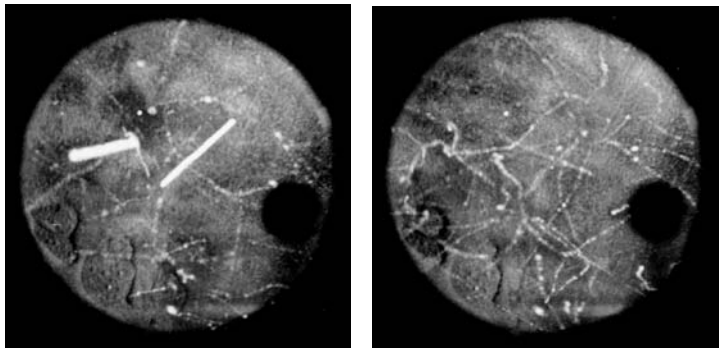


Figure 2.1
Tracks of α particles and electrons in a diffusion cloud chamber exposed to normal air in buildings. The different lengths and widths of α-particle tracks (left image) originate from projection effects

of electrons and one of ions in 1 cm^3 of air (at standard temperature and pressure).

ion dose

If the unit roentgen is expressed by the ion dose I in coulomb/kg, one obtains

$$1\,\mathrm{R} = 2.58 \times 10^{-4}\,\mathrm{C/kg}\ . \tag{2.21}$$

The tissue equivalent of roentgen is given by

$$1\,\mathrm{R} = 0.88\,\mathrm{rad} = 8.8\,\mathrm{mGy}\ . \tag{2.22}$$

For an approximate estimate of body doses for photon radiation it is generally sufficient to work out the photon equivalent dose according to

$$H_\mathrm{X} = \eta\, I_\mathrm{S}\ , \tag{2.23}$$

scale factor

where I_S is the standard ion dose in roentgen and the scale factor is given by

$$\eta = 38.8\,\mathrm{Sv\,(C/kg)^{-1}} = 0.01\,\mathrm{Sv/R}\ . \tag{2.24}$$

dose rate

To consider the time dependence of the dose equivalent or ion dose, we use the *dose rate*. The energy-dose rate is the change of the energy dose ΔD in the time Δt. Since the dose rate changes rapidly, particularly for radioactive sources with short half-life, it is advisable to use the differential notation (see Appendix Q). Depending on whether one prefers the notation $(\frac{\mathrm{d}}{\mathrm{d}t})$ introduced by Leibniz or the notation favored by Newton, as characterized by a dot over the quantity, one writes for the energy-dose rate

$$\frac{\mathrm{d}D}{\mathrm{d}t}\ \text{or, equivalently,}\ \dot{D}\ . \tag{2.25}$$

dose-equivalent rate

Correspondingly, also the dose-equivalent rate is given by

$$\frac{\mathrm{d}H}{\mathrm{d}t} \equiv \dot{H} \tag{2.26}$$

and the ion-dose rate by

ion-dose rate

$$\frac{\mathrm{d}I}{\mathrm{d}t} \equiv \dot{I} \ . \tag{2.27}$$

The physical units of these quantities are:

$$[\dot{D}] = \frac{\mathrm{J}}{\mathrm{kg\,s}} = \frac{\mathrm{W\,s}}{\mathrm{kg\,s}} = \frac{\mathrm{W}}{\mathrm{kg}} \ , \tag{2.28}$$

$$[\dot{H}] = [\dot{D}] \ , \tag{2.29}$$

$$[\dot{I}] = \frac{\mathrm{C}}{\mathrm{kg\,s}} = \frac{\mathrm{A\,s}}{\mathrm{kg\,s}} = \frac{\mathrm{A}}{\mathrm{kg}} \ . \tag{2.30}$$

$\dot{D}$ and $\dot{H}$ are therefore measured in watt per kilogram and $\dot{I}$ in ampere per kg.

The received dose can be related to the whole body (whole-body dose) or also only to specific parts of the body (partial-body dose). The dose equivalent that has accumulated within 50 years after a single incorporation[9] of radioactive substances in a certain organ or tissue is called '50-years dose-equivalent commitment'.

whole-body and partial-body dose

50-years dose-equivalent commitment

If a radiation exposure with an average per capita dose-equivalent rate $\overline{\dot{H}}(t)$ for a population group over an extended period has occurred, a dose-equivalent commitment is defined by

dose-equivalent commitment

$$H_\mathrm{f} = \sum \overline{\dot{H}}(t)\ \Delta t \ , \tag{2.31}$$

where one has to sum over the relevant time intervals Δt. If this dose rate $\overline{\dot{H}}(t)$ does not depend on the time, one has

$$H_\mathrm{f} = \overline{\dot{H}}\ t \ , \tag{2.32}$$

where t is the considered time interval.

The collective dose is the product of the total number of persons N by one person's average dose $\langle H \rangle$ in sievert or, more generally, the collective equivalent dose S is

collective dose

$$S = \sum_k P_k\ \langle H_k \rangle \ , \tag{2.33}$$

[9] When radioactive substances enter the human body, the radiation effects are different from those resulting from exposure to an external radiation source. Especially in the case of alpha radiation, which has a rather short range and normally never penetrates the skin, the exposure can be much more damaging after ingestion or inhalation. The terms ingestion and inhalation and the intake of radioactive compounds through wounds after accidents are usually subsumed under the expression *incorporation*.

Table 2.2
Tissue weighting factors w_T

organ or tissue	tissue weighting factor w_T
gonads	0.20
red bone marrow	0.12
colon	0.12
lung	0.12
stomach	0.12
bladder	0.05
chest	0.05
liver	0.05
esophagus	0.05
thyroid gland	0.05
skin	0.01
periosteum (bone surface)	0.01
other organs or tissue	0.05

where $\langle H_k \rangle$ is the per capita equivalent dose in an interval $H_k \ldots H_k + \Delta H_k$ and P_k the number of persons with radiation exposures in this interval.

effective dose equivalent

In many cases it is necessary to convert a partial-body dose into a whole-body dose. Therefore, a weighting factor w_T has to be attributed to the irradiated organs of the body. This effective dose equivalent is defined as

$$H_{\text{eff}} = \sum_{T=1}^{n} w_T H_T \ , \tag{2.34}$$

where H_T is the average dose equivalent in the irradiated organ or tissue and w_T is the weighting factor for the Tth organ or tissue.[10]

tissue weighting factor

For the purpose of radiation protection it is simply defined that the human has thirteen 'organs'. The weighting factors are normalized to 1 ($\sum w_i = 1$). These tissue weighting factors are compiled in Table 2.2.

radiation risk

It is assumed that the inhomogeneous irradiation of the body with an effective dose equivalent H_{eff} bears the same radiation risk as a homogeneous whole-body irradiation with $H = H_{\text{eff}}$.

The determination of the dose-equivalent rate by a pointlike radiation source of activity A can be accomplished using the following formula:

$$\dot{H} = \Gamma \frac{A}{r^2} \ . \tag{2.35}$$

In this equation r is the distance from the radiation source (in meters) and Γ a specific radiation constant which depends on the type and energy of the radiation. For β rays additionally the traveling

[10] In some cases the effective dose equivalent H_{eff} is also denoted with E in order to stress that in this case we are dealing with an effective dose.

Table 2.3
Dose constants Γ for some β- and γ-ray emitters[11]

radioisotope	**β dose constant** $\left(\frac{\text{Sv m}^2}{\text{Bq h}}\right)$
$^{32}_{15}$P	9.05×10^{-12}
$^{60}_{27}$Co	2.62×10^{-11}
$^{90}_{38}$Sr	2.00×10^{-11}
$^{131}_{53}$I	1.73×10^{-11}
$^{204}_{81}$Tl	1.30×10^{-11}

radioisotope	**γ dose constant** $\left(\frac{\text{Sv m}^2}{\text{Bq h}}\right)$
$^{41}_{18}$Ar	1.73×10^{-13}
$^{60}_{27}$Co	3.41×10^{-13}
$^{85}_{36}$Kr	3.14×10^{-16}
$^{131}_{53}$I	5.51×10^{-14}
$^{133}_{54}$Xe	3.68×10^{-15}
$^{137}_{55}$Cs	8.46×10^{-14}

dose constant

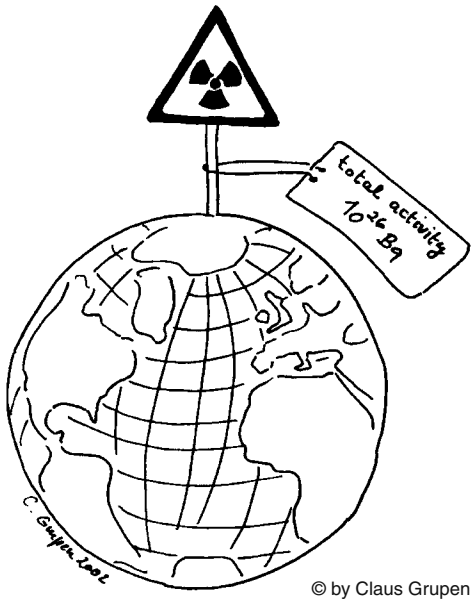
distance of electrons has to be considered. Table 2.3 lists the β and γ dose constants for some commonly used radiation sources. The $1/r^2$ dependence of the dose-equivalent rate is easily understood, if one considers that for isotropic emission (i.e. equally in all directions) the irradiated area for larger distances increases quadratically with distance r. The radiation emerging from the source has to pass through the surface of the virtual sphere (surface of sphere $= 4\pi r^2$), consequently the radiation intensity per unit area decreases like $1/r^2$ ('solid-angle effect').

$1/r^2$ law

The differences in the β and γ dose constants originate from the fact that electrons will normally deposit all of their energy in the body while the absorption power of the body for γ rays is much smaller. Differences in the β or γ dose constants for different radioisotopes have their origin in the different energy of the

energy absorption

[11] A chemical element is characterized by the number of positively charged nucleons (i.e. protons, with proton number $= Z$). Furthermore there are neutrons in the atomic nucleus which are essential for the binding of nuclei (neutron number $= N$). The atomic mass A is given by the sum of the proton and neutron numbers $Z + N$. Nuclei with fixed proton number but variable neutron number are called isotopes of the element with the atomic number Z. Isotopes which are radioactive are called radioisotopes. An isotope is characterized by the number of protons Z and neutrons N using the notation $^{A}_{Z}$*Element*. Since the name of the element is uniquely determined by Z, this index is frequently omitted, e.g. $^{137}_{55}$*Cesium* or ^{137}*Cesium*.



emitted β and γ rays. As an example ^{137}Cs radiates a photon of energy 662 keV and ^{60}Co two γ rays with energies 1.17 MeV and 1.33 MeV. Consequently the γ dose constant for ^{60}Co is larger than for ^{137}Cs, even though the absorption coefficient for MeV photons is somewhat smaller compared to 662-keV photons.

A pointlike ^{137}Cs γ-ray emitter of activity 10 MBq produces a dose-equivalent rate of 0.846 µSv/h at a distance of 1 m. A ^{60}Co source of the same activity leads to a dose-equivalent rate of 3.41 µSv/h at the same distance. The dose-rate ratio of these two sources corresponds roughly to the ratio of the deposited energies.

dose-rate ratio

2.1 Supplementary Information

Example 1

contamination
ambient-dose rate

A radiation officer detects a contamination with ^{131}I in a medical laboratory which leads to an ambient-dose rate of 1 mSv/h. He decides to seal the room and wait until the activity due to the iodine contamination has decayed to such a level that the ambient-dose rate is only 1 µSv/h. For how long has the room to be sealed?

The half-life of the ^{131}I isotope is 8 days. The dose rate and consequently the activity should be reduced by a factor of 1000. The decay law

$$N = N_0 \, \mathrm{e}^{-t/\tau}$$

decay time constant

leads to a time dependence of the activity A like

$$A = A_0\, \mathrm{e}^{-t/\tau} \ ,$$

where A_0 is the initial activity. With $A/A_0 = 10^{-3}$ and $\tau = T_{1/2}/\ln 2$ one has

$$\exp\left(-\frac{t\ \ln 2}{T_{1/2}}\right) = 10^{-3}$$

and

$$t = \left(T_{1/2}/\ln 2\right)\ \ln 1000 = 79.7\,\mathrm{days}\ .$$

Consequently about 10 half-lives ($(1/2)^{10} = 1/1024$) are required to reach the necessary reduction factor.

Example 2

specific activity

A historical example for the specific activity leads to the definition of the old unit *curie*:

The half-life of ^{226}Ra is 1600 years. This leads to the specific activity (i.e. the activity per gram) of:

$$A^* = \lambda\, N = \frac{\ln 2}{T_{1/2}}\,\frac{N_\mathrm{A}}{M_\mathrm{Ra}} = \frac{\ln 2}{1600\,\mathrm{yr}}\,\frac{6.022\times 10^{23}}{226}$$
$$= 3.7\times 10^{10}\,\mathrm{Bq} = 1\,\mathrm{curie}\ .$$

(N_A is the Avogadro constant and M_Ra the atomic weight of ^{226}Radium, $1\,\mathrm{yr} = 3.1536\times 10^7$ s.)

Example 3

modified dose quantities

The radiation units presented so far have been recommended by the International Commission on Radiological Protection (ICRP). In addition, also the International Commission on Radiation Units and Measurement (ICRU) has proposed a slightly modified concept of dose quantities in the field of radiation protection. These quantities differ from the units presented so far by higher specialization and stronger formalization. These specialized dosimetric units are frequently used in national radiation-protection regulations.

radiation field

If in a specific tissue, organ, or part of the body, T, the energy dose $D_{T,R}$ is caused by a radiation field of type R, then the equivalent or organ dose is obtained by using the radiation weighting factor w_R as follows:

$$H_{T,R} = w_R\ D_{T,R}\ , \tag{2.36}$$

where w_R is the radiation weighting factor given in Table 2.1.

radiation quality

Equation (2.36) defines the partial-body doses T for a given radiation field R. If several different types of radiation (α, β, γ, n) work together, the corresponding partial-body dose is given by

$$H_T = \sum_R H_{T,R} = \sum_R w_R\ D_{T,R}\ . \tag{2.37}$$

The effective dose equivalent $H_{\text{eff}} = E$ can be derived from Eq. (2.37) by weighting the different energy doses with the tissue weighting factors w_T, which have been presented in Table 2.2:

$$E = H_{\text{eff}} = \sum_T w_T \, H_T = \sum_T w_T \sum_R w_R \, D_{T,R} \ . \qquad (2.38)$$

operative units of personal dosimetry

Furthermore, dose units for penetrating external radiation (depositing most of their energy in the first 10 mm of tissue) and for radiation of low penetration depth (70 µm skin depth) have been introduced in many national radiation-protection regulations. In personal dosimetry these operative units are denoted with $H_{\text{p}}(10)$, $H_{\text{p}}(0.07)$.

depth dose

In the past these operative units had been determined with film badges (see Sect. 5.6). However, the measurement of the depth doses $H_{\text{p}}(10)$ and $H_{\text{p}}(0.07)$ with film badges is not very accurate. A precise value for the skin dose as derived from the penetration depth of the radiation can be obtained with more sophisticated dosimeters. Such a new type of dosimeter, called 'sliding-shadow' dosimeter, has been developed, which allows a reliable determination of the skin doses.[12] These dosimeters are optimized for a depth-dose determination and allow at the same time a determination of energy and angle of incidence of photons, and they can further discriminate between β and γ rays.

'sliding-shadow' method

The availability of this new measurement technique necessitated to convert the hitherto existing quantities $H_{\text{p}}(10)$ and $H_{\text{p}}(0.07)$ into the new quantities $H^*(10)$ and $H^*(0.07)$. The conversion factors depend on the photon energy and the angle of incidence. For environmental radiation, γ rays or X rays from X-ray tubes with accelerating voltages below 50 kV and above 400 kV the conversion factor is 1; i.e. the old and new depth doses are identical. For γ rays from radioactive sources which are frequently used as X-ray sources (e.g. ^{57}Co, ^{67}Ga, ^{75}Se, $^{99\text{m}}$Tc, ^{153}Gd, ^{153}Sm, ^{169}Yb, ^{170}Tm, ^{186}Re, ^{192}Ir, ^{197}Hg, ^{199}Au, ^{201}Tl, ^{241}Am) and for the radiation field of X-ray tubes operated with accelerating voltages between 50 kV and 400 kV, the conversion factors are $H^*(10)/H_{\text{p}}(10) = 1.3$ and $H^*(0.07)/H_{\text{p}}(0.07) = 1.3$. This means that the depth doses as determined with the old film badges have to be increased by 30%.

conversion factor for depth doses

More details on the new skin doses can be found in the article "New quantities in radiation protection and conversion coefficients"

[12] These 'sliding-shadow' dosimeters use a special arrangement of structured metal and plastic filters and directional indicators. In addition, β rays can be distinguished from γ rays, which is essential for a reliable individual depth-dose information. The different absorption coefficients of the filters used allow an accurate measurement of the skin dose over a wide energy range. The basic detector behind the arrangement of filters is still a sensitive film, like in the old film badge.

Proposal for a new unit for radiation protection

The common units for radiation doses (Gy, Sv) are not very persuasive for a broader audience. The layman also has difficulties to interpret a dose given in Gy or Sv. Even relatively low radiation exposures which can only be detected because of extraordinarily sensitive measurement devices (one can measure the decay of individual atomic nuclei without difficulty) occasionally lead to over-reactions in public discussions. It is, however, very important to express radiation levels, caused, for example, by CASTOR transports or nuclear power plants, in units which can be understood and interpreted by the layman. It is perfectly sufficient to appreciate the order of magnitude of a radiation exposure, i.e., in easily comprehensible and self-explaining units which can be judged upon intuitively.
Mankind has developed with permanent natural radiation caused by cosmic rays and terrestrial rays and by permanent incorporation by ingestion and inhalation of natural radioisotopes. There are no hints whatsoever that this radiation has created any biological defect, it may even have increased the biodiversity. The natural radiation dose is subject to regional variations, but the natural annual radiation dose does not fall below 2 mSv for anybody. This natural annual dose sets the scale on which to judge on additional radiation burdens by civilization, for example, by medical diagnosis.
It is therefore proposed to use this typical value of the inevitable annual dose (IAD) due to natural radiation as a scale against which additional radiation exposures should be judged in discussions in the public:[13]

$$\mathbf{1\,IAD = 2\,mSv}\ .$$

In these units the following table gives some typical radiation exposures.

type of radiation exposure	dose in IAD
X-ray of a tooth	0.005
radiation level by nuclear power plants	≤ 0.01/yr
CASTOR transport for accompanying persons	≤ 0.015
air flight London – New York	0.015
X-ray of the chest	0.05
mammography	0.25
scintigraphy of the thyroid gland	0.40
heavy smoker (more than 20 cigarettes per day)	0.50/yr
positron-emission tomography	4.0
computer tomography of the chest	5.0
limit for radiation-exposed persons in Europe	10
limit for radiation-exposed persons in the USA	25
maximum life dose for radiation-exposed persons in Europe	200
lethal dose	2000
local cancer therapy	$\approx 30\,000$

Based on these numbers everybody can judge independently on the realistic risk caused by radiation exposures.

[13] G. Charpak and R. L. Garwin proposed a similar unit; they set the scale by the body-intrinsic radioactivity which leads to an annual radiation dose of 0.2 mSv. They named this dose 1 DARI, where the acronym DARI stands for Dose Annuelle due aux Radiations Internes. Europhysics News 33/1, p. 14 (2002).

published by the British Committee on Radiation Units and Measurements (see also J. Soc. Radiol. Prot. Vol. 6, p. 131–136, (1986)).

Summary

The essential units of radiation protection are becquerel (Bq) for the activity, gray (Gy) for the purely physical energy deposition per mass unit, and sievert (Sv) for the energy dose weighted by the biological effectiveness. A further characteristic quantity for a radioactive isotope is its half-life $T_{1/2}$. Radioisotopes with large half-lives are associated with a low activity, and those with short half-lives with a high one. The activity alone is not a good measure for a possible biological damage. This damage depends on the type of emitter and, of course, on the distance to the radiation source.

2.2 Problems

Problem 1

A radioactive material possesses an approximately constant gamma activity of 1 GBq. Per decay 1.5 MeV are liberated. What is the daily energy dose if the ionizing radiation is absorbed in an amount of material of mass $m = 10\,\mathrm{kg}$?

Problem 2

In a nuclear physics laboratory a researcher has inhaled dust of a ^{90}Sr isotope by accident, which has lead to a dose rate of 1 µSv/h in his body. The physical half-life of ^{90}Sr is 28.5 yrs, the biological half-life for retention in the lung (see Chap. 13, Page 217) is only 80 days. How long does it take until the dose rate has decreased to 0.1 µSv/h?
(The biological half-life is defined by the time until 50% of the activity is eliminated by the body by normal biological activity.)

Problem 3

At a distance of 2 m from a pointlike ^{60}Co source a dose rate of 100 µSv/h is measured. What is the activity of the source?
(To solve this problem you should use information from Figs. 3.4 and 4.4.)

Problem 4

nuclear medicine

The radioisotope technetium 99m is frequently used in nuclear medicine. ^{99m}Tc is a metastable state of ^{99}Tc, it has a half-life of 6 h. What kind of activity has a patient who was administered an activity of 10 MBq ^{99m}Tc for a kidney examination after a period of two days? For this estimate one can assume that the effective half-life can be approximated by the physical half-life.

3 Basic Nuclear Physics

"Just as the letters of an alphabet can be variously ordered to create an infinite number of words, so diverse combinations of atoms produce an inexhaustible supply of entities."

Epicurus 341–270 B. C.

The chemical properties of elements are characterized by the number of positively charged nucleons (protons) and the (identical) number of electrons. Atoms consisting of a compact nucleus and an electron shell have diameters on the order of 10^{-10} m. Atomic nuclei are much smaller than atoms, their diameter is on the order of 10^{-15} m. Nearly all the mass of an atom is concentrated in the atomic nucleus.

building blocks of nuclei (nucleons)

In addition to protons in the nucleus there are further nucleons which are electrically neutral, namely neutrons. For light elements the number of protons is approximately equal to the number of neutrons; for heavier elements the neutron fraction dominates.

Based on the electrostatic repulsion of positively charged protons, atomic nuclei would disintegrate if there were not a stronger force binding the nucleons together. Protons and neutrons themselves are composite objects which consist of quarks. Positively charged nuclei and shell electrons are bound together by the electromagnetic interaction via the exchange of photons. In a similar way quarks in the nucleons are bound by the exchange of gluons. The residual interaction of gluons binds the nucleons together in the atomic nucleus, analogously to how the residual interaction of electric charges of nuclei and electrons is responsible for the binding of molecules. The strong interaction which glues the nucleons together is about a hundred times stronger than the electromagnetic interaction.

quarks and gluons

An atomic nucleus of mass number A consists of Z protons and N neutrons: $A = Z + N$. The atomic number Z of stable nuclei is related to the atomic mass approximately according to

$$Z_{\text{stable}} = \frac{A}{1.98 + 0.0155A^{2/3}} \ . \tag{3.1}$$

For light nuclei ($Z \leq 20$, calcium) $Z = A/2$ holds; for heavy nuclei one has approximately $Z = A/2.5$.

The atomic number Z characterizes the chemical properties of an atom. Nuclei with fixed Z and variable N are called isotopes. If the isotopes are radioactive, they are called radioisotopes. Nuclei with a fixed sum of protons and neutrons, i.e. constant mass number

isotopes

C. Grupen, *Introduction to Radiation Protection*,
Graduate Texts in Physics, DOI 10.1007/978-3-642-02586-0_3,

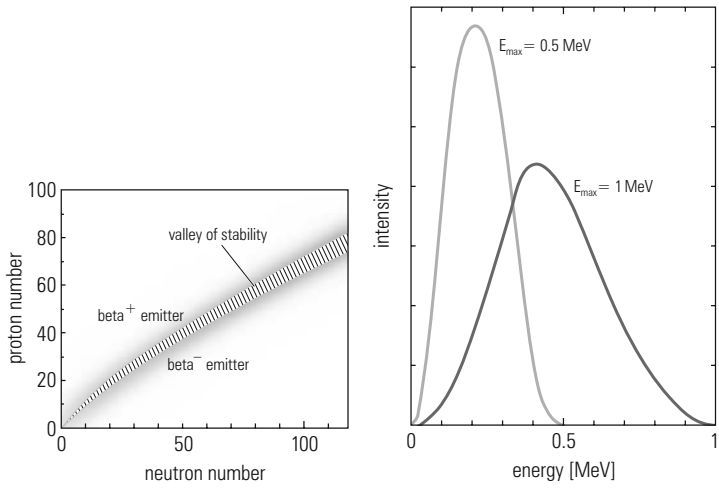


Figure 3.1
Neutron-to-proton ratio for stable nuclei (β^- particles are electrons and β^+ are positrons)

Figure 3.2
Two examples of energy spectra of electrons in nuclear β decay for two different maximum energies

isobars
isotones

A, are called isobars. Nuclei with fixed neutron but varying proton number are called isotones. Protons and neutrons are approximately of the same mass, $m_{\text{neutron}}/m_{\text{proton}} = 1.001\,38$.

β^- emitter

Nuclei with excess neutrons are normally β^- emitters. In this nuclear process a neutron (n) transforms into a proton (p) under emission of an electron (e^-) and an electron antineutrino ($\overline{\nu}_e$),

$$n \longrightarrow p + e^- + \overline{\nu}_e \ . \tag{3.2}$$

β^+ emitter

Free neutrons have a lifetime of 886 seconds. Light nuclei with excess protons are mostly β^+ emitters (see Fig. 3.1). In this case a proton decays into a neutron under emission of a positron (e^+) and a neutrino (ν_e),

$$p \longrightarrow n + e^+ + \nu_e \ . \tag{3.3}$$

Free protons are stable ($\tau_p > 10^{31}$ years), since there are no lighter baryons into which they could decay.

Since the transition energy can be shared between the three final-state particles in an arbitrary way, the energy spectra of electrons and positrons are continuous with a maximum energy $E_{\max}$ (see Fig. 3.2). In β^+ emitters also electron capture can occur. In this process a proton absorbs a shell electron (most frequently of the innermost shell, the K shell) to form a neutron under the emission of a neutrino,

electron capture

$$p + e^- \longrightarrow n + \nu_e \ . \tag{3.4}$$

β decays frequently lead to excited nuclear levels of the final-state nucleus ('daughter nucleus'). The excited daughter nucleus deexcites into the ground state under the emission of γ rays. Since the

energy difference between the excited nucleus and the ground state is fixed, γ rays, in contrast to decay electrons from nuclear β decay, have a discrete energy.

As an example for β decays let us consider the following decay:

$$\begin{array}{l} {}^{137}_{55}\mathrm{Cs} \longrightarrow {}^{137}_{56}\mathrm{Ba}^{*} + e^{-} + \overline{\nu}_{e} \\ \qquad\qquad \hookrightarrow \ {}^{137}_{56}\mathrm{Ba} + \gamma \end{array} \quad . \tag{3.5}$$

The electron can receive a maximum energy of 0.51 MeV (1.17 MeV if the decay proceeds directly into the ground state).[1] The photon from the decay of the excited Ba* has an energy of 662 keV. All this information is best summarized in a decay-level diagram (see Fig. 3.3).

decay-level diagram

Apart from the properties mentioned above, the branching ratio and the half-lives are given. For the case of $^{137}_{55}$Cs the decay proceeds to the excited barium level with a probability of 94% and directly into the ground state with a probability of 6%. The index 'm' on the barium nucleus (see Fig. 3.3) characterizes a metastable state with a half-life of 2.6 min.[2] In this decay-level scheme the vertical axis gives an idea of the transition energy.

branching ratio

metastable state

A radioisotope which is of particular importance for medical applications is $^{60}_{27}$Co. It decays under electron emission into the doubly excited state $^{60}_{28}$Ni** with subsequent emission of two γ rays with energies of 1.17 MeV and 1.33 MeV. It is these γ rays which are used in nuclear medicine for cancer treatment,

'cobalt bomb'

$$\begin{array}{l} {}^{60}_{27}\mathrm{Co} \longrightarrow {}^{60}_{28}\mathrm{Ni}^{**} + e^{-} + \overline{\nu}_{e} \\ \qquad\qquad \hookrightarrow \ \mathrm{Ni}^{*} + \gamma\,(1.17\,\mathrm{MeV}) \\ \qquad\qquad\qquad \hookrightarrow \ \mathrm{Ni} + \gamma\,(1.33\,\mathrm{MeV}) \end{array} \quad . \tag{3.6}$$

Figure 3.4 shows the decay-level scheme of $^{60}_{27}$Co.

[1] Energies in nuclear physics are usually measured in electron volts (eV). 1 eV is that energy which a singly charged particle receives, if it passes through a potential difference of one volt. Electrons in an old-fashioned TV set are usually accelerated up to an energy of 20 keV. 1 keV $= 10^3$ eV; 1 MeV $= 10^6$ eV.

[2] Relatively long-lived states of nuclei whose decay is forbidden by selection rules are called metastable. (Selection rules are established by conservation laws of quantities which are mostly conserved, but not in all kinds of transitions. An example is the isospin, which is a quantum number assigned e.g. to protons and neutrons. Protons and neutrons are grouped into an isospin doublet of isospin 1/2, with isospin projections of $+1/2$ for the proton and $-1/2$ for the neutron.) These excited levels are, however, not completely stable since the selection rules are not fully respected or are possibly only valid for a process which normally forms the main decay which dominates over weaker transitions.

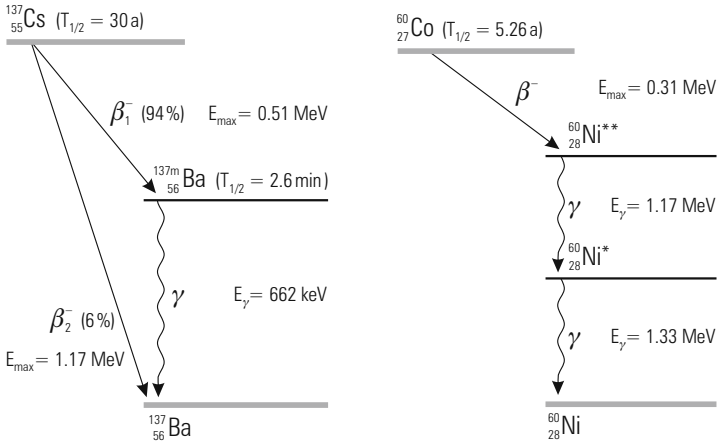
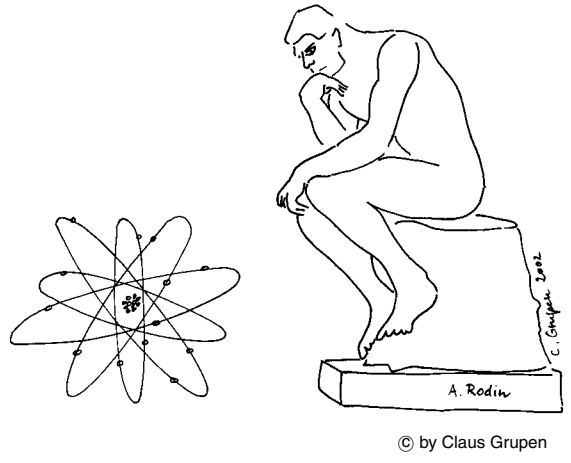


Figure 3.3
Decay-level diagram of $^{137}_{55}$Cs

Figure 3.4
Decay-level diagram of $^{60}_{27}$Co. The excited states of ^{60}Ni are short-lived



An example for pure β^- decay without γ emission is shown in Fig. 3.5. $^{90}_{38}$Sr is very important for aspects of radiation protection because it accumulates after incorporation particularly in bones. There it can create a substantial biological damage. For this reason it is called a 'bone seeker'.

'bone seeker' positron emitter

The positron emitter $^{22}_{11}$Na is of particular importance for imaging techniques in positron-emission tomography (PET) (Fig. 3.6).

It is rather difficult to read the transition energy $E_{\max}$ from the continuous β-ray spectra (see Fig. 3.2). The momentum spectrum of decay electrons can be described in first approximation by

$$N(p) \sim p^2(E - E_{\max})^2 \ , \tag{3.7}$$

where p is the momentum of the electrons.

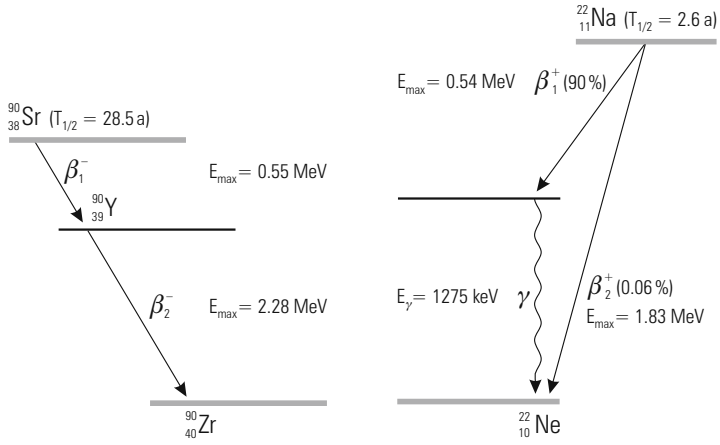


Figure 3.5
Decay-level scheme of $^{90}_{38}$Sr

Figure 3.6
Decay-level scheme of $^{22}_{11}$Na. The 'missing' branching ratio of about 10% is due to electron capture, which proceeds to the shown excited state of ^{22}Ne

If now $\sqrt{N(p)/p^2}$ is plotted as a function of the energy (Fermi–Kurie plot[3]), the transition energy can easily be determined (Fig. 3.7) and the β emitter can be reliably identified.

Fermi–Kurie plot

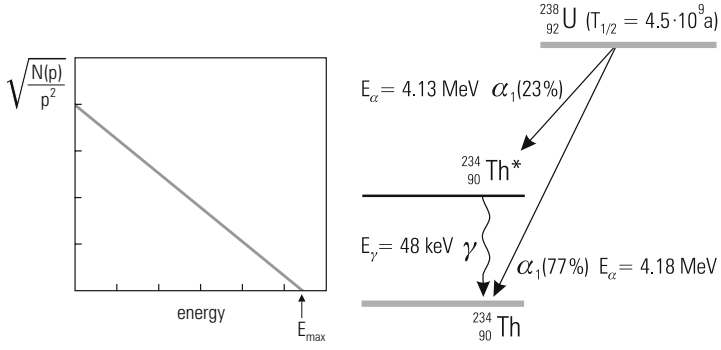


Figure 3.7
Fermi–Kurie plot of the spectrum for a β-ray emitter

Figure 3.8
Decay-level diagram of $^{238}_{92}$U

Heavy, high-mass nuclei tend to decay under the emission of an α particle, i.e. helium nucleus. This decay mode is frequently in competition to β^+ decay, but the proton excess can more easily be reduced by the emission of α particles. Also, there are theoretical reasons (nuclear shell model, strong binding of helium nuclei) why α decay is usually favored. Thus $^{238}_{92}$U decays into excited states of the $^{234}_{90}$Th isotope. Since the nuclear levels are characterized by fixed energies, the emitted α particles in this two-body decay are monoenergetic (see Fig. 3.8). Apart from α emission heavy nuclei

α decay

[3] This way of plotting the β-ray spectrum was first proposed by Franz Nevell Devereux Kurie. The similarity of his name with the name of Madame Curie is just an accident.

Determination of the half-life of ^{220}Rn

In a thorium-oxide radioactive source (with ^{228}Th) all radioisotopes of the thorium decay chain are in equilibrium,

$$^{228}\mathrm{Th} \xrightarrow{\alpha} {}^{224}\mathrm{Ra} \xrightarrow{\alpha} {}^{220}\mathrm{Rn} \xrightarrow{\alpha} {}^{216}\mathrm{Po} \xrightarrow{\alpha} {}^{212}\mathrm{Pb} \xrightarrow{\beta} {}^{212}\mathrm{Bi} \xrightarrow{\beta} {}^{212}\mathrm{Po} \xrightarrow{\alpha} {}^{208}\mathrm{Pb} \ .$$

^{224}Ra decays into the noble-gas isotope ^{220}Rn by α decay. This gaseous isotope is transferred into a small ionization chamber (see Sect. 5.1) by means of a small rubber blower. There it decays under α emission into ^{216}Po. ^{216}Po transforms itself into ^{212}Pb within a very short decay time by α emission. The α particles emitted from ^{220}Rn and ^{216}Po are measured practically at the same time. In these decays in total an energy of 13 MeV is deposited in the ionization chamber. Therefore, a very clear, nearly background-free signal is obtained. The count rate as a function of time is shown in Fig. 3.9 to the left in linear and to the right in semilogarithmic scale. Because of the exponential decay law the decay curve is a linear function in the semilogarithmic representation.
The activity can be described by

$$A = A_0 \, \mathrm{e}^{-t/\tau} \ .$$

This formula – using two measurements taken at different times – can be used to work out the half-life from the data according to

$$\ln A_1 = \ln A_0 - t_1/\tau \ , \ \ln A_2 = \ln A_0 - t_2/\tau \ .$$

By subtracting these two equations one arrives at a half-life according to the following relation:

$$T_{1/2} = \tau \ \ln 2 = \ln 2 \, \frac{t_2 - t_1}{\ln(A_1/A_2)} \ .$$

If one considers the measurement errors which are not plotted in the diagrams, one obtains

$$T_{1/2} = (55 \pm 2)\,\mathrm{s}$$

in good agreement with the value of 55.6 seconds, as given in the nuclear data tables.

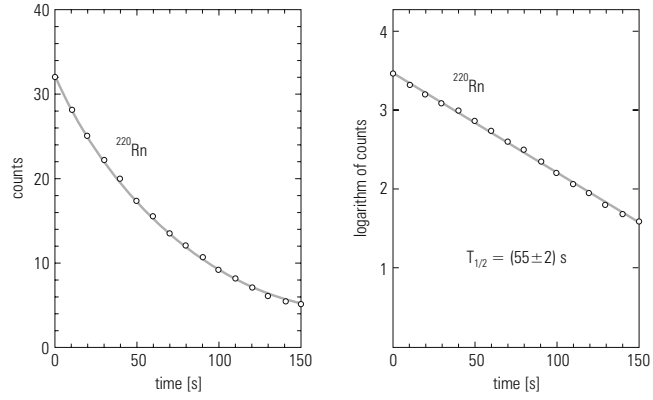


Figure 3.9
Lifetime determination of ^{220}Rn; in linear (left) and in semilogarithmic representation (right)

Determination of the absolute activity using the β–γ coincidence method

The absolute activity of a radiation source which emits electrons and photons at the same time (e.g. ^{137}Cs, ^{60}Co) can be determined with the beta–gamma coincidence method. For this purpose both a β-sensitive Geiger counter and a γ-sensitive one are required. In the ideal case the β counter measures only electrons and the γ counter only photons.
In the β counter one obtains a counting rate

$$N_\beta = \varepsilon_\beta \, A \ ,$$

where ε_β is the efficiency for electrons and A the activity of the source. Correspondingly one has

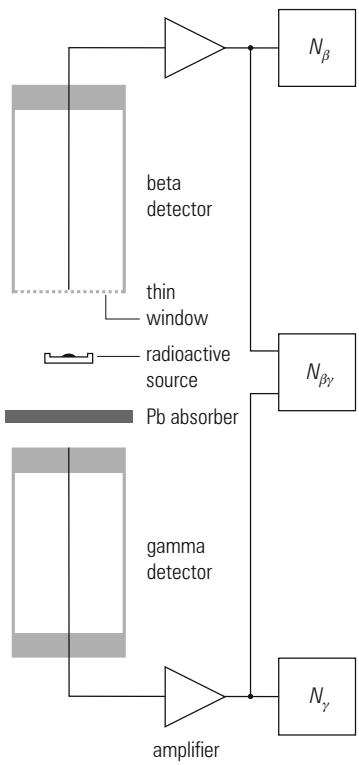
$$N_\gamma = \varepsilon_\gamma \, A \ .$$

A thin lead plate in front of the γ counter absorbs the electrons so that they are not recorded by the γ counter. The coincidence rate of both counters, therefore, is

$$N_{\beta\gamma} = \varepsilon_\beta \, \varepsilon_\gamma \, A \ .$$

From these relations the activity can be calculated:

$$A = \frac{N_\beta \, N_\gamma}{N_{\beta\gamma}} \ .$$



In practical cases some corrections are in order. Even though the efficiency of the β counter for γ rays is small, it will still also measure some photons. N_β and $N_{\beta\gamma}$ consequently will be too large. The number of events which are caused by photons in the β counter can be determined by absorption measurements. In addition, one has to consider the background rate and the chance-coincidence rate (see page 26). In the same way possible solid-angle effects have to be taken into account. If high counting rates are encountered one also has to correct for the dead time of the detectors.
However, the described method is only restricted to those radioactive sources which undergo a β transition with a subsequent γ decay.

Figure 3.10
Beta–gamma coincidence method for the determination of the absolute activity of radioactive sources

Chance coincidences

Measurements for rare events can be plagued by chance coincidences. If the single count rates of two counters are N_1 and N_2 and if the time resolution of the coincidence arrangement is τ, then the rate of uncorrelated coincidences is

$$N_{12} = 2 \times N_1 \times N_2 \times \tau \ .$$

The factor 2 originates from the fact that a coincidence will even occur if there is just a very small overlap of the two signals. If the pulse widths of the two counters are different (τ_1, τ_2), the chance-coincidence rate is modified to be

$$N_{12} = N_1 \times N_2 \times (\tau_1 + \tau_2) \ .$$

If the single count rates were $N_1 = N_2 = 1\,\text{kHz}$, one would obtain for a time resolution of 1 µs a chance-coincidence rate of

$$N_{12} = 2 \times 10^3 \times 10^3 \times 10^{-6}/\text{s} = 2/\text{s} \ .$$

Correspondingly the n-times chance-coincidence rates of n counters are given by

$$N_n = n \times N_1 \times N_2 \times N_3 \times \cdots \times N_n \times \tau^{n-1} \ ,$$

if N_i ($i = 1, 2, \ldots, n$) were the single count rates and if τ is the corresponding time resolution assumed to be the same for all counters.

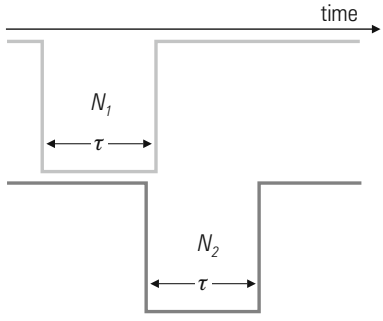


Figure 3.11
Illustration for the determination of the number of chance coincidences

(for $Z \geq 90$) can also decay by spontaneous fission.

nuclear fission

In nuclear disintegrations fission products are created which have a relatively large number of neutrons. The neutron excess can be reduced by β^- emission; it is, however, also possible that the neutrons are emitted directly (prompt neutrons or delayed neutrons). An example for an induced fission of $^{235}_{92}\text{U}$ is given by the reaction

neutron emission

$$^{235}\text{U} + n \longrightarrow {}^{236}\text{U}^* \longrightarrow {}^{139}\text{I}^* + {}^{96}\text{Y}^* + n \ . \qquad (3.8)$$

Initially a prompt fission neutron is emitted, but the highly excited iodine and yttrium nuclei will also emit a neutron each, finally reaching stable nuclear states by successive β^- decays.

Ra–Be source
Am–Be source

However, neutrons can also be emitted from radium–beryllium sources or americium–beryllium sources. The α particles from the

radium or americium decay create neutrons by interactions with beryllium,

$$\alpha + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{12}_{6}\mathrm{C} + n \ . \tag{3.9}$$

The most important properties of the different types of radiation are compiled in Table 3.1.

type of radiation	emitted particle	typical energy
α rays	${}^{4}_{2}\mathrm{He}$	4–6 MeV
β^- rays	e^-	$\approx$ 1 MeV
β^+ rays	e^+	$\approx$ 1 MeV
γ rays	γ	$\approx$ 1 MeV
neutrons	n	1–6 MeV
X rays	γ	10–100 keV

Table 3.1
Some properties of different types of radiation

level transitions in the atomic shell

As a result of a nuclear transmutation atomic electrons can also be emitted: an atomic nucleus will normally release its excess energy E_{ex} by γ emission. However, it is also possible that its excitation energy is transferred directly onto an electron in the atomic shell, which then can leave the atom with an energy $E_{\mathrm{ex}} - E_{\mathrm{bind}}$. Here E_{bind} is the electron binding energy in the relevant shell. For example, the ^{207}Pb nucleus can emit a photon of 570 keV from its excited state or it can emit an electron with $570\,\mathrm{keV} - E_{\mathrm{K}} = 482\,\mathrm{keV}$ or $570\,\mathrm{keV} - E_{\mathrm{L}} = 554\,\mathrm{keV}$, respectively, from the atomic shell. Such electrons are called *conversion electrons*. E_{K} and E_{L} are the binding energies of the K and L shell, $E_{\mathrm{K}} = 88\,\mathrm{keV}$, $E_{\mathrm{L}} = 16\,\mathrm{keV}$.

conversion electrons

If a vacancy in the atomic shell is produced by electron capture or conversion, the electrons in the atomic shell will try to reach a more favorable energetic state. In this way a vacancy in the K shell can be filled up by an electron from the L shell. The energy difference $E_{\mathrm{K}} - E_{\mathrm{L}}$ is liberated and can either be emitted as characteristic X rays with $E_{\mathrm{X}} = E_{\mathrm{K}} - E_{\mathrm{L}}$ or, if $E_{\mathrm{K}} - E_{\mathrm{L}} > E_{\mathrm{L}}$, it can be transferred directly to another L electron which will leave the atom with the energy $E_{\mathrm{K}} - 2E_{\mathrm{L}}$. Such an electron is called *Auger electron*.

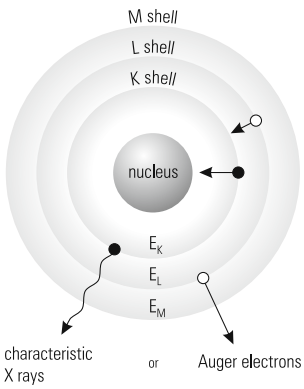


Figure 3.12
Illustration for the production of characteristic X rays and Auger electrons

Table 3.1 contains some characteristic properties of α, β, γ rays and neutrons. In addition, also X rays, which are of high relevance for radiation protection, are listed. X rays are very short-wavelength electromagnetic radiation similar to γ radiation. Apart from the typical energies of X rays (10–100 keV), which are normally somewhat smaller than the energies of γ rays, X rays are only different from γ rays by their production mechanism. X rays are produced if electrons are decelerated in the Coulomb field of atomic nuclei (this process is called bremsstrahlung; it is used in an X-ray tube to generate X rays – see also Chap. 10) or in atomic transitions in

bremsstrahlung

the atomic shell. Photons produced in an X-ray tube have a continuous bremsstrahlung spectrum, which is superimposed by sharp, monoenergetic X-ray lines which are characteristic for the material in which the electrons are decelerated (characteristic X rays, see Fig. 3.12; see also Fig. 10.3, page 162).

X rays

3.1 Supplementary Information

Example 1

An excited atomic nucleus (e.g. ^{137}Ba*) will emit its energy in the form of γ rays or conversion electrons. The conversion probability η is the ratio of the number of decays with emission of electrons to the total number of all transitions of the atomic nucleus, $\eta = N_{\text{conversion}}/(N_{\text{conversion}} + N_{\gamma\ \text{emission}})$. η is proportional to $Z^3\alpha^4$, where Z is the atomic number and α ($= \frac{1}{137}$) the fine-structure constant. Additionally, the conversion probability also depends on the excitation energy of the nucleus. In case of the metastable $^{137\text{m}}$Ba state with excitation energy 662 keV, $\eta = 8.4\%$; i.e., in 91.6% of the cases a photon will be emitted with this energy and in 8.4% of the cases a conversion electron will be emitted with energy 662 keV $- E_X$, where E_X is the binding energy in the X shell ($X = \text{K, L, M, }\ldots$). The conversion probability is large for low γ-ray energies and high atomic numbers. For example, the conversion probability for the metastable 59 keV transition of $^{60\text{m}}_{27}$Co is 98%. The low-energy γ quanta consequently are only emitted with a probability of 2%.

conversion probability

If the excitation energy of the nucleus is larger than twice the electron mass (511 keV/c^2), the ground state can also be reached by the emission of an electron–positron pair in rare cases. This process is called internal pair production.

internal pair production

Example 2

The ^{235}U isotope ($T_{1/2} = 7 \times 10^8$ yrs), which is of high importance for nuclear power plants, occurs with a natural isotopic abundance of 0.72%, while the ^{238}U isotope ($T_{1/2} = 4.5 \times 10^9$ yrs) is much more common with its isotopic abundance of 99.28%. This allows us, in principle, to estimate the age of the planet Earth if it is assumed that the uranium isotopes were originally of comparable abundance,

age of the Earth
isotopic balance

$$N(^{238}\text{U}) = N_0(^{238}\text{U})\, \text{e}^{-\lambda_1 t}\ ,$$
$$N(^{235}\text{U}) = N_0(^{235}\text{U})\, \text{e}^{-\lambda_2 t}\ .$$

Because of $N_0(^{238}\text{U}) = N_0(^{235}\text{U})$, $N(^{238}\text{U}) = 0.9928$, and $N(^{235}\text{U}) = 0.0072$ we have

$$N(^{238}\text{U})\, \text{e}^{\lambda_1 t} = N(^{235}\text{U})\, \text{e}^{\lambda_2 t}\ .$$

Consequently

$$\frac{N(^{238}\mathrm{U})}{N(^{235}\mathrm{U})} = \mathrm{e}^{(\lambda_2-\lambda_1)\,t} \ .$$

This relation can be solved for t and one obtains for the age of the Earth

$$t = \frac{1}{\lambda_2 - \lambda_1} \ln \frac{N(^{238}\mathrm{U})}{N(^{235}\mathrm{U})} \ ;$$

with $\lambda = \frac{\ln 2}{T_{1/2}}$ one gets

$$\begin{aligned} t &= \frac{T_{1/2}^{(1)}\, T_{1/2}^{(2)}}{\ln 2 \left(T_{1/2}^{(1)} - T_{1/2}^{(2)}\right)} \ln \frac{N(^{238}\mathrm{U})}{N(^{235}\mathrm{U})} \\ &= 5.9 \times 10^9 \text{ yrs} \approx 1.9 \times 10^{17} \text{ s} \ . \end{aligned}$$

This age agrees favorably well with the result of geological age determinations.

Example 3

classical explosive

The detonation power of a bomb is usually expressed in kilotons (kT) or megatons TNT equivalent, where TNT is the classical explosive trinitrotoluol. One kiloton TNT corresponds to a liberated energy of 9.1×10^{11} cal $= 3.8 \times 10^{12}$ joule.

The fission of a uranium nucleus releases an energy of approximately 200 MeV. 1 kT TNT, therefore, corresponds to a number N of fission processes:

$$\begin{aligned} N &= \frac{3.8 \times 10^{12}\,\mathrm{J}}{1.6 \times 10^{-13}\,\mathrm{J/MeV} \times 200\,\mathrm{MeV/fission}} \\ &= 1.19 \times 10^{23} \text{ fissions/kT} \ . \end{aligned}$$

nuclear-fission bomb

The Hiroshima bomb had a detonation power of 14 kT TNT. What kind of activity of ^{137}Cs was released in this explosion? Assuming that this radioactive fallout rained down on an area A of $20 \times 20\,\mathrm{km}^2$, the pollution due to ^{137}Cs per square meter can be worked out along the following lines:

$$N(\text{Hiroshima}) = 1.19 \times 10^{23} \times 14 = 1.663 \times 10^{24} \text{ fissions} \ .$$

Hiroshima

The Hiroshima bomb contained 64 kg uranium with a fraction of 80% ^{235}U. According to present-day estimations less than 1 kg was brought to fission. The fission yield of ^{137}Cs for such a bomb is on the order of 6.2% (see Fig. 12.1). Therefore, in total a number of

$$N_1 = 1.663 \times 10^{24} \times 6.2 \times 10^{-2} = 1.03 \times 10^{23}\ ^{137}\mathrm{Cs} \text{ atoms}$$

were released. The half-life of ^{137}Cs is 30 years. Therefore, the decay constant is worked out

$$\lambda = \frac{1}{\tau} = \frac{\ln 2}{T_{1/2}} = 7.3 \times 10^{-10}\,\frac{1}{\mathrm{s}}\ ,$$

consequently the total ^{137}Cs activity is

$$N_2 = \lambda \times N_1 = 7.53 \times 10^{13}\,\mathrm{Bq}\ (= 2036\,\mathrm{Ci})\ ,$$

corresponding to a ^{137}Cs pollution of the ground of

$$\frac{N_2}{A} = 188.25\,\frac{\mathrm{kBq}}{\mathrm{m}^2}\ .$$

Summary

Ionizing radiation is released in most nuclear transmutations. α rays are helium nuclei. $\beta^-(\beta^+)$ sources emit electrons (β^-) or their antiparticles (β^+ = positrons). In β^- decays neutrons are transformed into protons in the atomic nucleus under the emission of electrons and electron antineutrinos. In β^+ decays protons are transformed into neutrons under the emission of positrons and electron neutrinos. γ rays are normally a consequence of α and β decays. A neutron excess in fission products can be reduced by prompt neutron emission or by β^- decays. α and β decays alter the chemical nature of an element. As a consequence of this nuclear transition also processes in the atomic shell will follow. These lead to the emission of X rays and/or Auger electrons.

3.2 Problems

Problem 1 In heavy nuclei the neutron fraction dominates. Why?

Problem 2 In nuclear-fission processes predominantly β^--emitting radioisotopes are produced. Why?

Problem 3 Estimate how long it takes until an electron of 100 keV will be stopped in tissue (you may use information from Fig. 4.4 for the solution of this problem).

Problem 4 Compare the kinetic energy of a tennis ball of velocity 200 km/h ($m = 60$ g) with that of a 5 MeV α particle! Work out also the energy density for the tennis ball (diameter 6.5 cm) and those of the α particle (diameter 3.2×10^{-13} cm).

Problem 5 The fission of ^{235}U liberates an energy of approximately 1 MeV per nucleon. Work out the mass loss for the complete fission of one ton of uranium 235!

4 Interaction of Ionizing Radiation with Matter

"A careful analysis of the process of observation in atomic physics has shown that the subatomic particles have no meaning as isolated entities, but can only be understood as interconnections between the preparation of an experiment and the subsequent measurement."

Erwin Schrödinger

Charged particles (electrons, positrons, protons, helium nuclei, ...) will ionize matter in a direct way, in contrast to neutral particles (neutrons, neutrinos, ...) or short-wavelength electromagnetic radiation (X rays and γ rays), which will ionize only indirectly. Strictly speaking, radiation is never directly measured, rather it can only be detected via its interaction with matter. A large number of specific interaction processes exists. These interactions are characteristic for each of charged particles, neutrons, neutrinos, X rays, and γ radiation.

4.1 Detection of Charged Particles

In passing through matter, charged particles lose some kinetic energy by excitation of bound electrons and by ionization, e.g. for α particles:

$$\begin{aligned} \alpha + \text{atom} &\rightarrow \text{atom}^* + \alpha \\ &\quad \hookrightarrow \text{atom} + \text{photon} \quad \text{(excitation)} \ , \\ \alpha + \text{atom} &\rightarrow \text{atom}^+ + e^- + \alpha \qquad \text{(ionization)} \ . \end{aligned} \tag{4.1}$$

excitation and ionization: energy loss of charged particles

The energy loss of charged particles passing through matter depends on the particle velocity, its charge, and the properties of the traversed material. Slow particles spend a relatively large amount of time close to individual atoms; correspondingly, the interaction probability associated with a given energy transfer to the target atom is relatively large. If v is the particle velocity, one obtains for the energy transfer in collisions between charged particles

$$\Delta E \sim \frac{1}{v^2} \ . \tag{4.2}$$

Since the interaction is mediated by the electrical charges of the projectile (z) and the target (Z), the energy loss increases with larger

C. Grupen, *Introduction to Radiation Protection*,
Graduate Texts in Physics, DOI 10.1007/978-3-642-02586-0_4,

charges of the involved particles:

$$\Delta E \sim z^2 \, Z \ . \tag{4.3}$$

Finally, the electric field of the charged particle is distorted at high velocities – corresponding to high energies – due to relativistic effects. This results in an increase of the energy loss at high energies.

Bethe–Bloch relation

These dependences are described in the framework of the Bethe–Bloch relation, which relates the energy loss ΔE to the traversed distance Δx in the following way:

$$\frac{\Delta E}{\Delta x} \sim \frac{1}{v^2} z^2 \frac{Z}{A} \ln(a \, E) \ , \tag{4.4}$$

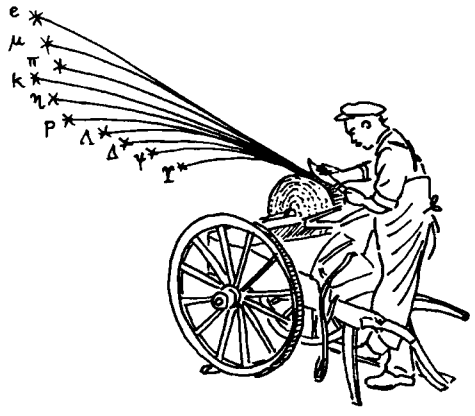
where

ΔE – energy deposited over the distance Δx,
v – velocity of the incident particle,
z – charge number of the projectile ($z_\alpha = 2$, $z_e = -1$),
Z, A – atomic number and mass number of the traversed material,
E – total energy of the projectile ($E = E_{\text{kin}} + m_0 c^2$) with E_{kin} – kinetic energy,
a – a material-dependent constant.

The average energy loss of relativistic electrons ($\approx$ MeV range) is approximately 2.5 keV/cm in air. That of α particles is much larger ($\approx$ 100 keV/mm in air) because of the higher charge ($\sim z^2$) and the lower velocities of α particles for energies typical for radioactive decays.

average energy loss

In the field of practical radiation protection it is sometimes desirable to consider only the local energy deposit, i.e. collisions with



"Creation of elementary particles in interactions."

relatively low energy transfer. The idea is that in collisions with large energy transfers long-range δ electrons are created which are weakly ionizing and therefore have only little biological effect, in contrast to the high ionization density generated by low energy transfers.[1] This led to the introduction of the concept of the linear energy transfer (LET). The linear energy transfer of charged particles is the ratio of the average energy loss ΔE, where only collisions with energy transfers smaller than a given cutoff parameter E_{cut} are considered, and the traversed distance Δx,

linear energy transfer (LET)

$$\mathrm{LET} = L_{E_{\mathrm{cut}}} = \left(\frac{\Delta E}{\Delta x}\right)_{E_{\mathrm{cut}}} . \tag{4.5}$$

The energy cut parameter is usually given in eV. A value of LET_{100} indicates that only collisions with energy transfers below 100 eV are considered. High linear-energy-transfer radiation corresponds to high biological effectiveness, and this type of radiation is very important for cancer treatment (see also Fig. 4.3).

Figure 4.1 shows the energy loss of electrons in air compared to the energy loss of protons and α particles. Since the energy loss varies considerably with energy, we have used the differential notation $\frac{\mathrm{d}E}{\mathrm{d}x}$ instead of $\frac{\Delta E}{\Delta x}$. Figures 4.2a and 4.2b show the average energy loss of electrons in copper (a) and tissue (b). The energy loss in thin absorbers is subject to large fluctuations which can be described by an asymmetric distribution ('Landau distribution').

proton therapy

specific energy loss

[1] The energy spectrum of ionization electrons falls off like $1/\epsilon^2$, where ϵ is the energy of the electrons knocked out from the atom. These electrons are also called 'knock-on electrons' or δ rays.

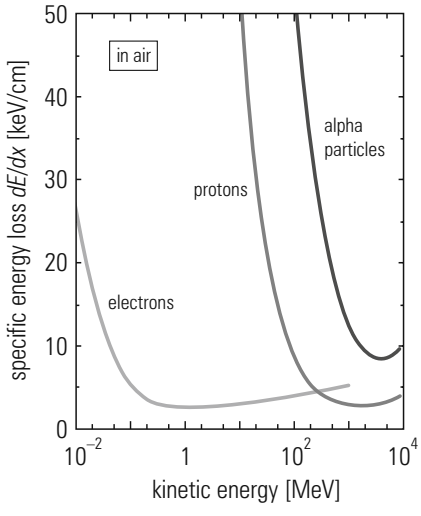


Figure 4.1
Energy loss of electrons, protons, and α particles in air as a function of energy

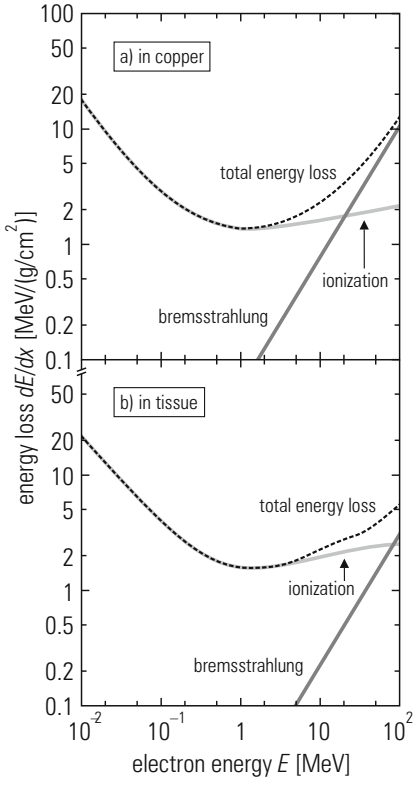


Figure 4.2
Specific energy loss of electrons in copper (a) and in tissue (b). The distance dx is not given in cm in this case, but in a nearly material-independent area density $\rho\,\mathrm{d}x$, where ρ is the density of the material. 1 g/cm^2 tissue corresponds almost exactly to 1 cm, while 1 g/cm^2 of copper is only 0.11 cm

range of charged particles

According to Eq. (4.4) the energy loss rises again at the end of the range of the particle (i.e. at low velocities). Figure 4.3 shows the relative energy loss (or dose, respectively) of negative pions, α particles, and nitrogen nuclei in comparison to ^{60}Co γ rays in tissue. As can be seen from this diagram, heavy ions are ideally suited for

tumor therapy

the irradiation of tumors. This is due to the fact that heavy ions exhibit, because of their large charge and their relatively low velocity,

Bragg peak

a very pronounced ionization peak ('Bragg peak') at the end of their range, which is a consequence of the z^2/v^2 dependence of the energy loss. Because of this physical phenomenon deep-seated tumors can be treated non-invasively with proton or nitrogen beams (or carbon beams) of variable energy. By vertical and horizontal beam-deflection techniques and by varying the energy of the heavy-ion or proton beam one can destroy very precisely regions of cancerous tissue while at the same time the healthy tissue is not strongly affected ('raster-scan technique').

microbeam radiation therapy

Another very promising technique for the treatment of tumors is microbeam radiation therapy (MRT). Here the tumor tissue is ir-

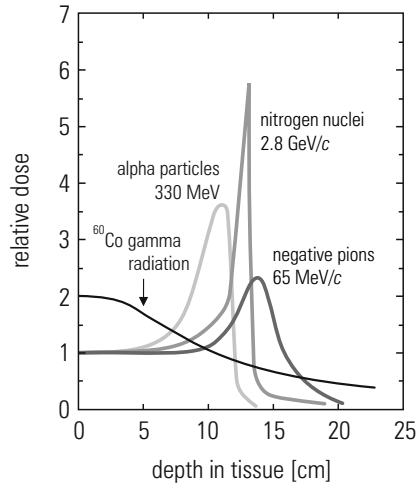


Figure 4.3
Relative dose as a function of depth in tissue for ^{60}Co γ rays, negative pions with momentum[1] 65 MeV/c, nitrogen nuclei (momentum 2.8 GeV/c), and α particles (kinetic energy 330 MeV)

radiated in microsteps along lines of typically 25 µm width and a mutual distance of 200 µm ('spatially fractionated irradiation'). The irradiation steps are implemented with the help of an intense synchrotron-radiation beam (see Sect. 9.1) operating at X-ray energies. An applied tissue dose per irradiated line element of about 600 Gy is lethal for the local tissue. The healthy tissue can withstand this way of irradiation by means of biological repair mechanisms much better than the cancerous tissue.

synchrotron radiation in the X-ray range

This technique is interesting because the treatment of metastatic tumors also appears possible, in contrast to the heavy-ion therapy which can only be applied for well-localized tumors. Therefore, heavy-ion therapy cannot be used for those metastatic tumors which are spread out.

The range of electrons in various materials and those of α particles in air is shown in Figs. 4.4 and 4.5. Electrons from radioactive sources have ranges of several meters in air, but they will already be stopped by a few mm of aluminum. The range of α particles with typical energies of around 5 MeV in air is approximately 4 cm. A sheet of paper is sufficient to absorb these α rays.

For higher energies additional energy losses come into play, like bremsstrahlung (see Fig. 4.2). Bremsstrahlung is produced if a charged particle is decelerated in the Coulomb field of an atomic nucleus. Because of the $1/m^2$ dependence of the bremsstrahlung

bremsstrahlung

[1] For massless or very energetic particles the energy is related to the momentum $p = m\,v$ via the relation $E = p\,c$. Therefore, the momentum is frequently measured in energy units per velocity of light, e.g. MeV/c or GeV/c.

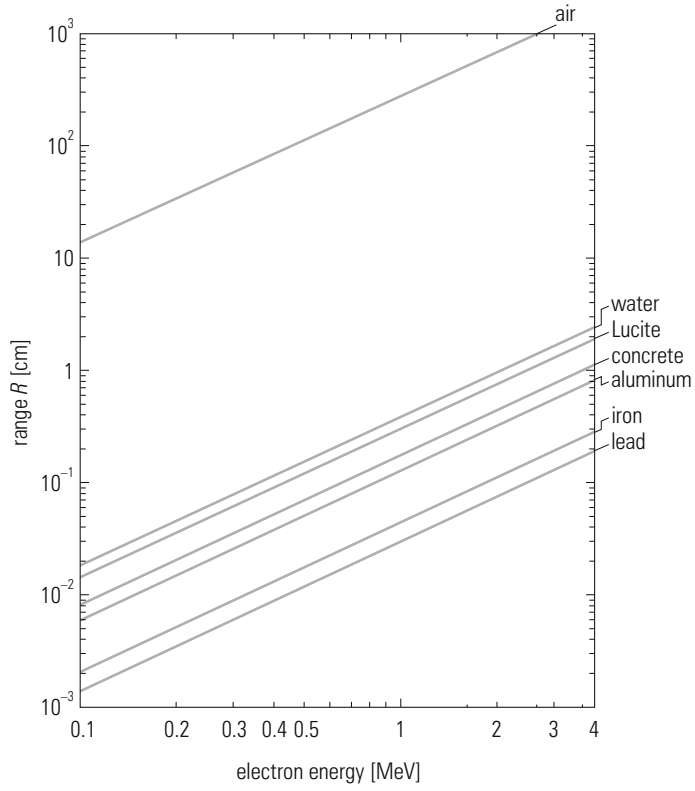


Figure 4.4
Range of electrons in various materials

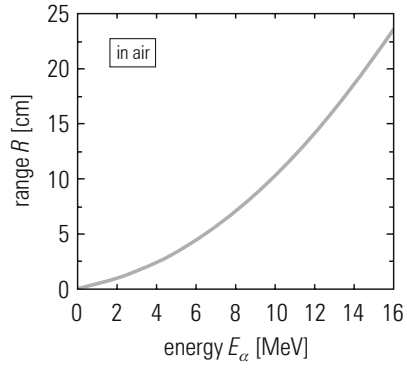


Figure 4.5
Range of α particles in air

energy loss this mechanism is practically only important in the field of radiation protection for the lightweight electrons ($m_e \approx \frac{1}{7300} m_\alpha$). For all other particles (protons, α particles, heavy nuclei) their high mass makes this type of energy-loss mechanism practically irrelevant in radiation physics. The energy loss of electrons in matter by bremsstrahlung can be parametrized by

Absorption of β rays

A Geiger–Müller counter allows the measurement of the absorption of β rays from a ^{90}Sr source. For this purpose an aluminum absorber of variable thickness is placed between source and detector. The count rate as a function of absorber thickness is shown in the figure. ^{90}Sr decays with a maximum β^- energy of 0.55 MeV into ^{90}Y, which itself transforms into ^{90}Zr with a transition energy of $E_{\beta_{\max}} = 2.28$ MeV (see Fig. 3.5). The electrons from the low-energy transition of the ^{90}Sr decay are absorbed relatively quickly (compare Fig. 4.4). The results of the absorption measurements for absorber thicknesses of more than 0.2 g/cm^2 Al (corresponding to 0.75 mm Al) are related to electrons from the ^{90}Y decay.
Even though the absorption of β rays cannot really be described by an exponential law from a theoretical viewpoint, an effective absorption coefficient for continuous β-ray emitters can still be given. A linear fit to the absorption data in the semilogarithmic plot allows to determine this effective absorption coefficient for β rays. Assuming that the experimental count rate follows an exponential,

$$N_i = N_0 \, \mathrm{e}^{-\kappa \, x_i} \qquad (i = 1, 2) \ ,$$

one can derive the absorption coefficient κ,

$$\kappa = \frac{\ln(N_1/N_2)}{x_2 - x_1} = 4.33 \, (\mathrm{g/cm^2})^{-1} \ .$$

The absorption coefficient for electrons from continuous β spectra can be approximated by the empirical relation

$$\kappa = 15/E_{\beta_{\max}}^{1.5}$$

($E_{\beta_{\max}}$ in MeV, κ in $(\mathrm{g/cm^2})^{-1}$) (see page 252). The κ value of 4.36 derived from this relation agrees well with the experimentally determined result.

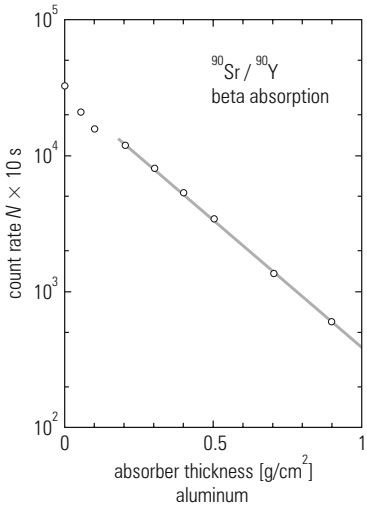


Figure 4.6
Absorption of electrons from a ^{90}Sr source in aluminum

Determination of the range of α rays

The range of α rays can be determined reasonably well with an expansion cloud chamber. α rays from an unsealed, collimated ^{226}Ra source are injected into a flat chamber, which is filled with a gas–vapor mixture (e.g. air–water vapor or argon–alcohol). By adiabatic expansion[3] of the chamber volume the temperature of the gas mixture is lowered, which brings the vapor into a supersaturated state. The vapor will condense as droplets on condensation nuclei, in this case on positive ions marking the ionization tracks of the α particles. The illuminated tracks of the α particles can easily be photographed and evaluated (see Fig. 4.7, left-hand part).

The determination of the range of α particles with electronic detectors is much more difficult. One has to take care that both the exit window of the source and the entrance window of the detector are extremely thin. A count-rate measurement of a ^{226}Ra source (α energy 4.8 MeV) with a Geiger–Müller counter leads to the results as shown in the right-hand part of Fig. 4.7.

Plotted is the count-rate dependence as a function of the absorber thickness between source and detector. The variable absorber thickness was realized by extremely thin polyethylene foils. If this count-rate dependence is differentiated, one can read the range of α particles from the position of the maximum of this differential curve (see lower insert in the figure). The result of 4.75 mg/cm^2, corresponding to 3.7 cm of air, agrees well with expectation.

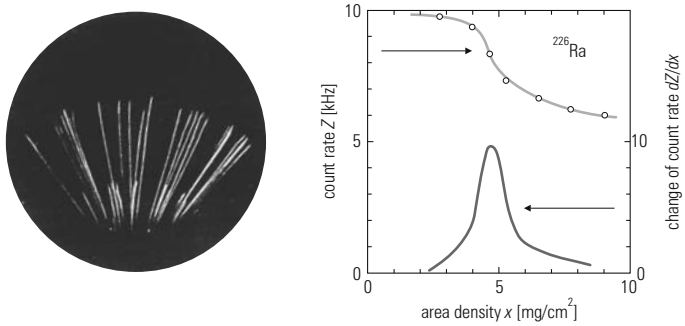


Figure 4.7
Tracks of 8.8 MeV and 6 MeV α particles in a cloud chamber (L. Meitner, K. Freitag; left); determination of the range of α rays by absorption measurements with thin polyethylene foils (right)

$$\frac{\Delta E}{\Delta x} \sim Z^2 E \ . \tag{4.6}$$

For high energies (for example, in lead, energies larger than 7.4 MeV, the 'critical energy'[2]) the radiation loss of electrons is larger than the energy loss by ionization and excitation (see Fig. 4.2).

shielding

prevention of bremsstrahlung

Electrons of high energy (several MeV, e.g. from an accelerator in the radiological department of a hospital) are best shielded with a sandwich consisting of a material of low atomic number followed by a layer of lead. In the absorber of low atomic number (e.g. plas-

[2] The critical energy is defined to be the energy, at which the energy loss by bremsstrahlung and the energy loss by ionization and excitation are the same.

[3] Any process that occurs without heat entering or leaving the system is called adiabatic.

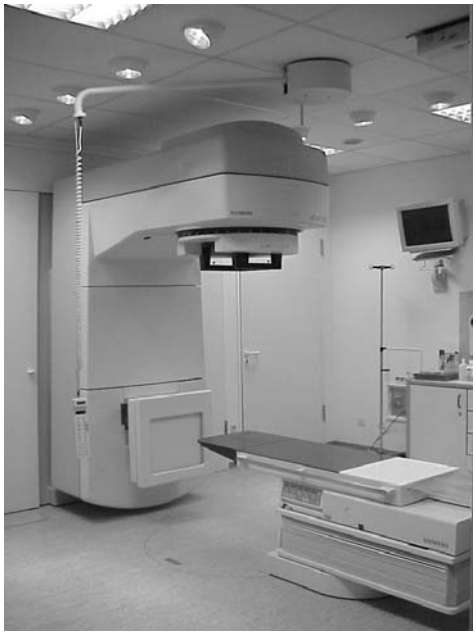


Figure 4.8
Linear accelerator, electron energy between 6 and 21 MeV with maximum photon energies of 6 to 21 MeV (type: Siemens KD-2, `www.ma.uni-heidelberg.de`)

tic) the electrons lose their energy by ionization and excitation almost without producing bremsstrahlung, and then the electrons are stopped in lead. In a pure lead absorber energetic electrons would produce bremsstrahlung against which it is very difficult to shield.

4.2 Detection of Neutrons

Neutrons, being neutral particles, cannot be measured directly. All detection techniques result in the production of charged particles in neutron interactions. These charged particles are then measured by the normal interaction processes like ionization, excitation, or scintillation.

neutron interactions

For neutrons with energies which are typical in the field of radiation protection ($E_{\mathrm{kin}} \leq 10\,\mathrm{MeV}$), the following detection reactions can be considered:

$$n + {}^{6}_{3}\mathrm{Li} \rightarrow \alpha + {}^{3}_{1}\mathrm{H} \ , \tag{4.7}$$

$$n + {}^{10}_{5}\mathrm{B} \rightarrow \alpha + {}^{7}_{3}\mathrm{Li} \ , \tag{4.8}$$

$$n + {}^{3}_{2}\mathrm{He} \rightarrow p + {}^{3}_{1}\mathrm{H} \ , \tag{4.9}$$

$$n + p \rightarrow n + p \ . \tag{4.10}$$

The cross sections[4] for these reactions depend strongly on the neutron energy (see Fig. 4.9).

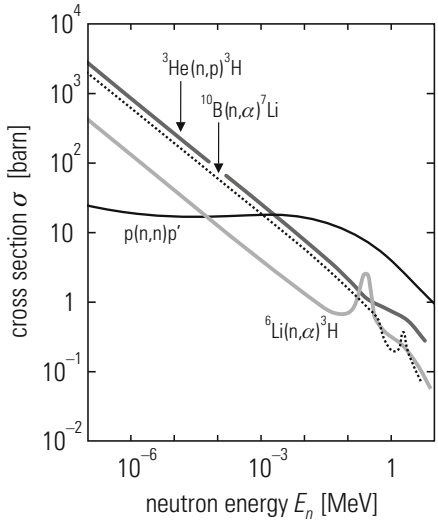


Figure 4.9
Interaction cross sections for neutron-induced reactions (1 barn $= 10^{-24}$ cm^2)

Thermal neutrons (neutrons at room temperature, ≈ 0.025 eV) can easily be measured with ionization chambers or proportional counters, which are filled with gas mixtures containing boron trifluoride (BF_3). Because of the large cross section for the reaction (4.9) (see also Fig. 4.9) ^{3}He is also an attractive alternative for the detection of slow neutrons. Higher-energy neutrons must first be decelerated ('moderated') so that they can be recorded with reasonable detection efficiency.

boron trifluoride counter

^{3}He counter

moderation (deceleration)

The moderation of non-thermal neutrons is best done with materials which contain many 'free' protons, i.e. lots of hydrogen, because neutrons can transfer a large fraction of their energy to partners of the same mass while in collisions with heavy nuclei mostly only quasi-elastic scattering processes with low energy transfers occur. Paraffin and water are common choices as moderators.

Semiconductor counters or scintillators which contain lithium are equally well-suited for neutron detection; also proportional counters with gas fillings, which contain ^{3}He or hydrogen (say, in form of CH_4), can be used equally well for neutron detection.

[4] A measure for the probability that a collision will occur between the incoming particle and the target, expressed as the effective area presented by the particle and the target in this particular interaction. If r_P is the radius of the projectile and r_T that of the target, the geometrical cross section is $\sigma = \pi(r_P + r_T)^2$.

reaction	threshold energy (MeV)
fission of ^{234}U	0.3
fission of ^{236}U	0.7
$n + {}^{31}\mathrm{P} \rightarrow p + {}^{31}\mathrm{Si}$	0.72
$n + {}^{32}\mathrm{S} \rightarrow p + {}^{32}\mathrm{P}$	0.95
fission of ^{238}U	1.3
$n + {}^{27}\mathrm{Al} \rightarrow p + {}^{27}\mathrm{Mg}$	1.9
$n + {}^{56}\mathrm{Fe} \rightarrow p + {}^{56}\mathrm{Mn}$	3.0
$n + {}^{27}\mathrm{Al} \rightarrow \alpha + {}^{24}\mathrm{Na}$	3.3
$n + {}^{24}\mathrm{Mg} \rightarrow p + {}^{24}\mathrm{Na}$	4.9
$n + {}^{65}\mathrm{Cu} \rightarrow 2n + {}^{64}\mathrm{Cu}$	10.1
$n + {}^{58}\mathrm{Ni} \rightarrow 2n + {}^{57}\mathrm{Ni}$	12.0

Table 4.1
Threshold reactions for determination of neutron energies

measurement of neutron energy

threshold counter

For applications in the field of radiation protection, it is also important to know the neutrons' energy, because the radiation weighting factors, and thereby the relative biological effectiveness, depend on it. For this purpose one uses neutron threshold detectors. Such a detector consists of a carrier foil that is coated with an isotope which only reacts with neutrons above a certain energy. The charged particles created in these reactions can be measured with plastic detectors via an appropriate etching technique. As plastic material usually polycarbonate foils are used. The local radiation damage is made visible by etching the plastic foil with sodium hydroxide (NaOH).

Table 4.1 contains suitable threshold reactions for the determination of the neutron energy.

4.3 Detection of Photons

Just as with neutrons, photons must first produce charged particles in an interaction process, which are then normally detected via processes of ionization, excitation, and scintillation. The interactions of photons are fundamentally different from those of charged particles since in a photon interaction process the photon is either completely absorbed (photoelectric effect, pair production) or scattered through relatively large angles (Compton effect).

photoelectric effect
Compton effect
pair production

It is possible to consider for charged particles a certain range – depending on their energy. In contrast, this is not possible for photons; only statistical probabilities can be given for the intensity attenuation when photons penetrate layers of material.

The intensity I_0 of a monoenergetic photon beam is attenuated in a certain layer of material of thickness x according to

attenuation of photons

Absorption of γ rays

The absorption of γ rays from a ^{60}Co source was investigated with a scintillation counter. For this purpose the electrons, with a maximum energy of 0.31 MeV were absorbed by a thin aluminum absorber. The remaining γ count rate is plotted in Fig. 4.10 as a function of the lead-absorber thickness. It is obvious that the energetic γ rays (1.17 MeV and 1.33 MeV, see Fig. 3.4) are only slowly absorbed in lead. The cross section for photon interactions has a minimum around these energies (see Fig. 4.12). This minimum is determined by the relatively low probability for the Compton effect which dominates in this energy range.
A fit to the experimental data in form of a straight line in the semilogarithmic plot leads to a value for the mass absorption coefficient of γ rays of average energy of 1.25 MeV in lead of

$$\mu_\mathrm{a} = \frac{\ln(I_1/I_2)}{x_2 - x_1} = 0.37\,\mathrm{cm}^{-1}$$

corresponding to $\mu = 0.033\,(\mathrm{g/cm^2})^{-1}$, in excellent agreement with the expectation.

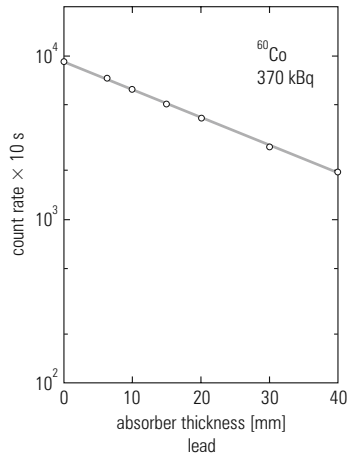


Figure 4.10
Absorption of γ rays from a ^{60}Co source in lead

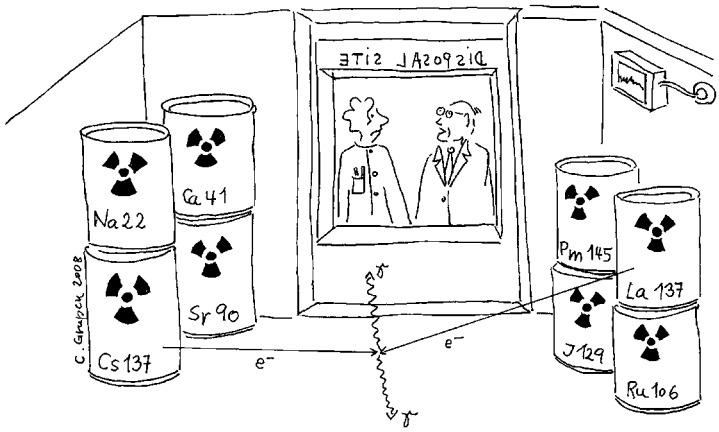
(see Appendix Q)

$$I = I_0\,\mathrm{e}^{-\mu x}\ , \tag{4.11}$$

where μ is the mass attenuation coefficient. This coefficient involves the probability of the different photon interaction processes. In the photoelectric effect and in pair production the photon is completely absorbed, while in the Compton process the photon 'survives' – although with reduced energy. Therefore the effect of photon absorption has to be distinguished from the photon intensity attenuation. For this purpose a Compton scattering coefficient is defined,

Compton scattering

$$\mu_\mathrm{cs} = \frac{E'_\gamma}{E_\gamma}\,\mu_{\text{Compton effect}}\ . \tag{4.12}$$



"We store β^+ emitters together with β^- emitters so that they annihilate one another."

In this relation E_γ and E'_γ are the energies of the photons before and after the scattering in the Compton process. The Compton absorption coefficient is then the difference between the total probability for the Compton effect and the Compton scattering coefficient:

absorption of photons

$$\mu_{\text{ca}} = \mu_{\text{Compton effect}} - \mu_{\text{cs}} \ . \tag{4.13}$$

Using the abbreviations $\mu_{\text{photoelectric effect}} = \mu_{\text{pe}}$, $\mu_{\text{pair production}} = \mu_{\text{pp}}$, and $\mu_{\text{Compton effect}} = \mu_{\text{c}}$ the mass attenuation coefficient μ for photons is

Compton absorption

$$\mu = \mu_{\text{pe}} + \mu_{\text{pp}} + \mu_{\text{c}} \ , \tag{4.14}$$

where $\mu_{\text{c}} = \mu_{\text{cs}} + \mu_{\text{ca}}$, and the mass absorption coefficient μ_{a} is given by

$$\mu_{\text{a}} = \mu_{\text{pe}} + \mu_{\text{pp}} + \mu_{\text{ca}} \ . \tag{4.15}$$

The mass attenuation coefficient μ is related to the cross sections for the various interaction processes of photons according to

$$\mu = \frac{N_{\text{A}}}{A} \sum_i \sigma_i \ , \tag{4.16}$$

where σ_i is the atomic cross section for the process i, A the atomic weight, and N_{A} the Avogadro constant. An equivalent relation holds for the mass absorption coefficient μ_a.

The cross section for the photoelectric effect, which is the liberation of an electron from the atomic shell,

photoelectric effect

$$\gamma + \text{Atom} \rightarrowtail \text{Atom}^+ + e^- \ , \tag{4.17}$$

depends very strongly on the atomic number of the absorber and the energy of the photon. Away from the absorption edges[5] the cross

absorption edge

section for the photoelectric effect is given by

$$\sigma_{\text{photo}} \sim \frac{Z^5}{E_\gamma^{3.5}} \ . \tag{4.18}$$

The photoelectric effect dominates at low energies (e.g. in the X-ray regime) and for heavy absorbers (lead, tungsten). In most cases the photoionization proceeds in the K shell (corresponding to 80% of the total photoelectric cross section).

The cross section in the vicinity of the absorption edges[5], where the photon energy coincides with the element's specific binding energy in the respective electronic shell, deviates quite strongly from the cross section as given in Eq. (4.18). Consequently the energy dependence of this cross section in the vicinity of the absorption edges must be considerably modified.

Compton effect

The Compton effect describes the photon scattering off quasi-free electrons of an atom,

$$\gamma + e^-_{\text{at rest}} \rightarrow \gamma' + e^-_{\text{fast}} \ . \tag{4.19}$$

The scattering probability is proportional to the number of potential scattering partners in the atom ($\sim Z$). The energy dependence of the Compton scattering cross section can be parametrized by

$$\sigma_{\text{Compton}} \sim Z \, \frac{\ln E_\gamma}{E_\gamma} \ . \tag{4.20}$$

Compton edge

For reasons of energy and momentum conservation the photon can only transfer energies up to a maximum value onto the electron ('Compton edge').

Pair production is the conversion of a photon into an electron–positron pair in the Coulomb field of an atomic nucleus,

$$\gamma + \text{nucleus} \rightarrow \text{nucleus}' + e^+ + e^- \ . \tag{4.21}$$

pair production

There is a threshold energy for this process because the photon has to create the rest masses m_e of the electron and the positron. One might think that the threshold energy would be just $E_\gamma > 2m_e c^2$; actually the threshold energy must be somewhat larger than twice the electron mass because also the nucleus, which acts as a scattering partner, will suffer a small recoil and thereby takes away a certain

[5] The cross section experiences a rapid increase at the absorption edges if the photon energy coincides with the excitation or ionization energy of a shell electron. The excitation energies are given by Moseley's law (see Sect. 9.2 'Photon Sources').

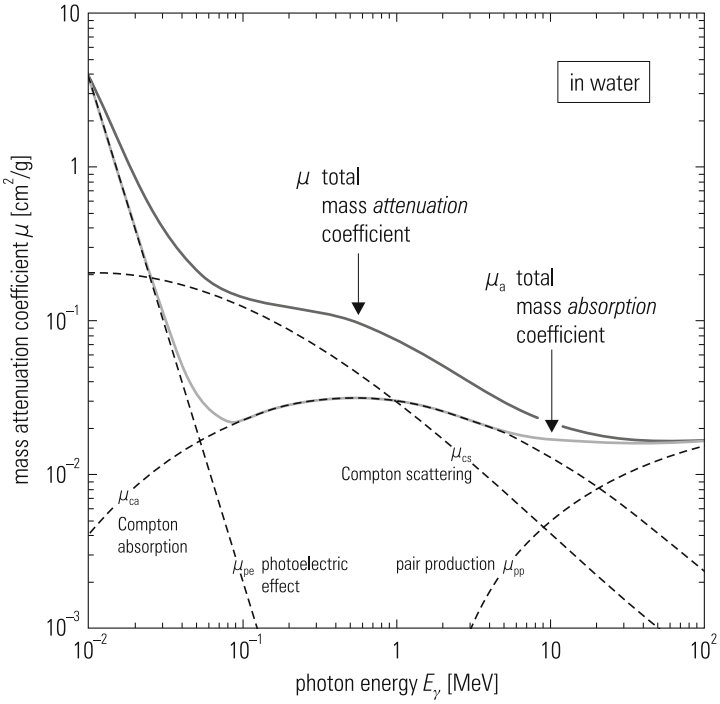


Figure 4.11
Energy dependence of the mass attenuation coefficient μ and mass absorption coefficient μ_a for photons in water. μ_{pe} describes the photoelectric effect, μ_{pp} pair production, μ_{cs} Compton scattering, and μ_{ca} Compton absorption. μ_a is the total mass absorption coefficient ($\mu_a = \mu_{pe} + \mu_{pp} + \mu_{ca}$) and μ the total mass attenuation coefficient ($\mu = \mu_{pe} + \mu_{pp} + \mu_c$ with $\mu_c = \mu_{cs} + \mu_{ca}$)

energy and momentum.[6] The cross section for pair production can be parametrized by

$$\sigma_{\text{pair}} \sim Z^2 \ln E_\gamma \quad . \tag{4.22}$$

For high energies (in the ultra-relativistic limit, $E_\gamma \gg 100\,\text{MeV}$) the cross section approaches an energy-independent constant value.

Figure 4.11 shows the mass attenuation and mass absorption coefficients for water as absorber and Fig. 4.12 those for lead. The mass absorption coefficient can be measured equally well in the unit cm^{-1} or in $(\text{g/cm}^2)^{-1}$, where

attenuation coefficient
absorption coefficient

$$\mu(\text{cm}^{-1}) = \mu\big((\text{g/cm}^2)^{-1}\big)\,\rho$$

(ρ – density of the absorber in g/cm^3).

As a consequence of the photoelectric and Compton effect an electron is missing in the atomic shell. If this vacancy is filled up by electrons from higher shells, the excitation energy of the shell can be emitted in form of characteristic X rays or by Auger electrons (see Chap. 3, page 27).

characteristic X rays
Auger electrons

[6] The exact value for the threshold energy is $E_\gamma = 2m_e c^2 + 2m_e^2 c^2 / m_{\text{nucleus}}$. For practically all nuclei the second term can be neglected. If, however, the pair production happens in the Coulomb field of an electron, the threshold energy is $E_\gamma = 4m_e c^2$.

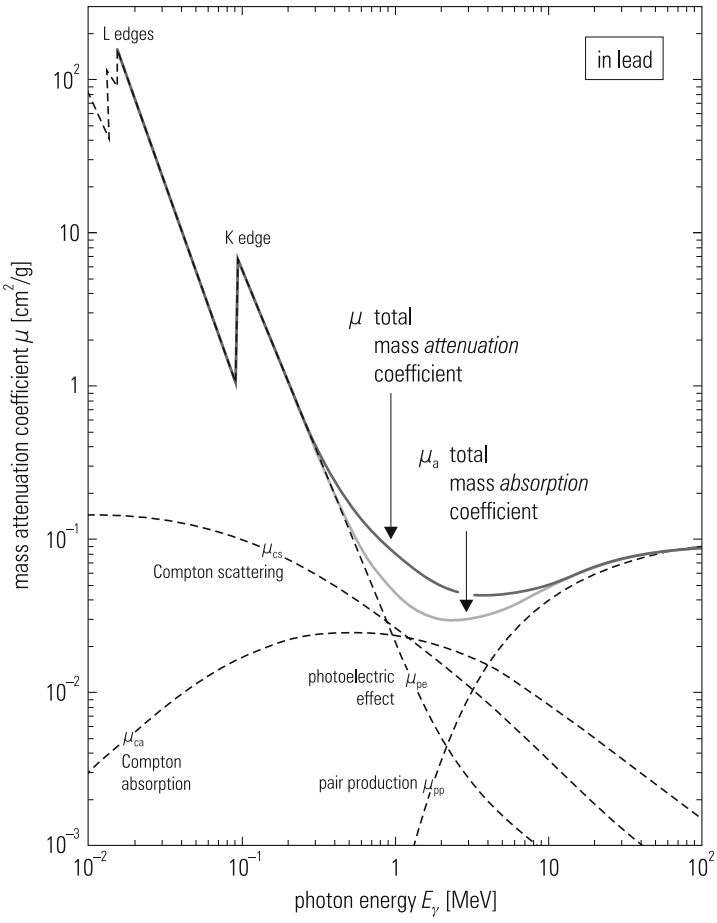


Figure 4.12
Energy dependence of the mass attenuation coefficient μ and mass absorption coefficient μ_a for photons in lead. μ_{pe} describes the photoelectric effect, μ_{pp} pair production, μ_{cs} Compton scattering, and μ_{ca} Compton absorption. μ_a is the total mass absorption coefficient ($\mu_a = \mu_{pe} + \mu_{pp} + \mu_{ca}$) and μ the total mass attenuation coefficient ($\mu = \mu_{pe} + \mu_{pp} + \mu_c$ with $\mu_c = \mu_{cs} + \mu_{ca}$)

4.4 Supplementary Information

Example 1

cosmic-ray muons

Energetic cosmic-ray muons will deposit about $2\,\mathrm{MeV/(g/cm^2)}$ in tissue. How many charge-carrier pairs will be created in a human germ cell (diameter 0.05 mm) if it is hit by a cosmic-ray muon and if the energy for the production of a charge-carrier pair is 30 eV?

The density of human tissue is about $1\,\mathrm{g/cm^3}$; therefore, a specific energy loss of $2\,\mathrm{MeV/(g/cm^2)}$ corresponds to a deposited energy of $2\,\mathrm{MeV/cm} = 0.2\,\mathrm{keV/\mu m}$. Let us approximate the cell by a cylindrical volume the height of which is assumed to correspond to the cell diameter. This leads to a deposited energy of 10 keV for the given cell diameter of $0.05\,\mathrm{mm} = 50\,\mu\mathrm{m}$, which in turn leads to a number of $10\,000\,\mathrm{eV}/30\,\mathrm{eV} = 333$ charge-carrier pairs.

mutations

Mutations can only be caused if a chromosome within a germ-cell nucleus will be hit. For an effective diameter for ionization in the chromosomes of about 0.5 µm the hit probability for a certain chromosome, if the cell has been hit, is

chromosome aberrations

$$\frac{(0.5\,\mu\text{m})^2}{(50\,\mu\text{m})^2} = 10^{-4} \ .$$

cosmic rays (muons)

Since the cosmic-ray-muon rate at sea level corresponds to about 1 muon/(cm^2 min), the hit probability for a particular chromosome is

$$\begin{aligned}\frac{(0.5\,\mu\text{m})^2}{10^8\,\mu\text{m}^2\ \text{min}} &= 2.5 \times 10^{-9}\ \text{ per minute} \\ &= 0.0013\ \text{ per year}\end{aligned}$$

corresponding to 1 hit every 761 years.

chromosome hits

A hit chromosome is the condition for the creation of a mutation, however, not every hit leads to a mutation. Very few 'successful' hits on chromosomes lead to a mutation which the cell can survive, i.e., most of the hits on chromosomes create mutations which cause the cell to die.

Example 2

As well as the activity A, the term specific activity A^* is used, particularly when dealing with the classification of nuclear waste. The specific activity is the activity per unit mass. For example, the specific activity of ^{54}Mn is worked out in the following way: the half-life of ^{54}Mn is 312 days;

$$A^* = -\frac{\mathrm{d}N}{\mathrm{d}t} = \lambda\, N = \frac{1}{\tau}\, N \ .$$

In this relation N is the number of atoms per gram,

$$\begin{aligned}A^* &= \frac{\ln 2}{T_{1/2}}\, N = \frac{\ln 2}{T_{1/2}}\, \frac{\text{Avogadro constant}}{\text{atomic weight in grams}} \\ &= \frac{0.6931}{312 \times \underbrace{24 \times 3600}_{\text{seconds per day}}} \times \frac{6.022 \times 10^{23}}{54\ \text{gram}} = 2.87 \times 10^{14}\, \frac{\text{Bq}}{\text{g}} \ .\end{aligned}$$

Since low-level detectors can easily measure count rates of 1 Bq, one obtains a sensitivity for ^{54}Mn of

$$m_{\min} = \frac{1\ \text{Bq}}{2.87 \times 10^{14}\ \text{Bq/g}} = 3.49 \times 10^{-15}\ \text{g} \ .$$

detection sensitivity

This shows that very small quantities of a radioisotope are detectable.

specific activity

In a normal nuclear physics laboratory radioactive sources with activities on the order of 10^6 Bq are handled. This would correspond to a mass of 3.5 nanograms for ^{54}Mn. Since masses of such small amount cannot easily be handled technically, the radioisotope is frequently mixed with a chemical equivalent but inactive isotope, e.g. ^{55}Mn. If the radioisotope ^{54}Mn with an activity of 10^6 Bq (corresponding to 3.5 ng) were mixed with 10 mg ^{55}Mn, the specific activity for this sample would be

$$A^* = \frac{10^6\,\mathrm{Bq}}{10\,\mathrm{mg} + 3.5\,\mathrm{ng}} = 10^8\,\mathrm{Bq/g} \ .$$

The low ^{54}Mn fraction in such a sample would be very difficult to detect with techniques of analytical chemistry.

Let us now assume that 1 mg ^{54}Mn is used for a radioactive source (i.e. a very strong source). The activity of this sample then is

$$A = 2.87 \times 10^{11}\,\mathrm{Bq} = 7.7\,\mathrm{Ci} \ .$$

What kind of energy dose would be measured under these circumstances at a distance of 30 cm in tissue of 1 cm thickness?

The energy flux per cm^2 at a distance of $r = 30$ cm is

$$W = A\,\epsilon\,\Omega \ ,$$

where

solid angle

ϵ – energy per decay (842-keV photon) and

Ω – solid-angle fraction $= \frac{1}{4\,\pi\,r^2}$.

$1/r^2$ dependence

Therefore, one gets

$$W = 2.87 \times 10^{11}\,\mathrm{Bq} \times 0.842\,\mathrm{MeV} \times \frac{1}{4\,\pi\,30^2\,\mathrm{cm}^2}$$
$$= 2.13 \times 10^7\,\frac{\mathrm{MeV}}{\mathrm{s\,cm}^2} \ .$$

The mass absorption coefficient for 842 keV photons in tissue is about $\mu = 0.035\,(\mathrm{g/cm}^2)^{-1}$ (see Fig. 4.11; water and tissue are comparable in this case); i.e., of the original photon intensity only the fraction

$$\frac{N}{N_0} = 1 - \mathrm{e}^{-\mu\,x\,\rho} = 1 - \mathrm{e}^{-0.035\,(\mathrm{g/cm}^2)^{-1} \times 1\,\mathrm{cm} \times 1\,\mathrm{g/cm}^3} = 0.0344$$

per g/cm^2 is absorbed in tissue of 1 cm thickness. This corresponds to an absorbed energy of

$$W^* = W\,\frac{N}{N_0} = 0.735 \times 10^6\,\frac{\mathrm{MeV}}{\mathrm{s\,g}}$$

Experimental determination of the distance law

A 370 kBq ^{60}Co source is mounted at variable distances from a scintillation counter. The attenuation of γ rays of energy 1.17 MeV and 1.33 MeV (see Fig. 3.4) from the ^{60}Co isotope in air can be neglected. The count rate as a function of the distance between source and scintillator is plotted in double logarithmic scale in Fig. 4.13. A line fit to the data leads to a slope of -2, which means that the count rate N varies like

$$N \sim r^{-2} \ ,$$

since such a dependence will provide the measured slope in the log–log scale:

$$\ln N \sim -2 \ \ln r.$$

The fact that the count rate decreases inversely proportional to the square of the distance follows easily from a consideration of the solid angle: the total solid angle (surface of a sphere) corresponds to $4\pi r^2$. A detector of area A at a distance r records only the solid-angle fraction $A/4\pi r^2$. Therefore, the count rate varies like $N \sim 1/r^2$. For radiation protection one learns from this behavior: keeping one's distance from a radioactive source is a very effective protection against radiation.

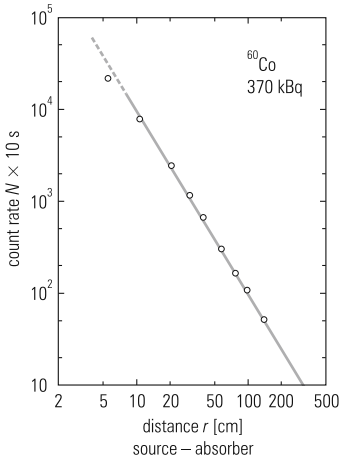


Figure 4.13
Distance law ($1/r^2$ law) for γ radiation from a ^{60}Co source

(1 cm^3 tissue $\widehat{=}$ 1 gram; 1 cm tissue $\widehat{=}$ 1 g/cm^2),

$$\begin{aligned} W^* &= 0.735 \times 10^6 \times 1.6 \times 10^{-13} \times 10^3 \,\mathrm{J/(s\,kg)} \\ &= 1.18 \times 10^{-4} \,\mathrm{Gy/s} \qquad (1\,\mathrm{MeV} = 1.6 \times 10^{-13}\,\mathrm{J}) \ , \end{aligned}$$

which leads to a dose rate of

$$\dot{D} = 0.42\,\mathrm{Gy/h} \ .$$

Because the dose rate varies with the inverse square of the distance, for a distance of 1 m one has

$$\dot{D}_{1\,\mathrm{m}} = \dot{D}_{0.3\,\mathrm{m}} \times \frac{(0.3\,\mathrm{m})^2}{(1\,\mathrm{m})^2} = 38\,\mathrm{mGy/h} \ .$$

Eventually, the deposited energy will be transformed into heat. What kind of heat power $\dot{Q}$ corresponds to a dose rate of 38 mGy/h?

$$\dot{Q} = 38 \times 10^{-3} \frac{\mathrm{W\,s}}{\mathrm{kg\,h}} = \frac{38 \times 10^{-3}}{3600} \frac{\mathrm{W}}{\mathrm{kg}}$$
$$= 1.06 \times 10^{-5} \frac{\mathrm{W}}{\mathrm{kg}} \mathrel{\widehat{=}} 1.06 \times 10^{-8}\,\mathrm{W/cm^3} \ ,$$

Heating by ionizing radiation?

since the density of tissue was assumed to be $\rho = 1\,\mathrm{g/cm^3}$. Expressed in units of calories (1 cal is the quantity of heat, which is required to warm up 1 g of water by 1° from 14.5°C to 15.5°C; 1 cal = 4.186 J), this corresponds to a heat flow of

$$\dot{Q} = 9 \times 10^{-3} \frac{\mathrm{cal}}{\mathrm{kg\,h}} \ ,$$

which results in a remarkably low increase of the temperature. Assuming an exposure time of one hour the deposited energy would have been

$$Q = 9 \times 10^{-3} \frac{\mathrm{cal}}{\mathrm{kg}} \ ,$$

which would lead, according to

$$\Delta T = \frac{Q}{c} \ , \quad c - \text{specific heat of tissue} \left(= 1 \frac{\mathrm{cal}}{\mathrm{g\,K}}\right) \ ,$$

to an increase in the body temperature of the exposed person by

$$\Delta T = 9 \times 10^{-6}\,\mathrm{K} = 9\,\mu\mathrm{K} \ .$$

These numbers clearly demonstrate that the danger of nuclear radiation cannot be traced back to an increase in the body temperature.

Example 3

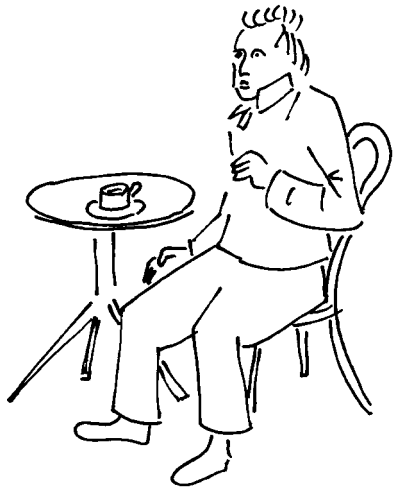
range of electrons

The range of electrons in water is about 1 cm. How is it possible to estimate the range of electrons in air given this information?

The range depends on the absorber material as Z/A. Since for both water and air this ratio is very similar[7], the range in air can be estimated from the density ratio (see also Fig. 4.4):

$$R_{\mathrm{air}} \approx R_{\mathrm{water}} \frac{\rho_{\mathrm{water}}}{\rho_{\mathrm{air}}} = 775\,\mathrm{cm} \ .$$

[7] The effective nuclear charge Z_{eff} and the effective atomic weight A_{eff} can be calculated from $Z_{\mathrm{eff}} = \Sigma f_i Z_i$, resp. $A_{\mathrm{eff}} = \Sigma f_i A_i$, where f_i are the mass fractions. For water one gets $Z_{\mathrm{eff}} = 6.8$ and $A_{\mathrm{eff}} = 14.3$ with $Z_{\mathrm{eff}}/A_{\mathrm{eff}} = 0.47$; for air one has 0.5.



"Oh my God, a cup of coffee amounts to 200 J/kg!"

Example 4

A researcher in a nuclear physics laboratory has forgotten to store a ^{60}Co source in a lead safe. As a consequence the source is lying around unshielded. The activity of the source is assumed to be 370 kBq (10 µCi). ^{60}Co emits per decay one electron with a maximum energy of 310 keV and two γ rays with energies 1.17 and 1.33 MeV (energy sum 2.5 MeV).

Work out the dose rate which students in the laboratory would receive, if their average distance from the source were 3 m. What kind of dose would they get per day in the nuclear physics lab assuming 8 hours exposure? Estimate the energy dose they would have received in the lab in comparison to the radioactivity from the natural environment.

To do this calculation (which is more an estimation) one should proceed in the following way:

1. First one should work out the effect of the electrons. Their range is approximated by **electron range**

$$R = 0.526\, E_{\mathrm{kin}}/\mathrm{MeV} - 0.095 \left(\mathrm{g/cm^2} \right) \ .$$

2. For the absorption probability of γ rays in 3 m of air one assumes a mass absorption coefficient in air of $\mu = 0.03\,\mathrm{cm^2/g}$ for an average energy $\langle E_\gamma \rangle = 1.25\,\mathrm{MeV}$. **$\gamma$ absorption**
3. What kind of fraction of γ rays will interact in the student? One should assume that the student consists essentially of water which is assumed to be tissue equivalent. The corresponding

Absorption of β and γ rays of isotopes from the ^{226}Ra decay chain

In the ^{226}Ra decay chain γ rays up to 2 MeV and β rays up to 3 MeV occur. The experimental results of absorption measurements (see Fig. 4.14) show that the β component is already completely absorbed after 3 mm of aluminum while photons have only been attenuated by about a factor of 2 even after 5 cm of aluminum. The attenuation coefficients can be described quite reasonably by exponential functions as can be seen from the semi-logarithmic plot of the data.

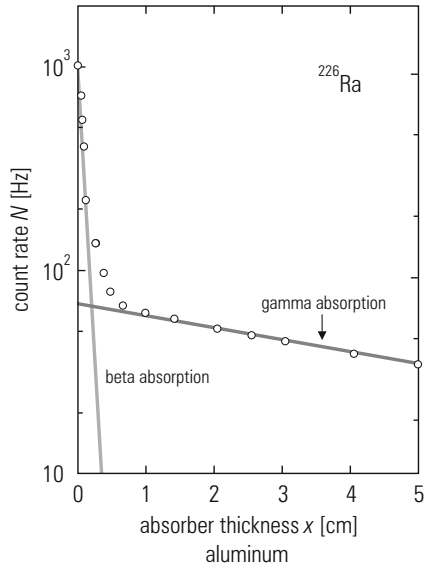


Figure 4.14
Absorption of β and γ rays from a ^{226}Ra source in aluminum

mass attenuation coefficient is $\mu_{\text{water}}(\langle E_\gamma \rangle = 1.25\,\text{MeV}) = 0.06\,\text{cm}^2/\text{g}$.

4. Then, one should estimate which fraction of the γ energy will be transferred to the student in this type of interaction, on average. Additionally, one should assume that for the photoelectric effect and pair production 100% of the energy is transferred in contrast to the Compton effect where only 50% is transferred.

solid-angle effect

5. One also must consider the solid angle (from the source) which the student occupies.
6. Then the relative relative biological effectiveness of β and γ rays should be considered.

relative dose

7. After the above calculation it will be interesting to know the dose rate, the total dose, and the dose ratio compared to the annual dose due to natural radioactivity (assumed to be about 2.3 mSv/yr).

The empirical formula for the range of electrons requires that the kinetic energy E is inserted in MeV; in this case one obtains the range R in $\mathrm{g/cm^2}$:

$$R = 0.526\, E_{\mathrm{kin}} - 0.095 \left(\mathrm{g/cm^2}\right)$$
$$= (0.526 \times 0.31 - 0.095)\ \mathrm{g/cm^2} = 0.068\,\mathrm{g/cm^2}\ .$$

To work out the range in air the density[8] of air is required, $\rho_{\mathrm{air}} = 1.29 \times 10^{-3}\,\mathrm{g/cm^3}$; this leads to

$$r = \frac{R}{\rho_{\mathrm{L}}} = \frac{0.068}{1.29} \times 10^3\,\mathrm{cm} = 52.8\,\mathrm{cm}\ .$$

effect of electrons

Since the maximum range of electrons in air is only about 50 cm, students which have an average distance of 3 m will not be exposed to electron radiation. For the following, therefore, we can neglect the effect of electrons.

The photons will also be partially absorbed in the three meter distance, but by no means completely. The initial intensity I_0 will be reduced to the intensity $I\,(3\,\mathrm{m})$ according to

$$I\,(3\,\mathrm{m}) = I_0\, \mathrm{e}^{-\mu\,\rho_{\mathrm{L}}\,x}\ .$$

Consequently, the absorption probability in air is given by

$$\alpha = 1 - \frac{I}{I_0} = 1.1\%\ .$$

We clearly see that γ rays are only very weakly absorbed in air.

effect of photons

Let us assume that the standard student is $l = 1.80\,\mathrm{m}$ large, has a weight of $m = 75\,\mathrm{kg}$, and an effective 'absorber thickness' of $d = 15\,\mathrm{cm}$. This leads to a width of the standard student of $b = 27.7\,\mathrm{cm}$ assuming the known density of tissue and water and a mass of $m = 75\,\mathrm{kg}$. The fraction of energy absorbed by the student is then worked out as

$$\beta = 1 - \mathrm{e}^{-0.06\times 15\times 1} = 59.3\%\ .$$

That is to say about 40.7% of photons will pass through the student without interaction.

For the estimation of the energy absorption it is sufficient to consider only the Compton process since in this energy range this is the dominant one. For the energies in question the cross section for pair production can be completely neglected anyway. In Compton scattering only 50% of the energy is transferred to the target.

[8] The density depends on pressure and temperature, for this example standard temperature and pressure conditions are assumed: $p = 1013\,\mathrm{hPa}$ and $T = 293\,\mathrm{K}$ (hPa = hectopascal, $1\,\mathrm{Pa} = 1\,\mathrm{N/m^2}$.)

solid-angle argument

The solid angle (from the source) which the student occupies can be estimated from the illustration in Fig. 4.15.

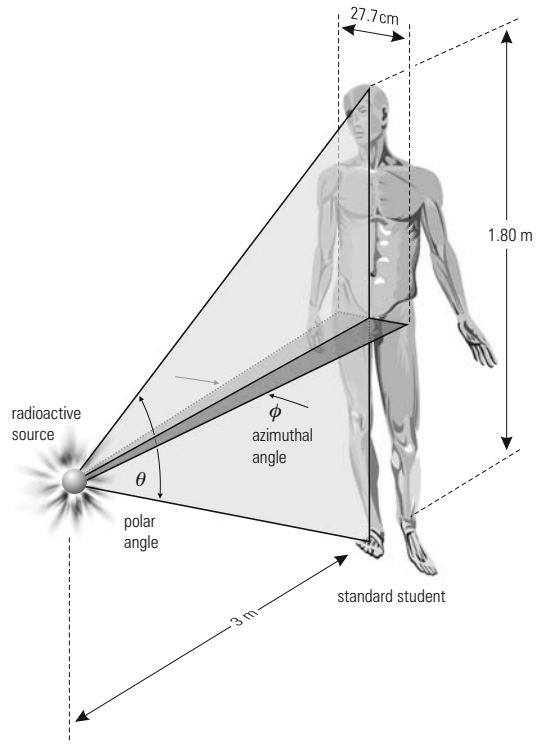


Figure 4.15
Illustration of the solid angle (from the source) which the student occupies

The angles θ and ϕ are calculated using this diagram to be[9]

$$\theta = 2 \times \arctan\left(\frac{0.9}{3}\right) = 33.4^\circ = 0.583\,\text{rad}\ ,$$

$$\phi = 2 \times \arctan\left(\frac{0.1385}{3}\right) = 5.30^\circ = 0.093\,\text{rad}\ .$$

This leads to a solid angle Ω' of

$$\Omega' = \theta\,\phi = 0.054\,\text{sterad}\ .$$

Since the student is not irradiated by electrons from the β decay, it is not necessary to consider a possible different biological effectiveness of β and γ rays. Anyway, it is the same for β and γ rays and it is equal to unity (see Chap. 2, Table 2.1).

[9] The trigonometric function 'tangent' describes the ratio of the opposite side to the adjacent side of a right-handed triangle. The arctan (on pocket calculators mostly given as $\tan^{-1}$) is the inverse function of tangent.

What we want to know is the energy-dose rate, the total dose, and the dose ratio to the annual dose due to natural radiation,

$$\text{dose rate}: \quad \dot{D} = \frac{W\,P}{m} \ ,$$

where

W – the absorbed energy per decay by the body of the student,
m – mass,
P – activity, including solid-angle and absorption factors.

$$\begin{aligned} P\,W &= \underbrace{\frac{1}{2}}_{\text{Compton}} \times \underbrace{\frac{\Omega'}{\Omega}}_{\text{solid angle}} \times \underbrace{\frac{59.3}{100}}_{\text{student}} \times \underbrace{\frac{98.9}{100}}_{\text{air}} \times 2.5\,\text{MeV} \times 10\,\mu\text{Ci} \\ &= \frac{1}{2} \times \frac{0.054}{4\,\pi} \times 0.593 \times 0.989 \times 2.5 \times 10^{6} \\ &\quad \times 1.602 \times 10^{-19} \times 10^{-5} \times 3.7 \times 10^{10}\,\frac{\text{J}}{\text{s}} \\ &= 1.87 \times 10^{-10}\,\frac{\text{J}}{\text{s}} \ . \end{aligned}$$

The dose rate, therefore, is calculated as

$$\begin{aligned} \dot{D} &= \frac{1.87 \times 10^{-10}}{75}\,\frac{\text{J}}{\text{s\,kg}} = 2.49 \times 10^{-12}\,\frac{\text{Gy}}{\text{s}} \\ &= 2.49 \times 10^{-12}\,\frac{\text{Sv}}{\text{s}} \ , \quad \text{because RBE} = 1 \ . \end{aligned}$$

The total dose on a work day of 8 h ≡ 28 800 s is given by

$$G = \dot{D}\,t = 2.49 \times 10^{-12} \times 28\,800\,\text{Sv} = 0.072\,\mu\text{Sv} \ .$$

The radiation level due to natural radioactivity is about 2.3 mSv per year, which leads to an exposure rate of 7.3×10^{-11} Sv per second, or 2.1 µSv in 8 h. This demonstrates that natural radiation leads to an exposure which is a factor of 30 larger than due to the unshielded source in the laboratory. This additional exposition can be almost neglected. The unshielded source would be only effective at very short distances, since in that case the solid angle will be much larger, and the effect of the electrons might also have to be considered.

Figure 4.16
Telescope probe for activity and contamination measurements at large distances (Graetz X50 DE detector with Geiger–Müller probe DE, GRAETZ radiation measurement technique GmbH)

determination of dose rates

dose comparison

Summary

Charged particles lose their energy in matter mainly by ionization and excitation. For electrons one has to consider the additional energy loss by bremsstrahlung. Because of the relatively large energy loss of charged particles, their range in matter is relatively short in most cases. In contrast to this, photons are attenuated only weakly when passing through matter, especially for the energies in the MeV range which are typical for the field of radiation protection. External radiation, therefore, usually consists of γ rays. Special care must be taken with neutrons, which have a relatively large range because they are electrically neutral. From the point of view of radiation protection neutrons are very unpleasant because by hitting the nuclei of cells they can create a substantial radiation damage.

4.5 Problems

Problem 1

The attenuation coefficient for 1-MeV gamma rays is assumed to be $0.12\,\mathrm{cm}^{-1}$ for concrete. What is the half-value and the tenth-value thickness?

Problem 2

The total beta-dose rate $\dot{D}_\beta$ of a pointlike 1-mCi ^{60}Co source at a distance of 5 cm is estimated by

$$\dot{D}_\beta = \Gamma_\beta \frac{A}{r^2} = 2.62 \times 10^{-11} \frac{\mathrm{Sv\,m^2}}{\mathrm{Bq\,h}} \times \frac{10^{-3} \times 3.7 \times 10^{10}\,\mathrm{Bq}}{0.05^2} = 388\,\mathrm{mSv/h}\ .$$

The total gamma-dose rate at the same position is

$$\dot{D}_\gamma = \Gamma_\gamma \frac{A}{r^2} = 3.41 \times 10^{-13} \frac{\mathrm{Sv\,m^2}}{\mathrm{Bq\,h}} \times \frac{10^{-3} \times 3.7 \times 10^{10}\,\mathrm{Bq}}{0.05^2} = 5\,\mathrm{mSv/h}\ .$$

Work out $\dot{D}_\beta$ and $\dot{D}_\gamma$ at a distance of 1 m.

Problem 3

The total attenuation coefficient (mass attenuation coefficient) for photons of 1 MeV in water is

$$\mu = 0.07\left(\mathrm{g/cm^2}\right)^{-1}\ .$$

By what factor will monoenergetic gamma radiation of 1 MeV be attenuated behind 1 m of water?

5 Detectors for Radiation Protection

"The same principle of measurement as in cosmic radiation can of course also be applied to ordinary beta and gamma rays."

Walter Bothe

It is impossible to smell, see, taste, or sense ionizing radiation. Humans have no senses for α, β, and γ rays, therefore, one has to develop detectors to replace the missing capability to see, smell, taste, or sense ionizing radiation. The necessity for the measurement of radiation exposures originates from the fact that this type of radiation has to be surveyed, controlled, and limited. Humans also have to be protected against unexpected exposures. On the one hand, the surveillance of radiation-exposed workers, the measurement of external radiation exposures, contaminations, and incorporations, in particular, in working areas, are very important. On the other hand, the environment has to be protected against unnecessary exposures. The latter point of view includes the determination of radiation exposures of the population, the monitoring of the disposal of radioactive waste into the environment, and the examination of the distribution of radioactive material in the biosphere (atmosphere, soil, water, food). In addition, national radiation-protection authorities also have realized that radiation exposures from natural sources have to be considered. In certain situations natural radiation can increase the radiation level for individuals of the population quite considerably. Therefore, these natural sources cannot be neglected in the framework of radiation protection.

limitation of radiation exposures

protection of the environment

natural radiation sources

The radiation detectors used in the field of radiation protection have to be reliable and robust and their measurements have to be reproducible. It is important to note that for different types of radiation adequate detectors must be used.

In the following the measurement principles of radiation detectors normally used in the field of radiation protection will be presented.

5.1 Ionization Chamber

A very simple radiation detector is the ionization chamber (see Fig. 5.1). Radiation incident into an ionization chamber will produce electrons and ions by ionization of the counter-gas filling. These

C. Grupen, *Introduction to Radiation Protection*,
Graduate Texts in Physics, DOI 10.1007/978-3-642-02586-0_5,

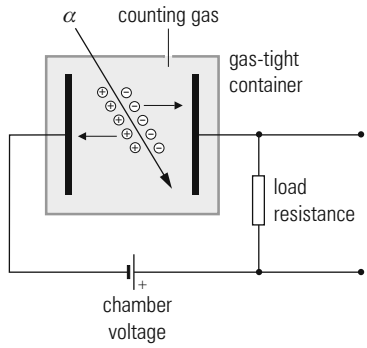


Figure 5.1
Working principle of an ionization chamber

charge carriers are collected in a constant homogeneous electrical field. Since there is no gas gain in this type of chamber, the signals are very small. Therefore, these signals have to be amplified electronically. Ionization chambers are excellently suited for the measurement of α rays which deposit their total energy in the chamber volume. Since the chamber signals are proportional to the energy, these detectors allow α-ray-spectroscopy measurements. Ionization chambers also permit an accurate measurement of the ion dose and the ion-dose rate via a measurement of the chamber current.

ionization chamber

A novel passive personal dosimeter is based on a combination of an ionization chamber with a special transistor as storage cell. For this purpose, one uses a MOSFET transistor (Metal Oxide Semiconductor Field Effect Transistor) with an open floating gate. This MOSFET transistor is integrated into a small ionization chamber with tissue-equivalent walls. The open gate is charged up by electrons which tunnel through a thin oxide layer. In this way a relatively stable charge level is reached so that this type of detector represents a memory cell. This electrically created charge level is modified by charge carriers which are produced by ionizing radiation incident into the ionization chamber and onto the tissue-equivalent chamber walls. The created charge carriers drift to the open floating-gate electrode of the MOSFET transistor where they change the pre-existing

MOSFET transistor with floating gate

memory cell

Figure 5.2
Dose–area-product meter combining a standard parallel-plate ionization chamber with separate display unit (type DIAMENTOR SET CI, PTW-Freiburg, Germany)

Figure 5.3
Shadow-free ionization chambers of 6 cm^3 and 75 cm^3 volume for absolute dosimetry, e.g. in mammography (type 34060, PTW-Freiburg, Germany)

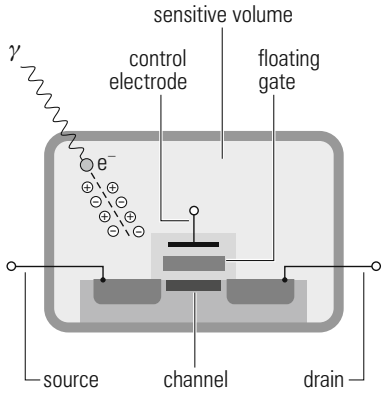


Figure 5.4
Principle of the ion-storage dosimeter DIS

charge level. The modified charge level is a measure of the deposited dose. The charge variation can be determined by means of measuring the conductivity of the transistor. The principle of this direct-ion-storage (DIS) dosimeter is sketched in Fig. 5.4. The efficiency of this electronic personal dosimeter is constant within ±20% over a wide energy range (12 keV to 6 MeV).[1]

DIS dosimeter

5.2 Proportional Counters and Geiger–Müller Counters

The detection technique in sealed proportional counters and Geiger–Müller counters is the same as in ionization chambers. But in contrast to ionization chambers, one measures the current and voltage signals and counts them instead of measuring the chamber current. The mechanical and electrical setup of a cylindrical gas counter is shown in Fig. 5.5. Depending on the high voltage[2] one distinguishes between proportional counters and Geiger–Müller counters. The electrical field in the cylindrical counter is inhomogeneous – its field strength varies inversely proportional with the distance to the anode wire. The charge carriers produced by ionization will drift depending on the sign of their charge to the anode or cathode. The electrons drift to the anode wire. When they approach the anode they

proportional counter
Geiger–Müller counter

[1] A. Fiechtner, Chr. Wernli, Strahlenschutz Praxis 2/2001, p. 32; RADOS: `www.rados.com`

[2] The high voltage depends on the counter geometry, the anode-wire diameter, and the gas filling. Typical values for the proportional regime are around 500 volt for anode wires with 30 µm diameter for an argon/methane gas filling of 80 : 20. For otherwise identical conditions Geiger–Müller tubes require somewhat higher voltages, like about 1500 volt.

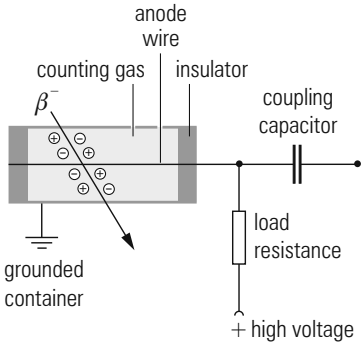
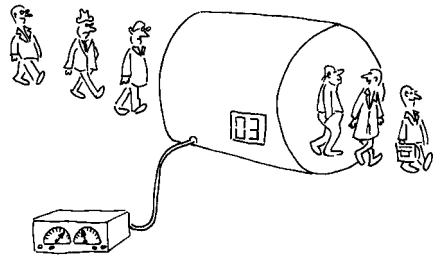


Figure 5.5
Sketch of a cylindrical gas counter



gas gain

will encounter stronger and stronger field strengths. If they gain on their mean free path, i.e. between two collisions with gas molecules, an energy from the electrical field which is larger than the ionization energy of the gas, then gas amplification starts. This charge-carrier amplification sets off an avalanche. In the proportional range gas-gain factors of about 10^4 are achieved. The discharge in the proportional counter is localized to the position where the particle has passed through the chamber. Since the output signal in the proportional counter is proportional to the energy loss (or the energy, if the particle is completely absorbed in the detector volume), strongly ionizing α particles and weakly ionizing β rays can be distinguished in this operation mode.

energy measurement
energy-loss measurement

For higher anode voltages a transition from the proportional range to the Geiger–Müller regime is observed. The discharge in the counter volume will spread laterally along the whole anode wire and gas gains of 10^8 up to 10^{10} are reached. The signals in the Geiger–Müller counter are independent of the type and energy or energy loss of the incident particle. Therefore, it is impossible to distinguish different particle types with this detector. The advantage is that the signal amplitudes are rather large so that no sensitive amplifiers are needed for the signal analysis.

Figure 5.6
Proportional counter; dose-rate range 5×10^{-2} to 5×10^{3} µSv/h (type LB 6360, BERTHOLD TECHNOLOGIES GmbH & Co. KG)

Figure 5.7
Geiger–Müller counter; dose-rate range 10^{-4} to 1 Sv/h (type LB 6361, BERTHOLD TECHNOLOGIES GmbH & Co. KG)

detection efficiency

The detection efficiency for charged particles in both counter types is close to 100%. Photons, however, will only be measured with an efficiency on the order of a few per cent. This is because photons first have to create charged particles in the chamber volume, and the interaction probability is relatively small because of the low target density of the gas filling.

gas flow detector

Proportional counters and Geiger–Müller counters allow the measurement of low doses and activities. They are also an excellent detector for dose-rate measurements. A problem with a sealed proportional counter or Geiger–Müller counter is that low-energy α and β radiation might easily be absorbed in the chamber walls. For low-energy α and β rays, therefore, open gas flow detectors are frequently used. Radioactive samples (e.g. ^{14}C for radioactive carbon dating) are installed inside the counter, so that an absorption in the chamber walls is avoided. For large-area counters for the measurement of activities and contamination (see Fig. 5.10) the gas volume is terminated by an extremely thin plastic foil. This entrance window normally is also transparent for α and β rays. Large-area counters are frequently used as personal radiation monitors. They mostly contain several parallel anode wires and they are operated in the proportional regime ('multi-wire proportional chamber').

Figure 5.8
Large-area counter as contamination monitor for α, β, and γ rays; display in s^{-1} or in Bq/cm^2 (type Contamat FHT 111 M, ESM Eberline Instruments GmbH)

To find out the optimal working point of a gas counter, the count rate as a function of the high voltage is measured (Fig. 5.13, page 65). The obtained dependence exhibits a plateau, where the counting rate (which is given by the radioactive source used) is independent of the applied high voltage or where there is only very little variation

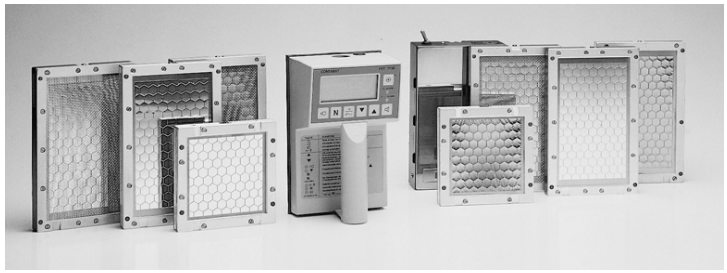


Figure 5.9
Contamination monitors with different gas flow detectors, windowless tritium counters, and a scintillation detector (ESM Eberline Instruments GmbH)

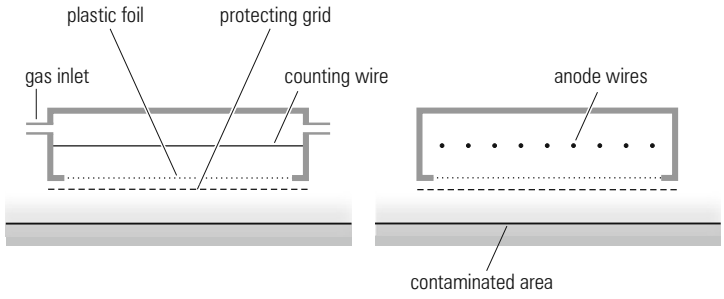


Figure 5.10
Large-area counter for the activity and contamination measurement (views parallel and perpendicular to wires)

count-rate plateau

with the voltage. The length of the count-rate plateau and its slope is a measure of the quality of the counter. The working point is best chosen right at the center of the count-rate plateau.

5.3 Scintillation Counters

scintillation effect

Scintillation counters cannot only be used for the measurement of charged particles but also for the detection of γ rays (Fig. 5.17). The photons are absorbed by the scintillation-counter medium undergoing photoelectric effect, Compton scattering, or pair production. The created electrons or positrons excite in the scintillator medium electrons in atomic shells into higher states. Upon excitation the scintillator gives off light. The light yield is proportional to the deposited energy in the scintillator. To produce a photon in the visible spectral range an energy loss of about 100 eV is required. The scintillation photons will be propagated via a light guide to the photocathode of a photomultiplier. This photomultiplier then converts the incoming scintillation photons via the photoelectric effect into photoelectrons, which will be amplified in the photomultiplier by secondary emission on dynodes. In this way signals of about 50 mV at the output of the photomultiplier are obtained.

photomultiplier

Suitable scintillation materials are inorganic doped crystals (NaI(Tl), CsI(Tl), LiI(Eu), ...), organic liquids (p-terphenyl, anthracene), or polymerized solids. The organic scintillation coun-

Separation of α and β rays

The absorption behavior of α and β rays is investigated with a setup consisting of an end-window counter and a ^{226}Ra source. To allow the α rays to be measured the window of the radioactive source and the end window of the counter have to be extremely thin (very low mass area density). At the same time the distance between source and detector can only be on the order of 1 cm, because the range of α particles in air amounts to only 4 cm ($\widehat{=}$ 5.2 mg/cm^2). Thin polyethylene foils (1.25 mg/cm^2) and aluminum foils (3.5 mg/cm^2) are used as absorber materials. The absorption of electrons can be approximated by

$$I = I_0 \, \mathrm{e}^{-\kappa \, x}$$

with $\kappa = 7.4\,(\mathrm{g/cm^2})^{-1}$ in good agreement with the empirical relation

$$\kappa = 15/E_{\beta_{\max}}^{1.5}$$

($E_{\beta_{\max}}$ in MeV, κ in $(\mathrm{g/cm^2})^{-1}$) for β energies occurring in the radium decay chain. The absorption of the short-ranged α particles cannot be described by an exponential function. In contrast they can be characterized by a fixed range on the order of 5 mg/cm^2.

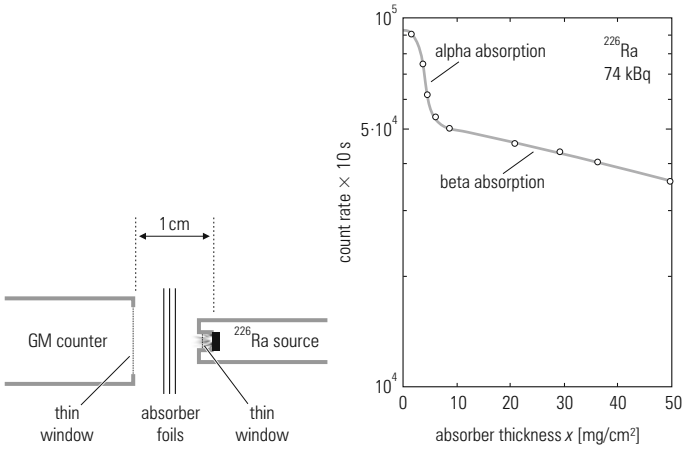


Figure 5.11
Separation of α and β rays by absorption in thin polyethylene foils

ters consist mostly of three components, one of which is the primary scintillator (e.g. naphthalene), a wavelength shifter (e.g. butyl PBD[3]), and a solving agent (e.g. Uvasol[4] for liquid scintillators or PMMA[5] for polymerized solids). The primary scintillation material is not transparent for its own scintillation light. Therefore, the wavelength shifter has to shift the primary light into a lower frequency range for which the scintillator is transparent. At the same

scintillation mechanism
wavelength shifter

[3] PBD = 2-(4-tert.-butylphenyl)-5-(4-biphenyl-1,3,4-oxadiazole)

[4] trade name of Merck, Germany

[5] polymethylmethacrylate (also known under the name Plexiglas ® or Lucite)

Determination of the dead time of a Geiger–Müller counter

The ionizing power of particles and the following gas amplification produces a large number of charge carriers which will decrease the external field strength. Therefore, the counter is for a certain time insensitive for further particle registration. This time is called dead time. Only when the charge carriers produced by the ionization of the incident particle are removed from the sensitive volume, can further particles be recorded. The counter is said to be dead after each particle passage for a certain time τ. The amount of the time where the counter is insensitive for particle measurements per unit time is $N\tau$ if N is the count rate. This means that the counter is only sensitive for the fraction $1 - N\,\tau$. The true count rate N_{true} is obtained after correction for dead-time effects to be

$$N_{\text{true}} = \frac{N}{1 - N\,\tau} \ .$$

The figure shows the measured count rates in a Geiger–Müller counter for variable source strengths. For an ideal detector without any dead time N_{true} would be N. The experimental data, however, show that dead-time effects play a decisive rôle. The relation $N_{\text{true}} = f(N, \tau)$ is solved for τ and yields

$$\tau = \frac{1}{N} - \frac{1}{N_{\text{true}}} = \frac{N_{\text{true}} - N}{N_{\text{true}}\,N} \ .$$

The experimental data yield a value for the dead time of this particular Geiger–Müller counter of

$$\tau = 100\,\mu\text{s} \ .$$

Activity measurements in the high-rate domain with Geiger–Müller counters therefore must be corrected for dead-time losses!

Rate measurements with Geiger–Müller counters on board American space probes (Explorer I) in the late fifties showed suddenly extremely low count rates when they flew through the Van Allen radiation belts, so that the physicists were afraid that the detectors stopped to work properly. The apparent low count rates were, however, related to the extremely high particle fluxes in the Van Allen belts which produced extremely large effective dead times.

For scintillation counters (see Chap. 5.3) the dead times are much smaller (typically $\tau \approx$ nanoseconds). Therefore, scintillation counters are highly superior over Geiger–Müller counters for high-rate measurements.

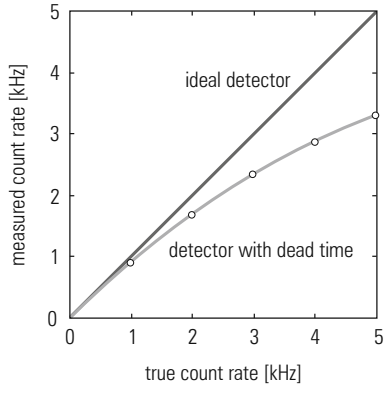


Figure 5.12
Determination of the dead time of a Geiger–Müller counter by measuring the rate dependence for known activity

Characteristic of a Geiger–Müller counter

The experimentally determined count rate in a Geiger–Müller counter depends on the applied high voltage. Below a certain threshold voltage no signals at all will be recorded. Only if the number of charge carriers in the avalanche is sufficiently large, will the electronic readout register a signal. Then for a large range the count rate is practically independent of the applied high voltage (plateau range). At the end of the plateau the count rate rises again due to after-discharges. A further increase of the high voltage would finally destroy the Geiger–Müller counter. The working point of the counter is best chosen to be in the middle of the plateau. Good Geiger–Müller counters exhibit a slope of the plateau below 2% per 100 V.

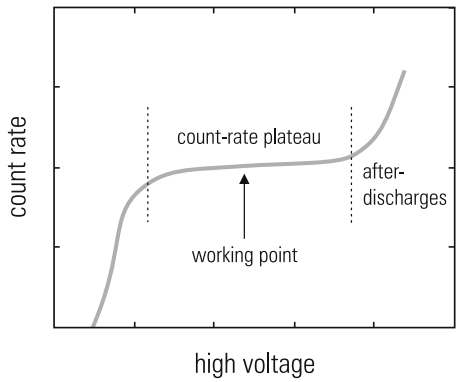


Figure 5.13
Count-rate characteristic of a Geiger–Müller counter

time the frequency of the light can be adjusted to the spectral sensitivity of the photomultiplier. Liquid and plastic scintillators have the large advantage that their shape can be adjusted to the required measurement geometry.

Because of the excellent detection efficiency for photons, scintillation counters (mainly inorganic scintillation counters) are used for the detection of γ rays and for γ-ray spectroscopy. They can also be used for high-precision dose-rate measurements.

Figure 5.14
Activity and dose-rate measurements for α, β, and γ rays with a Geiger–Müller counter (Graetz X 5 DE, pulse detector 18526 D, GRAETZ radiation measurement technique GmbH)

Figure 5.15
Analog radiation and contamination monitor with an end-window Geiger–Müller counter (MINI-INSTRUMENTS LTD, Thermo Eberline Trading GmbH)

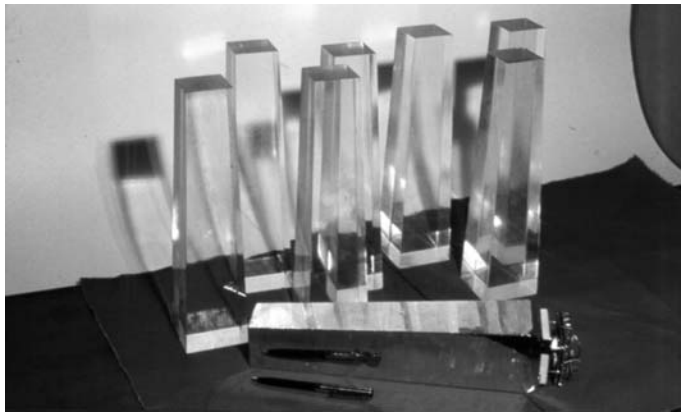


Figure 5.16
Thallium-doped CsI scintillation crystals used as electromagnetic calorimeter for an experiment at an electron–positron collider (Photo credit Boris Shwartz, Budker Institute for Nuclear Research)

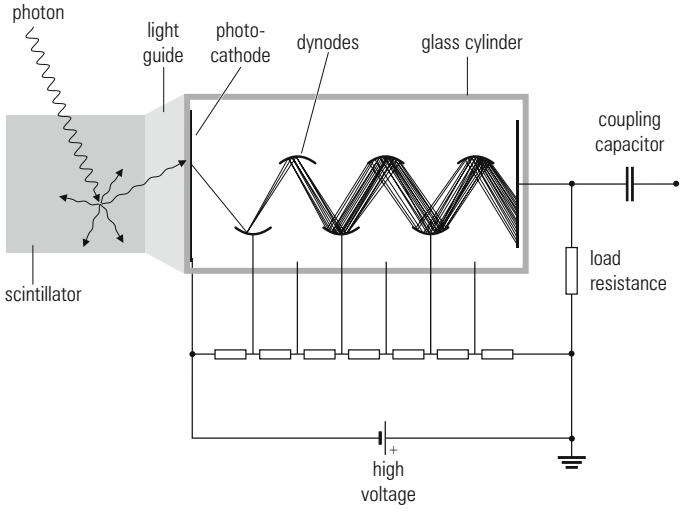


Figure 5.17
Sketch of a scintillation counter with photomultiplier readout

5.4 Semiconductor Counters

Semiconductor counters have a superior energy resolution over scintillation counters. In semiconductor counters, which are mostly based on silicon or germanium, only about 3 eV are required to produce an electron–hole pair. Hence, more electron–hole pairs are produced for a fixed energy deposit compared to the number of photons generated in scintillation counters. The electron–hole pairs created by α, β, or γ rays are collected in an external electrical field, before they can recombine ('solid-state ionization chamber').

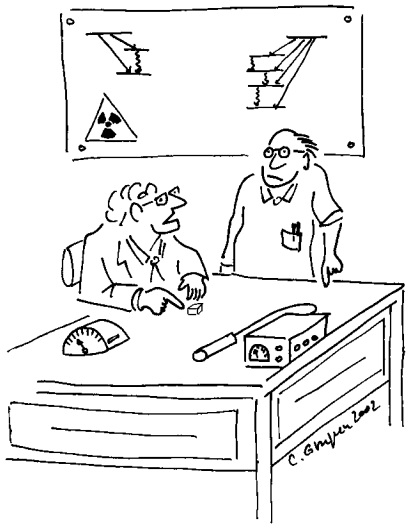
solid-state ionization chamber

Figure 5.21 shows, for example, the complexity of the gamma-ray spectrum of ^{88}Y. Apart from characteristic γ-ray lines, one sees structures that are related to positron annihilation into photons ($e^+ e^- \rightarrow \gamma\,\gamma$). In this case the electron–positron pairs were created

annihilation (positron annihilation)

Figure 5.18
Dose-rate meter with a NaI scintillation detector; dose-rate range 40 nSv/h–2 mSv/h (type SCINTO, S.E.A. GmbH)

Figure 5.19
Portable digital gamma-ray spectrometer with a NaI scintillation detector for the measurement of dose rates and for isotope identification (type identiFINDER, ICx Radiation GmbH)



"This monitor is so small because it has to detect microscopic particles!"

by pair production (Eq. (4.21)) of photons of energy 1.8362 MeV. If one or both annihilation photons escape from the detector, so-called pair peaks are produced (sometimes these pair peaks are also called escape peaks). If one photon escapes, a single-escape peak will be found, if both annihilation photons leave the detector, a

Statistical effects in radiation measurements

A simple procedure for testing the functionality of proportional or scintillation counters is to measure the so-called background rate. The background rate originates from the radiation of the natural environment (see Chap. 11). As with all statistical phenomena the result of such a measurement is subject to certain fluctuations, which are not related to the inaccuracy of the measurement, but have their origin in the stochastic character of the radioactive decay. In the following figure the results of sixty measurements of the environmental activity which have been measured with a scintillation counter are plotted for measurement intervals of 10 seconds each. For low background rates the entries into the histogram can be described by an asymmetric Poisson distribution (negative values cannot occur):

$$f(N,\mu) = \frac{\mu^N \mathrm{e}^{-\mu}}{N!} \quad , \quad N = 0, 1, 2, 3, \ldots \quad .$$

In this distribution μ is the average value $\mu = \frac{1}{k} \sum_{i=1}^{k} N_i$ of k measurements. $N!$ is a shorthand for the product of $1 \times 2 \times 3 \times 4 \times \ldots \times N$, called N factorial.
For higher count rates, as is typical for this experiment, the Poisson distribution can be approximated by a Gaussian distribution. This Gaussian is symmetrical around its average value. The function

$$f(N,\mu) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(N-\mu)^2}{2\sigma^2}\right)$$

describes the from of a Gaussian. The width of the Gaussian can be described by its standard deviation σ. Within $\mu \pm \sigma$ one finds 68.27% of all measurement values and within $\mu \pm 2\sigma$ there are 95.45% of the measured values. From the histogram (or the fit to the data) the full width at half maximum (FWHM) can easily be read. This full width at half maximum is related to the standard deviation by

$$\Delta N_{\mathrm{FWHM}} = 2 \times \sqrt{2 \times \ln 2}\, \sigma = 2.355\, \sigma \quad .$$

The statistical error for a single measurement is given by the square root of the count rate.
For the measurements at radioactive sources the background effect always has to be considered. This background rate can vary for different places because the environmental activity also depends on where it is measured.

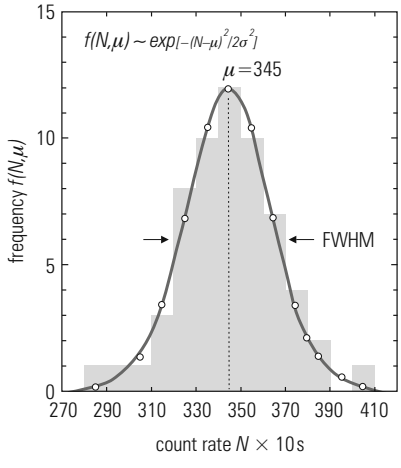


Figure 5.20
Measurement of the statistical fluctuations and fit by a Gaussian

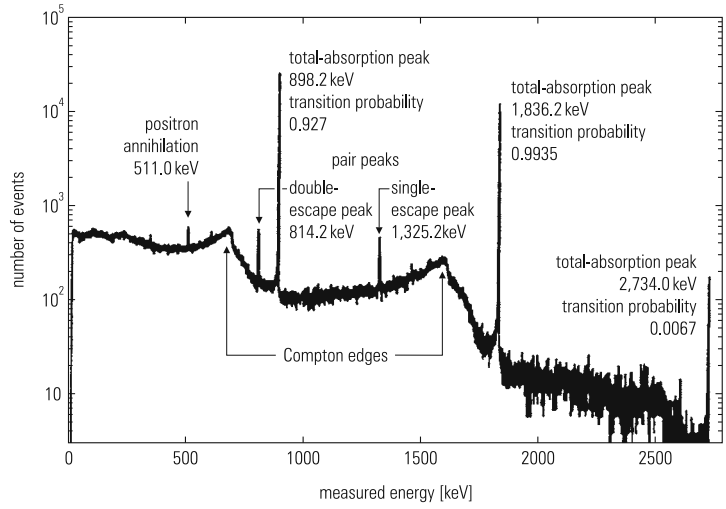


Figure 5.21
Gamma spectrum of ^{88}Y recorded with a high-purity germanium detector. ^{88}Y decays by positron emission or electron capture (EC) into an excited state of ^{88}Sr. The excited ^{88}Sr nucleus transforms itself by a cascade decay (898 keV and 1836 keV) or with smaller probability directly (2734 keV) into the ground state

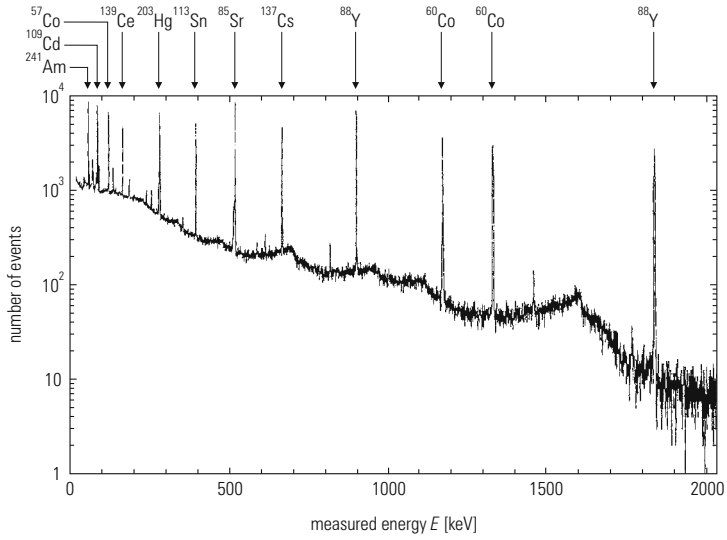


Figure 5.22
Photopeak identification in a mixture of radioisotopes based on the pulse-height spectrum recorded with a high-purity germanium detector

double-escape peak is formed. It can also happen that the positron annihilation occurs outside the detector, e.g. in the shielding material surrounding it. In the case that just one annihilation photon is measured, one finds a characteristic line at 511 keV corresponding to the electron mass. Apart from these processes one observes the Compton background and the associated Compton edges. These features are also observed in Fig. 5.22 where different radioisotopes can be identified by the so-called photo peaks or full-absorption peaks.

Compton background

Because of their high energy resolution, semiconductor counters are ideally suited for γ spectroscopy and the identification of

γ spectroscopy

isotope identification

Figure 5.23
High-purity germanium detector for the measurement of γ rays. Detectors in different cryostat configurations and shieldings (EG&G)

Figure 5.24
Ion-implanted silicon detectors, PIPS (Passivated Implanted Planar Silicon Detectors), for the measurement of α particles (Canberra Eurisys GmbH)

radioisotopes via their characteristic γ-ray lines. Figure 5.22 shows the pulse-height spectrum of a mixture of radioisotopes, recorded with a high-purity germanium crystal detector (see Fig. 5.23) which allows to separate the different γ-ray lines with high accuracy. Ion-implanted silicon detectors are also used for high-resolution α spectroscopy (see Fig. 5.24).

5.5 Neutron Dosimeters

For the purpose of neutron dosimetry these neutral particles first have to create charged particles in nuclear interactions. Suitable neutron converters have already been described in the chapter on interactions of particles and radiation with matter (Sect. 4.2). For the measurement of neutrons in a Geiger–Müller counter or proportional counter one can use boron trifluoride as a counting medium (BF_3) to eventually measure the α particles from the reaction $n + {}^{10}\mathrm{B} \rightarrow \alpha + {}^{7}\mathrm{Li}$. In a LiI(Eu) scintillator one takes advantage of the interaction $n + {}^{6}\mathrm{Li} \rightarrow \alpha + {}^{3}\mathrm{H}$ for the production of α particles and tritons.

boron-trifluoride counter

lithium-iodide scintillator

fission neutrons

Figure 5.26 shows the energy distribution of fission neutrons, as they are created in the fission of $^{235}\mathrm{U}$ by thermal neutrons.

Apart from boron-trifluoride counters and albedo dosimeters also nuclear-track detectors are used to a large extent for fast, ener-

Figure 5.25
Neutron dose-rate meter with polyethylene moderator; counting gas: ^{3}Helium/methane; detector response in µSv/h (model LB 6410, BERTHOLD TECHNOLOGIES GmbH & Co. KG)

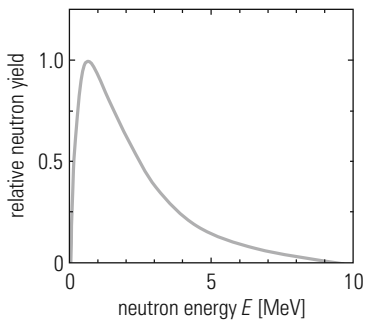


Figure 5.26
Energy spectrum of fission neutrons from ^{235}U fission by thermal neutrons

getic neutrons. These track-etch detectors can measure neutrons in the energy range from 2 to 70 MeV. Typical applications are works at accelerators, the handling of radium–beryllium sources in the laboratory, or the measurement of the high-energy neutron component in cosmic rays at large flight altitudes. This last measurement is of particular importance for the flying personnel. Track-etch dosimeters made from dedicated materials are largely insensitive against alpha, beta, and gamma rays. Neutrons produce a certain local radiation damage in the material, which can be made visible by etching, e.g. with a solvent like NaOH. The evaluation of nuclear-track detectors is quite cumbersome, because the etch cones produced by neutrons are relatively small and frequently demand scanning the etched material with a microscope (see also Sect. 4.2, page 41).

5.6 Personal Dosimeters

personal dosimetry

In the field of personal dosimetry one has to distinguish between directly and indirectly readable dosimeters. Ionization chambers can be constructed as pen-type pocket dosimeters (Fig. 5.27) which allow a direct reading of the received dose on a scale calibrated in milli- or microsievert. The sensitive volume of a pen-type pocket dosimeter consists essentially of a capacitor, which is charged to a certain voltage. The irradiation of the chamber gas leads to a dose-proportional current which discharges the capacitor slowly. Just as with an electrometer the charge state of the capacitor is read with the help of a quartz dial which is imaged via a built-in optic to a scale calibrated in milli- or microsievert. If one uses pen-type pocket dosimeters for X rays, one has to consider that low-energy X rays can easily be absorbed in the walls of the dosimeter. Furthermore, the sensitivity of a pen-type pocket dosimeter varies considerably

pen-type pocket dosimeters

sensitivity

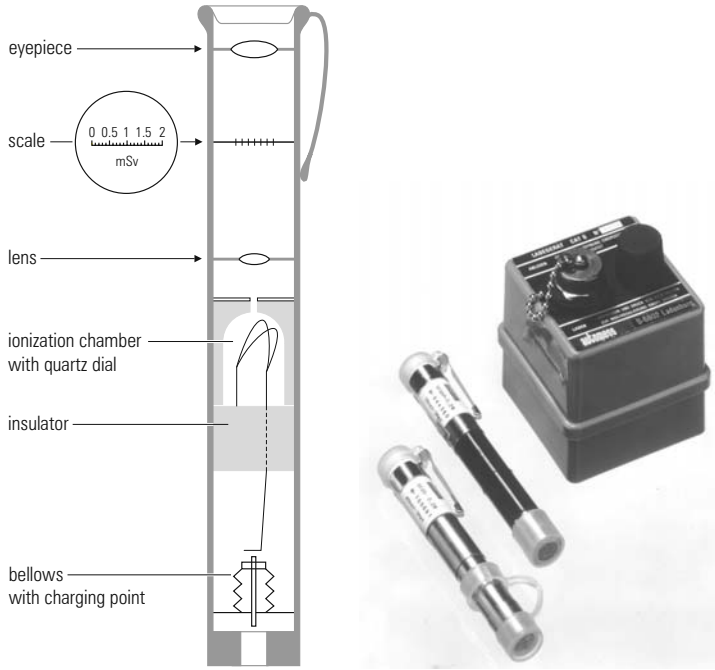


Figure 5.27
Pen-type pocket dosimeter

Figure 5.28
Pen-type pocket dosimeter with charging unit, sensitivity depending on the type varying from 18 keV to 3 MeV; scales from 1 mSv up to 2 Sv (SEQ5 and SEQ6R, automess GmbH)

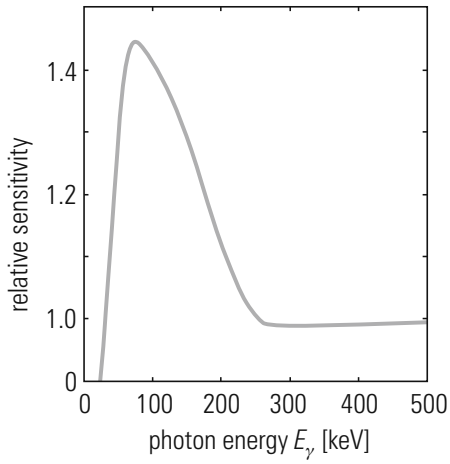


Figure 5.29
Relative sensitivity of a pen-type pocket dosimeter in its dependence on the photon energy

for energies below 300 keV due to the strong dependence of the photoelectric cross section on the photon energy (see Fig. 5.29).

film badge

The most popular and well-known indirectly readable dosimeter is the film-badge dosimeter (Fig. 5.30). These dosimeters use the blackening of a photographic film (X-ray film) as a measure for the received dose. By metal absorbers (Cu, Pb) of different thickness information about the intensity, direction of incidence, radiation type,

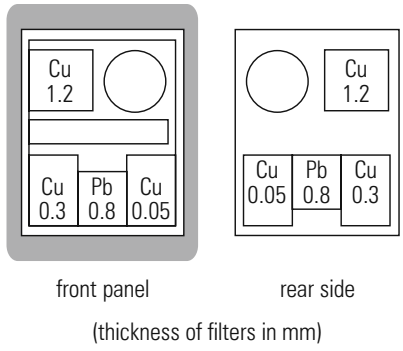


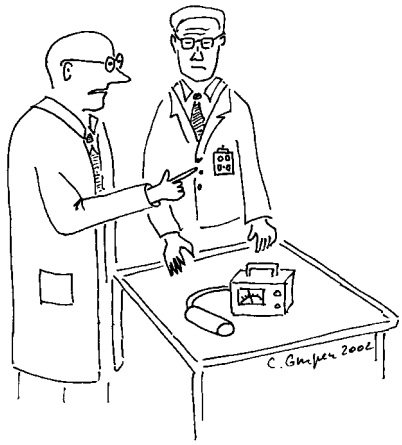
Figure 5.30
Film-badge dosimeter with indicated positions of different absorbers

Figure 5.31
Film-badge dosimeter with X-ray films in a multifilm cassette for the detection of X rays, γ rays, and β rays. The energy domains for X rays and γ rays are 5 keV–9 MeV, for β rays > 300 keV (GSF – Forschungszentrum für Umwelt und Gesundheit GmbH (research center for environment and health))

and even the energy can be achieved. A hole in the cassette also allows the measurement of low-energy β rays. Because of the high degree of information, the mechanical stability, and the possibility of permanent documentation, official dosimeters are mostly film badges. There are, however, several disadvantages of film badges, namely, the limited durability of films, the sensitivity to humidity and high temperature, the limited measurement accuracy, and the laborious way of reading the information.

possibility of documentation

The film dosimeters hitherto described have their limitations in determining the skin dose parameters $H_p(10)$ and $H_p(0.07)$. New types of dosimeters optimized for the measurement of the penetration of radiation into the skin, like the 'sliding-shadow' dosimeters (see page 16) have become available. These dosimeters also allow a determination of the photon energy and their angle of incidence.



"And these bagdes are supposed to protect us effectively from radiation?"

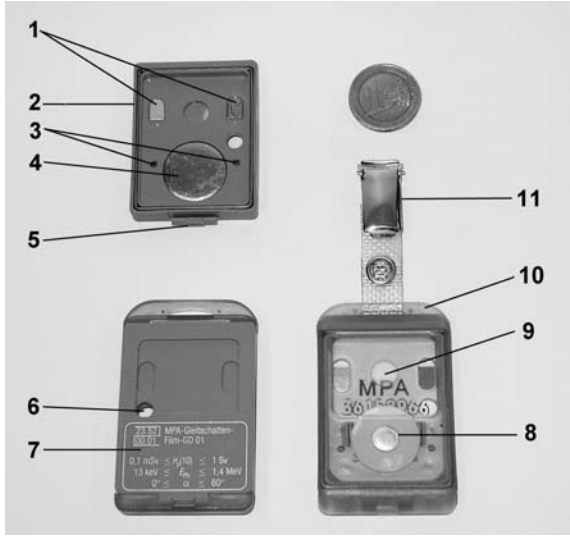


Figure 5.32
'Sliding-shadow' dosimeters with special films for the detection of X rays, γ rays, and β rays. The energy-detection limits for X rays and γ rays are 13 keV–1.4 MeV; 1 – β-radiation indicator (offset arranged on front side and rear side), 2 – shielding frame, 3 – direction indicator (offset arranged on front side and rear side), 4 – metal filter, 5 – cassette shutter, 6 – film inspection hole, 7 – label indicating the film type, 8 – 'sliding-shadow' filter, 9 – filter made of plastic, 10 – transparent front, 11 – mounting clip (examination authority for materials North Rhine-Westfalia)

Furthermore they can discriminate between β and γ rays. Figure 5.32 shows such a frequently used 'sliding-shadow' dosimeter.

phosphate-glass dosimeters

Phosphate-glass dosimeters can be used in the field of radiation protection because they will give off a characteristic fluorescence radiation under exposure to ultraviolet light, where this fluorescence radiation is proportional to the intensity of the received energy dose. This type of dosimeter is frequently constructed in a spherical form which partially compensates for the distinct energy

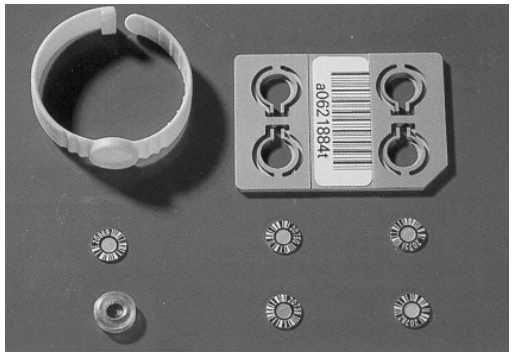


Figure 5.34
Metal finger-ring dosimeters with thermoluminescence detector (LiF(Mg, Ti)) for X rays and energetic β and γ rays. The luminescence detector chip is mounted on an adjustable ring (HARSHAW TLD, Thermo Eberline Trading GmbH)

dependence of the dose reading ('spherical dosimeter'). By using γ-ray filters (from tin) or neutron filters (from plastic with boron content) the identification of the radiation type also appears possible (Fig. 5.33). Phosphate-glass dosimeters have a large measurement range, a very low long-term fading, and they can be analyzed repeatedly so that the information they contain is available for multiple documentation. One of the disadvantages of these types of dosimeters is related to the fact that the analysis of these dosimeters requires a rather expensive readout system.

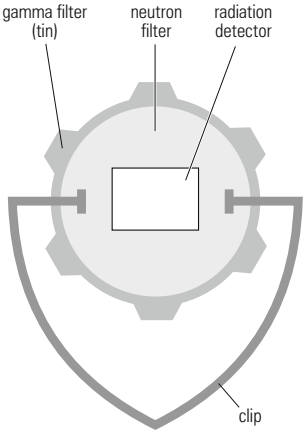


Figure 5.33
Phosphate-glass spherical dosimeter

thermoluminescence dosimeter

Thermoluminescence dosimeters (TLDs) take advantage of the property of some inorganic compounds (e.g. LiF) to give off light when they are heated up after excitation with ionizing radiation. The light intensity is proportional to the received energy dose. A distinct advantage of thermoluminescence dosimeters is that even for very small dimensions they exhibit a high sensitivity and they can be used just as phosphate-glass dosimeters as finger-ring dosimeters. A disadvantage is certainly the tedious analysis and the fact, that the heating-up of the thermoluminescence dosimeter erases the dose information. However, this can also be considered as an advantage, because after heating up the thermoluminescence material this type of dosimeter can be used anew.

An interesting candidate giving useful applications for the measurement of low-level radiation are thermoluminescence badges containing the rare-earth metal thulium in the form of thulium acetate or thulium acetylacetonate. This material has a very high radiation sensitivity, with the added advantage that low-energy X rays and γ rays can be separately detected. Thulium emits light in the ultraviolet (375 nm) and in the visible range (465 nm).

albedo neutron dosimeter

Albedo neutron dosimeters measure low-energy neutrons which are backscattered from the body of the person who carries such a dosimeter. They mostly consist of thermoluminescence sheets in which neutrons can be detected via reactions with boron or lithium.

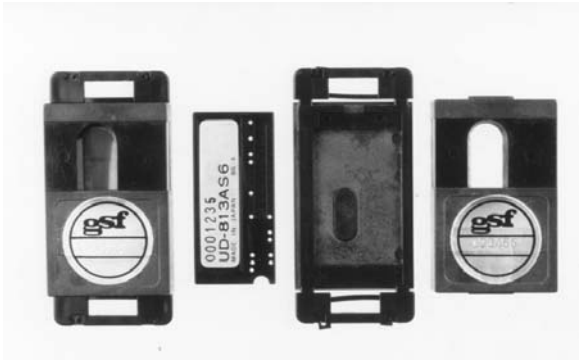


Figure 5.35
Albedo neutron dosimeter and thermoluminescence multi-element detector for the measurement of X rays and γ rays as well as thermal and epithermal neutrons; measurement range 0.1 mSv up to 2 Sv (GSF – Forschungszentrum für Umwelt und Gesundheit GmbH (research center for environment and health))

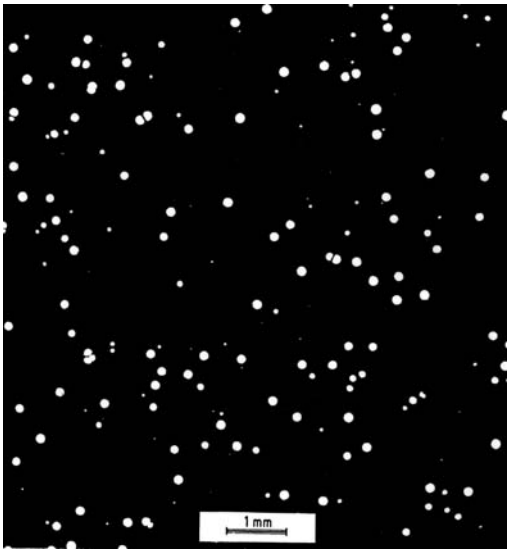


Figure 5.36
Microphotograph of a nuclear-track detector showing etch holes of diameter between 80 µm and 150 µm due to the impact of α particles from radon decay (see also `www.radonlab.net/tracketch.htm`)

The calibration depends, however, on the person that carries this type of dosimeter.

radon measurement
plastic detectors

For radon monitoring, plastic detectors can be used (cellulose-nitrate sheets). The α rays which occur in the decay chain of the radon isotopes will produce a local radiation damage in the plastic material which can be etched with soda solution and hence made visible.

accident dosimetry
hair activation

Occasionally, a problem occurs with the determination of body doses after radiation accidents if no dosimeter information is available (accident dosimetry). A possibility to work out the received body dose after the fact is given by the so-called hair-activation method. Hair contains sulphur with a concentration of 48 mg sulphur per gram hair. By neutron interactions (e.g. after a reactor accident) the sulphur can be activated according to

$$n + {}^{32}\mathrm{S} \rightarrow {}^{32}\mathrm{P} + p \ . \tag{5.1}$$

In this way the radioisotope phosphorus 32 is produced, which has a half-life of 14.3 days. In addition to this, radioactive silicon 31 is produced by

$$n + {}^{34}\mathrm{S} \rightarrow {}^{31}\mathrm{Si} + \alpha \ . \tag{5.2}$$

The ^{31}Si radioisotope interferes with the phosphorus-activity measurement. The half-life of the ^{31}Si isotope, however, amounts to only 2.6 h. Therefore, one waits until this activity has decayed before the ^{32}P activity is measured. In case of a surface contamination of the hair substantial cleaning is also necessary before the phosphorus activity of the hair is measured.

Phosphorus 32 is a pure beta-ray emitter. The maximum energy of the electrons is 1.71 MeV. Because of the low expected count rates, a detector with high efficiency and low background is required. For example, an actively and passively shielded end-window counter can be used. The received radiation dose can be inferred from the phosphorus-32 activity with the help of the known activation cross section.

blood activation

A further possibility of accident dosimetry is given by the procedure of blood activation. Human blood contains about 2 mg sodium per milliliter. This concentration is about the same for all humans.

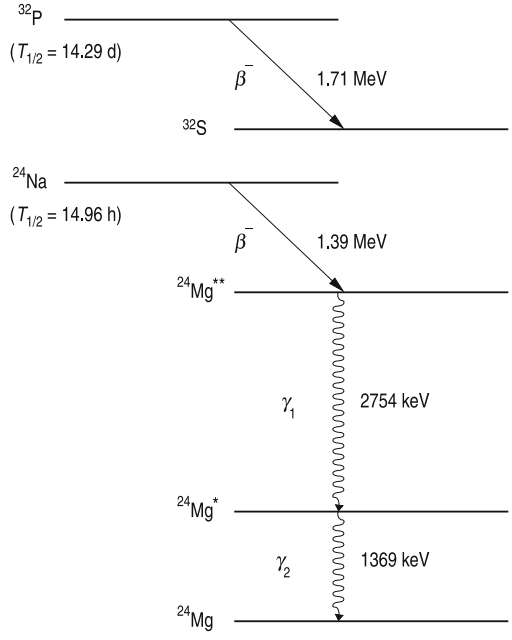


Figure 5.37
Decay-level scheme of $^{32}_{15}$P

Figure 5.38
Decay-level scheme of $^{24}_{11}$Na

By the capture of thermal neutrons the stable ^{23}Na isotope transforms into radioactive ^{24}Na,

$$n + {}^{23}\mathrm{Na} \rightarrow {}^{24}\mathrm{Na} + \gamma \ . \tag{5.3}$$

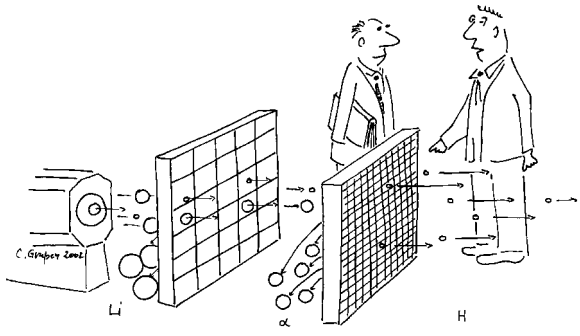
Again activities of short-lived radioisotopes produced in this neutron-capture process can interfere with the ^{24}Na-activity measurement. After a suitable decay time the remaining activity of ^{24}Na ($T_{1/2} = 15\,\mathrm{h}$, $E_{\beta^-_{\max}} = 1.39\,\mathrm{MeV}$ with subsequent γ emissions) can be recorded and used as basis for the determination of the received dose.

The presented radiation detectors help to identify radioisotopes, to determine the amount of radioactivity release, to monitor possible illegal clearance of radioactive material, and to observe the effect of radiation on the environment and on humans. In typical surveillance programs for nuclear power plants it is required that the different ways of exposure due to external and internal radiation, the release rates into water and air, the concerned food chains, and the identity of the released radioisotopes have to be determined. The corresponding measurement techniques have to be very sensitive, since the permitted dose-rate limits for the release of radioactive material into the environment for the normal population are usually quite low.

monitoring of radiation exposure

Dose-rate measurements for personal dosimetry predominantly employ ionization chambers and Geiger–Müller counters. Because of the energy and directional dependence of these detectors, the frequently unknown mixtures of types of radiation, and the impossibility to record low-energy β-ray emitters, the measurement errors are quite substantial (20% to 50%). If the activity and dose of a mixture of different γ-ray sources has to be determined, the uncertainty of the measurement can amount to 100% and even more.

measurement accuracy



"Our isotope separator!"

Table 5.1
Typical applications of different measurement techniques for personal dosimetry

dosimeter	principle of operation	radiation type measurement range	advantages and disadvantages
film badge	photo-chemical blackening	γ, β 0.1 mSv–5 Sv	can be documented, insensitive for low-energy γ rays
pen-type pocket dosimeter	ionization chamber	γ 0.03–2 mSv, also other ranges of measurement	very sensitive, permanently readable, insensitive for α and β rays, cannot be documented
directly readable dosimeter ('pocket dosimeter')	ionization or proportional chambers and GM counters	γ 0.1 µSv–10 Sv	permanently readable, cannot be documented
TLD dosimeter	thermo-luminescence measurement	γ, (β) 0.1 mSv–10 Sv	suitable for the measurement of low doses, cannot be documented
phosphate-glass dosimeter	photo-luminescence measurement	γ 0.1 mSv–10 Sv	can be documented, can be read repeatedly
albedo neutron dosimeters	neutron moderation by the carrier	n, γ 0.1 mSv–10 Sv	calibration depends on the human carrier
track-etch dosimeter	material damage in polycarbonate films	n 0.5 mSv–10.0 mSv	can be documented, the evaluation requires the knowledge of the radiation field
radon personal dosimeter	material damage in cellulose nitrate films	α 75–7000 kBq h/m^3 [a]	can be documented

[a] For a trimonthly surveillance (corresponding to 500 working hours) this corresponds to an average radon concentration at the workplace of 150–14 000 Bq/m^3.

Figure 5.39
Directly readable dose-rate meter with GM counter (model 6150 AD6, automess GmbH)

Figure 5.40
Directly readable alarm dosimeter with dose and dose-rate alarms (model ADOS, automess GmbH)

Typical domains, where different measurement techniques for personal dosimetry are used, are compiled in Table 5.1.

It can be noticed that there is only one personal detector for α rays in Table 5.1, namely, the radon personal dosimeter. Due to the short range of α particles in air or clothing, the external irradiation by α rays mostly represents no radiation risk. An exception consists of radon inhalation in a radon environment.

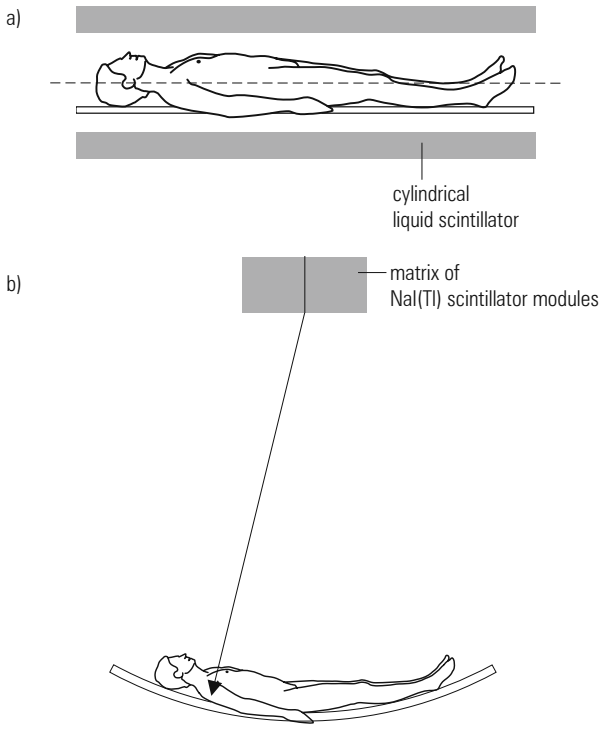


Figure 5.41
Sketch of a whole-body counter for the measurement of incorporations: (a) 4π geometry, (b) bend geometry

5.7 Measurement of Incorporations and Contaminations

measurement of incorporations

A very important point in the radiation-protection measurement technique is the measurement and monitoring of incorporations and contaminations. To prevent inhalations the activity concentration of air must be measured. This can be done directly by guiding part of the inhaled air through a detector. In indirect measurements the respiratory air can be pressed through a filter whose activity is to be analyzed. For a known amount of air that has been pressed through the filter the activity of the respiratory air can be worked out. In a

measurement of contaminations

very similar way also possible contaminations of water can be determined. In the case of water enrichment techniques are usually preferable over direct measurement.

whole-body counter

The determination of the body activity after an assumed incorporation can be performed with a whole-body counter (Fig. 5.41). A measurement of the activity of biological excretions (urine, feces) also gives evidence about possible incorporations.

danger due to incorporation

Incorporations cannot be excluded in accidents with the release of radioactive material. One also has to take care of possible incor-

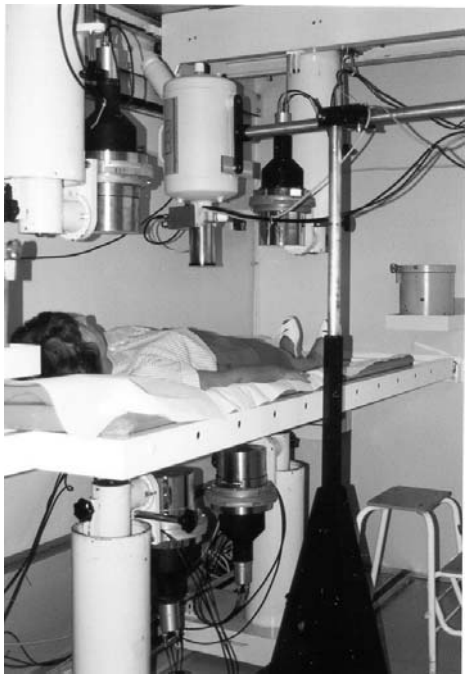


Figure 5.42
Whole-body counter with NaI(Tl) detectors and semiconductor counters (`www.strz.uni-giessen.de`)

porations in case of increased activity values in rooms and respiratory air, and in work places in which unsealed radioactive sources are handled. In particular, if tools and work places are contaminated, incorporations can easily occur.

If unsealed radioactive material is handled, the measurement of possible contaminations is mandatory. Direct measurements are best done with a large-area counter, where it is important that the counter gets as close as possible to the contaminated area without touching it to avoid contamination of the detector. Wipe tests or using adhesive tapes are established techniques for indirect measurements of contaminations. In both cases it has to be considered that only part of the contamination is recovered with wipe tests. Wipe tests on dry surfaces will typically recuperate about 20% of the activity. In contrast, wipe tests of wet surfaces and techniques with adhesive tapes allow to recover about 50% of the activity.

wipe test

test with adhesive tapes

The results of incorporation measurements have to be compared to limits of the maximum annual intake by inhalation and ingestion which are defined in national radiation-protection regulations. If incorporations by a radioisotope i with measured activity A_i have been recorded and if the limit according to the radiation-protection regulations for this radioisotope is given by $A_i^{\max}$, in total, the relation for all isotopes

limits

$$\sum_{i=1}^{n} \frac{A_i}{A_i^{\max}} \leq 1 \tag{5.4}$$

must be satisfied. If the limits are exceeded, the appropriate authority must be informed.

calibration of detectors

For all dose and contamination measurements a calibration of the used detectors with well-defined test techniques is absolutely necessary. Also a radioisotope analysis with identification of the main radioisotopes is mandatory since the quality factors describing the biological effect of radiation exposures depend on the type of radiation.

5.8 Supplementary Information

Example 1

proportional counter

The radial dependence of the electric field strength in a proportional counter is given by

$$E(r) = \frac{U_0}{r \ \ln\left(r_\mathrm{a}/r_\mathrm{i}\right)} \ ,$$

where U_0 is the anode voltage, r_a the radius of the proportional counter, and r_i the anode-wire radius. Typically proportional counters have diameters on the order of 1 cm and anode wires of 30 µm diameter. With these values the field strength at the anode wire for an operating voltage of 1500 V is

field-strength dependence

$$E(r = r_\mathrm{i}) = \frac{1500\,\mathrm{V}}{15 \times 10^{-6}\,\mathrm{m} \times \ln\left(\frac{5\,\mathrm{mm}}{15\times10^{-3}\,\mathrm{mm}}\right)} = 172\,\mathrm{kV/cm}$$

and at the outer boundary of the counter

$$E(r = r_\mathrm{a}) = \frac{1500\,\mathrm{V}}{5 \times 10^{-3}\,\mathrm{m} \times \ln\left(\frac{5\,\mathrm{mm}}{15\times10^{-3}\,\mathrm{mm}}\right)} = 516\,\mathrm{V/cm} \ .$$

voltage signal

The voltage signal on the anode wire after the passage of a particle through the counter can be worked out from the equation relating the created charge to the voltage,

$$\Delta U = \frac{e\,N}{C}\,A \ ,$$

where e is the elementary charge, N the number of primarily produced charge-carrier pairs, C the capacity of the counter, and A the gas-gain factor.

charge-carrier production by an α particle

If an α particle of 5 MeV is absorbed in the proportional counter and if $W = 25\,\text{eV}$ is the energy required for the production of one charge-carrier pair, then one obtains

$$N = \frac{5\,\text{MeV}}{25\,\text{eV}} = 2 \times 10^5 \ .$$

With a typical gas gain of $A = 10^3$ and a capacity of 10 pF one gets ($e = 1.602 \times 10^{-19}$ coulomb)

$$\Delta U = 3.2\,\text{V} \ .$$

charge-carrier production by an electron

In contrast to α particles the counting gas has a low absorption power for electrons of energy 1 MeV. Hence, they only deposit a fraction of their energy in the detector. Assuming an energy loss of $\Delta E = 2.5\,\text{keV/cm}$ a relativistic electron produces only about

$$N = \frac{\Delta E}{W} = 100$$

charge-carrier pairs, which would lead to a signal of

$$\Delta U = 1.6\,\text{mV} \ .$$

Such small signals generally require an electronic amplification in the subsequent circuitry. This example shows that electrons and γ rays (which lead to electron-like signals) can easily be distinguished from α rays.

Example 2

activity measurement

If a counter is used to determine the activity of a radioactive source, one might believe that the count rate (the number of decays per second) represents the activity of the source. However, the measured rate is usually much smaller than the activity of the radioactive source. This relates to a number of reasons which are going to be explained in this example:

A sealed, pointlike ^{241}Am source is measured with a counter and leads to a count rate of $R = 100\,\text{s}^{-1}$. The counter has a sensitive area of $10\,\text{cm}^2$, a diameter of 1 cm, and is operated at a distance of 20 cm from the source. Since the radioactive source is sealed, all α particles emitted from the source are absorbed. The counter, therefore, only measures the photons of energy 60 keV. If the source emits these γ rays isotropically (which is generally the case) the counter 'sees' only a certain solid-angle fraction

solid-angle fraction

$$f_1 = \frac{\text{sensitive area of the counter}}{\text{spherical surface at the distance to the counter}}$$
$$= \frac{10\,\text{cm}^2}{4\pi \times 20^2\,\text{cm}^2} = 0.002 \ .$$

Part of the photons will be absorbed already in the air and will not reach the counter. This fraction can be worked out to be

$$1 - \mathrm{e}^{-\mu_{\mathrm{air}}\, x_{\mathrm{air}}} \approx 8 \times 10^{-4} \ ,$$

absorption effect

if μ_{air} is the mass absorption coefficient for 60-keV photons in air ($\mu_{\mathrm{air}} = 0.03\,(\mathrm{g/cm^2})^{-1}$) and x_{air} is the traversed distance in $\mathrm{g/cm^2}$,

$$x_{\mathrm{air}} = 20\,\mathrm{cm} \times \rho_{\mathrm{air}} = 0.0258\,\mathrm{g/cm^2} \ ;$$

which means that only the fraction

$$f_2 = \mathrm{e}^{-\mu_{\mathrm{air}}\, x_{\mathrm{air}}} = 0.9992$$

reaches the counter. A further fraction of photons will additionally be absorbed in the wall of the counter. If this chamber wall is made up from aluminum of 0.5 mm thickness (density ρ_{Al}), the fraction of not absorbed photons can be determined from the area density

$$\begin{aligned} x_{\mathrm{Al}} &= 0.05\,\mathrm{cm} \times \rho_{\mathrm{Al}} = 0.05\,\mathrm{cm} \times 2.7\,\mathrm{g/cm^3} \\ &= 0.135\,\mathrm{g/cm^2} \end{aligned}$$

and the relation

$$f_3 = \mathrm{e}^{-\mu_{\mathrm{Al}}\, x_{\mathrm{Al}}} = \mathrm{e}^{-0.15 \times 0.135} = 0.98 \ ,$$

where $\mu_{\mathrm{Al}} = 0.15\,(\mathrm{g/cm^2})^{-1}$ is the mass absorption coefficient for 60-keV photons in aluminum. This result tells us that most of the photons will not be absorbed in the counter wall. This is certainly of advantage because the photons will finally reach the sensitive volume of the counter, but to be recorded in that volume they first have to undergo an interaction in the counting gas. For an effective gas layer of 1 cm Xe/CO_2 (90 : 10) the area density at standard temperature and pressure is

$$x = 1\,\mathrm{cm} \times 5.5 \times 10^{-3}\,\mathrm{g/cm^3} = 5.5 \times 10^{-3}\,\mathrm{g/cm^2} \ .$$

The mass absorption coefficient for Xe/CO_2 can be taken from standard tables or the literature (e.g. Particle Data Group "Review of Particle Properties" Journal of Physics G **33** (2006)) to be

detection efficiency

$\mu_{\mathrm{Xe/CO_2}} = 5\,(\mathrm{g/cm^2})^{-1}$. This leads to an absorption probability in the counting gas of

$$f_4 = 1 - \mathrm{e}^{-\mu_{\mathrm{Xe/CO_2}}\, x_{\mathrm{Xe/CO_2}}} = 1 - \mathrm{e}^{-5 \times 5.5 \times 10^{-3}} = 0.027 \ ,$$

which means that only 2.7% of the photons are recorded.

In addition to these mentioned effects further corrections may be necessary due to the following phenomena:

- backscattering from the chamber wall,
- self-absorption in the source and its seal,
- reduced electronic detection efficiency,
- dead-time effects at high count rates.

activity determination

If the latter four effects can be neglected, the activity of the source is obtained to be

$$A = \frac{R}{f_1\ f_2\ f_3\ f_4} = 1.9 \times 10^6\,\mathrm{Bq}\ .$$

If the dead time τ of the counter is large, one has to consider that within the fraction $R\ \tau$ of the time no signals can be recorded. The dead-time-corrected rate then is

$$R^* = \frac{R}{1 - \tau\ R}\ ,$$

which leads to

$$R^* = \frac{100}{1 - 100 \times 10^{-4}}\,\mathrm{s}^{-1} = 101\,\mathrm{s}^{-1}$$

dead-time effect

for a dead time of $\tau = 100\,\mu\mathrm{s}$. Dead-time effects become only important, if $R\ \tau \ll 1$ is no longer valid. In our example the dead-time correction represents only a 1% effect.

Example 3

In a scintillation counter a photon from the β decay of ^{137}Cs to ^{137}Ba will be recorded. In inorganic scintillators such as NaI(Tl) an average energy of 25 eV is required for the production of a scintillation photon. The 662-keV photon thus produces about $N = 26\,500$ photons. Via a light guide these photons are guided to a photomultiplier. The light-guide system typically has a transfer probability of $\eta_1 = 20\%$. Out of those photons arriving at the photocathode only about every fifth photon produces a photoelectron, which means the quantum efficiency also has a value of $\eta_2 = 20\%$. These produced photoelectrons are transferred with $\eta_3 = 80\%$ probability to the dynode system, in which the signal is amplified. If the amplification factor of the photomultiplier is assumed to be $A = 10^6$, a number of

quantum efficiency

$$R = \eta_1\,\eta_2\,\eta_3\,N\,A = 8.48 \times 10^8$$

electrons reaches the anode. Each electron (in absolute) carries the elementary charge $e = 1.602 \times 10^{-19}$ coulomb. The total arriving charge $Q = e\,R$ is collected in a time interval $\Delta t = 10\,\mathrm{ns}$ and leads to a current I of

$$I = \frac{Q}{\Delta t} = 13.6\,\mathrm{mA}\ .$$

voltage signal

If the photomultiplier is terminated with a resistor of 50 Ω, one obtains a voltage signal of

$$\Delta U = I\ R = 680\,\mathrm{mV}\ .$$

Example 4

The measurement of the signal amplitude in a scintillation or semiconductor counter allows the determination of the particle energy and thereby the identification of the radioisotope. Each energy measurement, however, is associated with a statistical and systematic error. Let us first consider the statistical error using the following example:

An 88-keV photon of a ^{109}Cd isotope produces in a plastic scintillation counter about

$$N_{\mathrm{plastic}} = 880$$

statistical error

scintillation photons (in this case it is assumed that $W = 100\,\mathrm{eV}$ is the energy required for the production of one photon in plastic material). This number is subject to statistical fluctuations, which are characterized by the square-root error,

$$N_{\mathrm{plastic}} = 880 \pm \sqrt{880} = 880 \pm 29.7\ .$$

These photons create

$$N^* = \eta_1\,\eta_2\,\eta_3\,N_{\mathrm{plastic}} = 28 \ \text{(with same } \eta_{\mathrm{i}} \text{ as in Example 3)}$$

electrons in the photocathode at the entrance of the dynode system of the photomultiplier. The relative energy resolution $\Delta E/E$ is related to the statistical fluctuation of this number. This leads to a relative energy resolution $\Delta E/E$ of

$$\left.\frac{\Delta E}{E}\right|_{\mathrm{plastic}} = \frac{\Delta N^*}{N^*} = \frac{\sqrt{28}}{28} = \frac{1}{\sqrt{28}} = 18.9\%\ .$$

energy resolution

In an inorganic scintillation counter ($W = 25\,\mathrm{eV}$) with the same collection properties four times as many photons contribute to the signal. Therefore,

$$\left.\frac{\Delta E}{E}\right|_{\mathrm{NaI(Tl)}} = 9.5\%\ .$$

In a semiconductor counter the energy required for the production of an electron–hole pair is about 3 eV, and (almost) all charge carriers are collected. This leads to

Determination of the detection efficiency for γ rays

The determination of the efficiency of radiation detectors requires a careful analysis including the actual activity of the radioactive sources (production date and half-life!), the shielding of the source, the thickness of the entrance window of the detector, and the exact geometry of the whole experimental setup. Given the activity A of the radioactive source assumed to be pointlike and the distance r from the source to the detector (with a sensitive area F), the detector will only be reached by a number of particles

$$N = A \, \frac{F}{4\pi r^2}$$

due to solid-angle reasons. Of these particles or γ rays a certain fraction ϵ will be absorbed either in the source, the air, or in the entrance window of the detector. Thereby only $(1 - \epsilon)\, N$ particles can be recorded in the detector. If the experiment yields a count rate of R per unit time in the detector volume, the detection efficiency is worked out to be

$$\eta = \frac{R}{(1 - \epsilon)\, N} \ .$$

In principle, the fraction of particles which are absorbed can be calculated numerically. In most cases, however, it is possible to arrange conditions such that $\epsilon \ll 1$. Furthermore, one has to consider that – depending on the experimental setup – some γ rays can produce electrons between source and detector via photon interactions. These electrons will be detected with 100% probability in the detector and, therefore, may present a systematic error for the efficiency determination.
Measurements of the detection efficiency for γ rays of ^{60}Co and those of ^{226}Ra (where α and β rays had been shielded) yielded an efficiency for a Geiger–Müller counter (with argon/neon filling with halide quenching agent) after consideration of all corrections of

$$\eta_{\mathrm{GM}} = 1\%$$

and for a NaI(Tl) scintillation counter (for ^{60}Co γ rays) of

$$\eta_{\mathrm{sc}} = 15\% \ .$$

The last value is also in good agreement with a simple consideration about the absorption of γ rays in a NaI(Tl) crystal: The absorption coefficient for ^{60}Co γ rays in NaI(Tl) is $\mu = 0.02\,(\mathrm{g/cm^2})^{-1}$. The density of NaI(Tl) is $\rho = 3.67\,\mathrm{g/cm^3}$. The effective crystal thickness d_{eff} can be worked out from the actual depth of $d = 3.8\,\mathrm{cm}$ at a diameter of 2.5 cm to be $d_{\mathrm{eff}} = 2.4\,\mathrm{cm}$, because the effective thickness traversed by γ quanta in the crystal depends on the position and direction of incidence, x, θ, and ϕ (position, polar, and azimuthal angle). Under these assumptions the expected detection efficiency can be worked out to be

$$\eta_{\mathrm{sc}} = 1 - \frac{I}{I_0} = 1 - \mathrm{e}^{-\mu\, d_{\mathrm{eff}}\, \rho} = 16\% \ ,$$

which is in good agreement with the experimental value.

Determination of the detection efficiency for γ rays (continued)

The efficiency of radiation detectors depends, of course, also on the detector material and the geometry. For Geiger–Müller counters the detection efficiency for photons can be increased, if gas fillings of a high atomic number (e.g. xenon) are used, because the photon absorption coefficient rises significantly with atomic number Z. At the same time the photon detection probability in scintillation counters depends on the crystal type and the detector geometry.

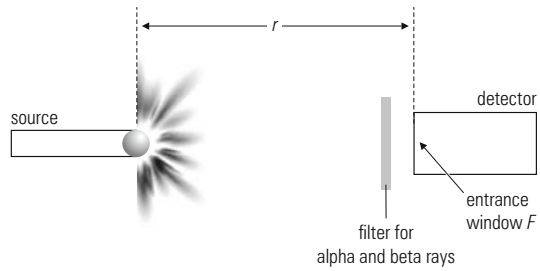


Figure 5.43
Arrangement for the measurement of the detection efficiency of γ rays in a Geiger–Müller counter and a scintillation counter

$$\left.\frac{\Delta E}{E}\right|_{\text{semiconductor}} = 0.58\% \ .$$

It is obvious that semiconductor counters (in particular, high-purity germanium detectors) have excellent energy resolutions (compare Figs. 5.21 and 5.22).

systematic error

If one assumes that in addition to the statistical counting error a systematic error of 3% has to be added, possibly caused by an unstable electronic readout, the total error is obtained by quadratic addition of the individual errors (if the errors are not correlated):

$$\left.\frac{\Delta E}{E}\right|_{\text{plastic}}^{\text{total}} = \sqrt{(18.9\%)^2 + (3\%)^2} = 19.1\% \ .$$

For the inorganic NaI(Tl) crystal one gets

$$\left.\frac{\Delta E}{E}\right|_{\text{NaI(Tl)}}^{\text{total}} = \sqrt{(9.5\%)^2 + (3\%)^2} = 9.9\% \ .$$

total error

The energy resolution of the semiconductor in this example would be dominated by the systematic error, namely:

$$\left.\frac{\Delta E}{E}\right|_{\text{semiconductor}}^{\text{total}} = \sqrt{(0.58\%)^2 + (3\%)^2} = 3.06\% \ .$$

Summary

The interactions of charged and neutral particles are the basis for the development of radiation detectors. The ionization of gases is normally used for proportional counters and Geiger–Müller counters, and the excitation of solid materials is taken advantage of for scintillation counters. Scintillation counters and gas counters are robust devices for the determination of the dose and dose rate. These detectors can also be used to provide an alarm if the dose or the dose rate is exceeded. The blackening of X-ray films leads to the production of film badges which provide a documentation of the received dose. High-precision measurements with semiconductor counters (silicon or high-purity germanium counters) allow unique radioisotope identification via the characteristic γ lines produced by the isotopes. Inorganic scintillation counters (e.g. NaI(Tl)) also allow an identification of radioisotopes even though the resolution is limited compared to semiconductor counters.

5.9 Problems

Problem 1

A pen-type pocket dosimeter has a chamber volume of 2.5 cm^3 and a capacity of 7 pF. Originally it was charged to a voltage of 200 V. After some time spent in a nuclear power plant it only shows a voltage of 170 V. Work out the received dose.
The density of air is $\rho_L = 1.29 \times 10^{-3}\,g/cm^3$.

Problem 2

At a distance of $d_1 = 10\,cm$ from a pointlike radioactive γ-ray emitter a rate of $R_1 = 90\,000$ signals per second is measured in a proportional counter. At a distance $d_2 = 30\,cm$ a count rate of $R_2 = 50\,000$ signals per second is obtained. Work out the dead time τ of this counter.

Problem 3

A high-purity germanium detector (diameter $d = 3\,cm$) measures at a distance of $r = 1\,m$ γ radiation from a pointlike ^{60}Co source with a detection efficiency of 8%. Within one minute a count rate of 3350 signals at a background rate of 350 signals per minute is obtained. What is the activity of the source? (Since the absorption of γ rays in air is rather low, it can be neglected in this case.)

Problem 4

A contaminated work area is decontaminated in three subsequent steps by a dry wipe technique. Let us assume that for one wiping step $\varepsilon = 20\%$ of the activity is removed. After the whole procedure a residual contamination of 512 Bq/cm^2 is found. What was the original contamination?

6 International Safety Standards for Radiation Protection

"Insisting on perfect safety is for people who don't have the balls to live in the real world."

Mary Shafer

safety standards

European Directive

dose limits
exemption levels
clearance levels

The International Commission on Radiological Protection (ICRP) has proposed safety standards to protect the health of workers and the general public against the dangers arising from ionizing radiation. The recommendations are laid down in a European Directive (Council Directive 96/29/EURATOM) which was presented to the Member States of the European Community. The report requested the different countries to integrate the proposed dose limits, exemption levels, clearance levels, and, in general, the regulations of the European Directive into national law so that compliance with the basic standards is ensured. The recommended limits contained in the directive must be respected, even though the national regulations are allowed to impose more stringent levels, but there is no room for allowing higher, more generous levels.

European countries have completed this integration into national law over a period of several years, e.g. Germany published the radiation-protection regulations in 2001, and France followed in 2003. The regulations in different countries are not completely identical, but the guidelines are the same all over Europe.

American Directive

In contrast, other countries, e.g. the United States of America, have regulations which differ distinctly from the European Directive. For example, the annual whole-body dose limit for workers exposed to ionizing radiation in the US is 50 mSv compared to 20 mSv in European countries. Other differences are that in the US the old radiation units (rad and rem) are still in use (1 Sv = 100 rem, 1 Gy = 100 rad).

In the following the main features of the European directive are presented, which should cover essentially all European countries, and after that the regulations of the United States and other countries will be described. The limits given in the main body of this book are based on the regulations of the European Directive and the recommendations of the International Commission on Radiological Protection (ICRP, `www.icrp.org/`).

C. Grupen, *Introduction to Radiation Protection*,
Graduate Texts in Physics, DOI 10.1007/978-3-642-02586-0_6,

6.1 European Directive

The guidelines of the European Directive are intended to:

- respect the maximum permissible doses compatible with adequate safety;
- respect the maximum levels of exposure and contamination;
- consider the fundamental principles governing the health surveillance of workers.

The Directive has defined safety standards in the following way:

- the limit on the effective dose for exposed workers is 100 mSv in a consecutive five-year period, subject to a maximum effective dose of 50 mSv in any single year. In accordance with this, most Member States have defined an annual limit of 20 mSv.
- the annual limit on the equivalent dose for the lens of the eye is 150 mSv.
- the annual limit on the equivalent dose for the skin is 500 mSv.
- the annual limit on the equivalent dose for the hands, forearms, feet, and ankles is 500 mSv.

annual limit 20 mSv in the EU

Under exceptional circumstances, excluding radiological emergencies, occupational doses for some identified workers may exceed the annual dose limits above, provided that such exposures are limited in time and confined to certain working areas. The maximum exposure as defined for the five-year period must, however, be respected.

emergency situations

The dose limits for apprentices and students aged 18 or over are identical to the ones mentioned. However, the dose limits for apprentices and students aged between 16 and 18 are reduced to 6 mSv per year for the whole-body dose. Correspondingly, the dose limits for this age group is also lower for the eyes (50 mSv/yr), the skin (150 mSv/yr), and hands (150 mSv/yr).

apprentices and students

For the general public the annual dose limit is 1 mSv. In special circumstances a higher effective dose may be authorized in a single year, provided that the average over five consecutive years does not exceed 1 mSv per year. Correspondingly, the annual limit for the eyes for the general public is 15 mSv/yr and 50 mSv/yr for the skin.

annual dose limit 1 mSv for the public

The general recommendation is that reasonable steps must be taken to ensure that the exposure of the population as a whole is kept as low as reasonably achievable (ALARA principle). This last recommendation has been restricted, e.g. in Germany, to keep the level as low as possible.

ALARA principle

In the framework of formulating the fundamental principles governing the operational protection of exposed workers, ‘controlled areas’ and ‘supervised areas’ or ‘surveyed areas’ areas are defined.

controlled area surveyed area

Controlled areas must be delineated and access to the area shall be restricted to individuals who have received appropriate instructions on radiation-protection standards. For supervised areas the restrictions are less severe, and the potential exposures are expected to be smaller. However, radiological surveillance of the working environment must be organized in accordance with the provisions of the standards of radiation protection.

exclusion area

In addition to surveyed areas ($\leq$ 6 mSv/yr) and controlled areas ($\leq$ 20 mSv/yr) also 'exclusion areas' ($\leq$ 3 mSv/h) are defined. Admittance to exclusion areas is only permitted for exceptional radiological situations, like e.g. radiation accidents.

category-A workers

category-B workers

For the purposes of monitoring and surveillance a distinction of exposed workers into two categories is made. Category-A workers are those who are liable to receive an effective dose greater than 6 mSv per year or equivalent doses greater than 3/10 of the dose limits for the lens of the eye, skin, and extremities as defined above (just as 6 mSv is 3/10 of the annual dose limit (20 mSv) for exposed workers). Category-B workers are those working in areas where there is the possibility to be exposed to ionizing radiation in excess of an annual dose of 1 mSv. The actually received doses must be individually monitored by an appropriate dosimetric service. It also has to be demonstrated that category-B workers are correctly classified. In case of accidental exposure the relevant doses and their distribution in the body shall be assessed.

The exposures have to be documented and retained during the working life involving exposure to ionizing radiation of the exposed workers, and afterwards until the individual has or would have attained an age of 75 years, but in any case not less than 30 years from the termination of the work involving exposure.

students and apprentices

The exposure conditions and operational protection of students and apprentices aged 18 or over are equivalent to those of exposed workers of category A or B. Students and apprentices aged between 16 and 18 years shall be treated equivalently as category-B workers only (i.e., their possible annual doses are restricted to a range of 1 mSv to 6 mSv).

medical surveillance

The medical surveillance of category-A workers lies in the responsibility of approved medical practitioners or approved occupational health services. This medical surveillance includes a medical examination prior to employment or classification as a category-A worker. The purpose of this thorough examination is to determine the worker's fitness for a position as category-A worker. The medical fitness must be periodically reviewed, at least once a year.

The European Directive closes with asking the Member States of the European Community to bring into force the laws, regula-

tions and administrative provisions necessary to comply with this Directive before 13 May 2000. No European country was able to implement the Directive within this time limit. The Member States were given a certain freedom to implement the Directive, with the following constraint: If a Member State is to adopt dose limits which are stricter than those laid down in the Directive, it shall inform the Commission and the other Member States of its regulations. It is, however, not permitted to adopt more liberal dose limits.

exemption limits

Amongst appendices to the Directive exemption limits for the quantity or activity concentration of radioisotopes are defined. The European Commission has also published guidance on the clearance levels of building material arising e.g. from the dismantling of nuclear installations. Furthermore, the European Commission has introduced the concept of general clearance levels (in activity per unit mass): default values, for materials arising from any practice, any type of material, and any pathway of recycling or reuse.[1] The "Guidance on General Clearance Levels for Practices" contains a wealth of information on all conceivable radiation risks and exposures presented in the form of detailed tables with explanations. It covers man-made radiation equipment as well as natural sources (e.g. radon exposures).

clearance levels

6.2 American Directive

The American regulations on radiation protection are laid down in the 'Code of Federal Regulations' issued by the 'National Archives and Records Administration' available from the 'United States Government Printing Office'. Under 'Title 10: Energy' the 'Occupational Radiation Protection' regulations are defined for the Department of Energy in the document called '10CFR 835'. In the following the main items of the regulations, taken from the 'Code of Federal Regulations', are sketched in abridged form.

occupational dose limits

The occupational dose limits for general employees shall be controlled such that the following limits are not exceeded in a year:

- a total effective dose equivalent of 5 rems (50 mSv);
- the sum of the deep dose equivalent for external exposures and the committed dose equivalent to any organ or tissue other than the lens of the eye of 50 rems (500 mSv);

[1] Practical Use of the Concepts of Clearance and Exemption; Part I: Guidance on General Clearance Levels for Practices; Part II: Application of the Concepts of Exemption and Clearance to Natural Radiation Sources; Recommendations of the Group of Experts established under the terms of Article 31 of the European Treaty.

- a lens-of-the-eye dose equivalent of 15 rems (150 mSv); and
- a shallow dose equivalent of 50 rems (500 mSv) to the skin or to any extremity.

annual dose limit 50 mSv USA

All occupational doses received during the current year, except doses resulting from planned special exposures and emergency exposures shall be included when demonstrating compliance with the above limits. Doses from background, therapeutic and diagnostic medical radiation, and participation as a subject in medical research programs shall not be included in dose records or in the assessment of compliance with the occupational dose limits.

The total effective dose equivalent during a year shall be determined by summing the effective dose equivalent from external exposures and the committed effective dose equivalent from intakes during the year. Determinations of the effective dose equivalent shall be made using the standard-weighting-factor values as provided by the regulations (10CFR 835.2 Definitions). The radiation and tissue weighting factors in the US regulations (see the following tables) are very similar, but not identical, to those of the European Directive which are given in the main body of the book.

standard weighting factor

radiation weighting factor

tissue weighting factor

Table 6.1
US quality factors ('radiation weighting factors')

radiation type	quality factor
X rays, gamma rays, positrons, electrons	1
neutrons, less than 10 keV	3
neutrons, over 10 keV	10
protons and singly charged particles of unknown energy with rest mass greater than one atomic mass unit	10
alpha particles and multiply charged particles (and particles of unknown charge) of unknown energy	20

Table 6.2
US weighting factors for various organs and tissues

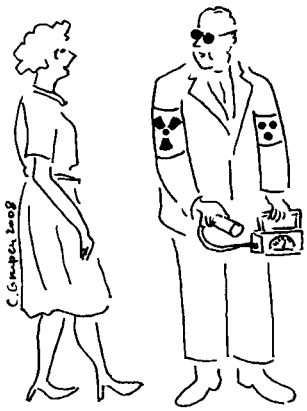
organs or tissues	weighting factor
gonads	0.25
breasts	0.15
red bone marrow	0.12
lungs	0.12
thyroid gland	0.03
periosteum, bone surface	0.03
other organs or tissue	0.30
whole body	1.00

planned special exposures

For planned special exposures the following conditions must be fulfilled:

- A planned special exposure may be authorized for a radiological worker to receive doses in addition to and accounted for separately from the doses received under the limits specified above, provided that each of the following conditions is satisfied:
  * the planned special exposure is considered only in an exceptional situation when alternatives that might prevent a radiological worker from exceeding the standard limits are unavailable or impractical;
  * the contractor management or employer specifically requests the planned special exposure, in writing; and
  * joint written approval is received from the appropriate DOE Headquarters program office and the Secretarial Officer responsible for environment, safety, and health matters.
- Prior to requesting an individual to participate in an authorized planned special exposure, the individual's dose from all previous planned special exposures and all doses in excess of the occupational dose limits shall be determined.
- An individual shall not receive a planned special exposure that, in addition to the doses determined above, would result in a dose exceeding the following:
  * in a year a value of 5 rem (50 mSv); and
  * over the individual's lifetime, five times the numerical values of the dose limits established for radiation workers (i.e. it should not exceed 25 rem (250 mSv)).
- Prior to a planned special exposure, written consent shall be obtained from each individual involved. Each such written consent shall include:
  * the purpose of the planned operations and procedures to be used;
  * the estimated doses and associated potential risks and specific radiological conditions and other hazards which might be involved in performing the task; and
  * instructions on the measures to be taken to keep the dose ALARA considering other risks that may be present.
- Records of the conduct of a planned special exposure shall be maintained and a written report submitted within 30 days after the planned special exposure to the approving organizations.
- The dose from planned special exposures is not to be considered in controlling future occupational doses of the individual, but is to be included in records and reports.

radiological worker



"I should have known that handling too many radioactive sources can cause a cataract!"

ALARA principle

limits for the embryo/fetus

Limits for the embryo/fetus are regulated along the following conditions:

- The dose-equivalent limit for the embryo/fetus from the period of conception to birth, as a result of occupational exposure of a declared pregnant worker, is 0.5 rem (5 mSv).
- Substantial variation above a uniform exposure rate should be avoided.
- If the dose equivalent to the embryo/fetus is determined to have already exceeded 0.5 rem (5 mSv) by the time a worker declares her pregnancy, the declared pregnant worker shall not be assigned to tasks where additional occupational exposure is likely during the remaining gestation period.

pregnancy

Specific occupational dose limits for minors are defined as:

- The dose-equivalent limits for minors occupationally exposed to radiation and/or radioactive materials at a DOE activity are 0.1 rem (1 mSv) total effective dose equivalent in a year, 1.5 rem (15 mSv) for the lens of the eye, and 5 rem (50 mSv) for the skin.

limits for the public

Furthermore, limits for members of the public entering a controlled area are defined in the following way:

- The total effective dose-equivalent limit for members of the public exposed to radiation and/or radioactive material during access to a controlled area is 0.1 rem (1 mSv) in a year.

monitoring and surveillance

The American Directive also regulates the following general requirements concerning technical aspects of monitoring and surveillance:

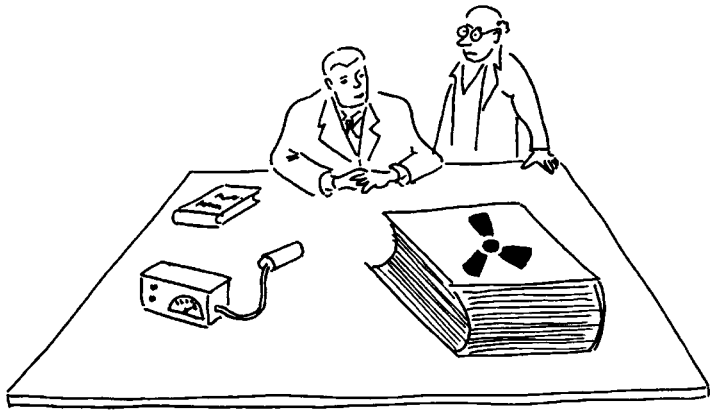
- Monitoring of individuals and areas shall be performed to:
  * demonstrate compliance with the regulations in this part;
  * document radiological conditions;
  * detect changes in radiological conditions;
  * detect the gradual buildup of radioactive material;
  * verify the effectiveness of engineering and process controls in containing radioactive material and reducing radiation exposure; and
  * identify and control potential sources of individual exposure to radiation and/or radioactive material.
- Instruments and equipment used for monitoring shall be:
  * periodically maintained and calibrated on an established frequency;
  * appropriate for the type(s), levels, and energies of the radiation(s) encountered;
  * appropriate for existing environmental conditions; and
  * routinely tested for operability.

The regulations define also special radiological areas:

- Within high- and very-high-radiation areas: **radiation areas**
  - * The following measures shall be implemented for each entry into a high-radiation area:
    - * The area shall be monitored as necessary during access to determine the exposure rates to which the individuals are exposed.
    - * Each individual shall be monitored by a supplemental dosimetry device or other means capable of providing an immediate estimate of the individual's integrated deep dose equivalent during the entry. **supplemental dosimetry device**
- Within controlled areas: **controlled areas**
  - * Each access point to a controlled area shall be posted whenever radiological areas or radioactive-material areas exist in the area.
  - * Individuals who enter only controlled areas without entering radiological areas or radioactive-material areas are not expected to receive a total effective dose equivalent of more than 0.1 rem (1 mSv) in a year.
  - * Signs used for this purpose may be selected by the contractor to avoid conflict with local security requirements.
- Within radiological areas and radioactive-material areas: **radiological areas**
  - * Radiological areas and radioactive-material areas are divided into the following categories and should be posted with conspicuous signs bearing the wording:
  - * Radiation area. The words "Caution, Radiation Area" shall be posted at each radiation area. **radiation areas**
  - * High-radiation area. The words "Caution, High Radiation Area" or "Danger, High Radiation Area" shall be posted at each high-radiation area.
  - * Very-high-radiation area. The words "Grave Danger, Very High Radiation Area" shall be posted at each very-high-radiation area.
  - * Airborne radioactivity area. The words "Caution, Airborne Radioactivity Area" or "Danger, Airborne Radioactivity Area" shall be posted at each airborne radioactivity area. **airborne activity**
  - * Contamination area. The words "Caution, Contamination Area" shall be posted at each contamination area. **contamination area**
  - * High-contamination area. The words "Caution, High Contamination Area" or "Danger, High Contamination Area" shall be posted at each high-contamination area.
  - * Radioactive-material area. The words "Caution, Radioactive Material(s)" shall be posted at each radioactive-material area.

nuclear accident dosimetry

It must be remembered that the effective US dose units are given in rem, and the US activities are given in curie (Ci). Also the old unit 'roentgen' is still in use. In a very detailed annex to the US regulations (under the item 'Nuclear accident dosimetry') limits on activity and concentration of radioisotopes in air are given in a similar way as in the European Directive.



"Our new radiation-protection manual!" © by Claus Grupen

6.3 Other Countries

6.3.1 Australia

The Australian Radiation Protection and Nuclear Safety Regulations have been published 1999 as Statutory Rules under `www.comlaw.gov.au/ComLaw/Legislation/LegislativeInstrumentCompilation1.nsf/0/2E2B83BDE995DE10CA256F71004F21F6/$file/AusRadProtNucSafe1999.pdf`. The regulations are laid down in a very detailed document.

main dose limits

The main dose limits are:

* The effective dose limit for occupational exposures is 20 mSv annually, averaged over 5 consecutive calendar years.
* However, the effective dose for a person subject to occupational exposure must not, in any year, be greater than 50 mSv.
* The effective dose limit for public exposure is 1 mSv annually.
* The effective dose limit for an unborn child is to be consistent with the effective dose limit for public exposure.

The limits for the partial-body doses are defined as:

limits for partial-body doses

* The annual equivalent-dose limit for the lens of the eye is 150 mSv for occupational exposure and 15 mSv for public exposure.
* For occupational exposure, the annual equivalent-dose limit to the hands and feet is 500 mSv.
* The annual equivalent-dose limit to the skin is 500 mSv for occupational exposure and 50 mSv for public exposure. The annual equivalent-dose limit to the skin applies to the average dose received by any 1 cm^2 of skin.

ANSTO

The maximum annual dose measured at the center of Australia's nuclear science capabilities and expertise site ANSTO (Australian Nuclear Science and Technology Organisation) was in one case 65.9 mSv which exceeded the annual dose limit of 50 mSv for one year. The worker exposed to this high-level radiation was removed from the radiation work for the remainder of the year. Typical effective doses at this site are, however, around 1 mSv/yr and maximum effective doses around 10 mSv/yr.

ARPANS

The ARPANS (Australian Radiation Protection and Nuclear Safety) regulations prescribe the need for emergency plans. The Regulatory Assessments Principles address the various aspects for emergency plans, procedures, and preparedness to be assessed. These rules are laid down in the Regulatory Assessments Principles.

In a detailed appendix exemption limits for all radioisotopes are given. The Australian regulations also contains rules for non-ionizing radiation.

6.3.2 Brazil[2]

The general dose limits in Brazil as given by the document CNEN NE 3.01 (`http://cfhr.epm.br/download/aulas/fisica/Limites__Doses.pdf`) are:

general dose limits

* The effective dose limit for radiation-exposed workers is 20 mSv /yr. For five consecutive years the total effective dose is limited to 100 mSv. It must not exceed 50 mSv/yr in any year of this period. According to the Brazilian regulations a dose of 50 mSv corresponds to a stochastic lethal cancer risk of 5×10^{-4}. This value

radiation-exposed workers

[2] I thank Prof. Dra. Simone Coutinho Cardoso, Instituto de Física, Universidade Federal do Rio de Janeiro, Laboratório de Física da Radiação Gama, Rio de Janeiro, Prof. Dr. Fernando Marroquim Leao de Almeida Jr., Instituto de Física, Universidade Federal do Rio de Janeiro, Ilha do Fundão, Rio de Janeiro, and Prof. Dra. Regina Bitelli Medeiros, Universidade Federal de São Paulo, Coordenadora do Núcleo de Proteção Radiológica, for helping me with the interpretation of the Brazilian radiation-protection regulations.

corresponds to a risk factor of 1% per sievert, which is lower by a factor of 5 compared to the risk factor as given by the ICRP.

* For radiation-exposed workers the limit on the annual dose equivalent to extremities or the skin is 500 mSv; the dose limit for the lens of the eye is 150 mSv.

women

* The abdomen dose limit for women in childbearing years should not exceed 10 mSv in a period of three consecutive months.

pregnancy

* For pregnant women working in radiation areas their activities must be controlled and, if necessary, restricted in such a way that it is improbable, from the moment of the notification of the pregnancy, that the fetus receives more that 1 mSv during the remaining portion of the period of gestation.

students or apprentices

* Students or apprentices over 18 should not get more than 10% of the limits for radiation-exposed workers in a single exposure.

individuals under 18

* Individuals under 18 are not supposed to be exposed to radiation (except, of course, for environmental radiation).

general public

* The annual whole-body dose limit for members of the general public is 1 mSv. In exceptional circumstances an annual dose limit of 5 mSv may be agreed to by the authorities if the average over a five-year period does not exceed 1 mSv/yr. The limits for the lens of the eye is 15 mSv/yr and those for the skin is 50 mSv/yr for the general public. The annual dose limit for any organ or tissue is 1 mSv divided by the corresponding organ or tissue weighting factor.

Depending on the contamination of work places different categories are defined. In general the limits on contaminations of work surfaces are more stringent by a factor of 10 for α emitters compared to β radiation.

6.3.3 Canada

The Canadian radiation-protection regulations are laid down by the Canadian Nuclear Safety Commission under `http://canadagazette.gc.ca/partII/2000/20000621/html/sor203-e.html`.

whole-body dose limits

The main whole-body dose limits are given by:

nuclear-energy worker

* for a nuclear-energy worker: 50 mSv for a one-year dosimetry period and 100 mSv for a five-year dosimetry period;

pregnancy

* for a pregnant nuclear-energy worker: 4 mSv. This dose should not exhibit strong exposure peaks (within the limits of ≤ 4 mSv), but it should rather be balanced over the gestation period;

general public

* for a person who is not a nuclear-energy worker (i.e. general public) the annual dose limit is 1 mSv.

Special limits are defined as follows:

special limits

nuclear-energy worker

* for a nuclear-energy worker the annual limits for the lens of the eye is 150 mSv, for the skin 500 mSv, and hands and feet 500 mSv;

other persons

* for any other person the corresponding limits are: lens of the eye (15 mSv), skin (50 mSv), and hands and feet (50 mSv).

emergency and remedial work

During the control of an emergency and the consequent immediate and urgent remedial work, the effective dose and the equivalent dose may exceed the applicable dose limits as given above, but the effective dose shall not exceed 500 mSv and the equivalent dose received by the skin shall not exceed 5000 mSv. When a licensee becomes aware that a dose of radiation received by and committed to a person or an organ or tissue may have exceeded the dose limit as given above, the licensee shall

actions in case of exceeded dose limits

* immediately notify the person and the radiation commission of the dose;
* require the person to leave any work that is likely to add to the dose;
* conduct an investigation to determine the magnitude of the dose and to establish the causes of the exposure;
* identify and take any action required to prevent the occurrence of a similar incident; and
* within 21 days after becoming aware that the dose limit has been exceeded, report to the radiation commission the results of the investigation or on the progress that has been made in conducting the investigation.

The organ or tissue weighting factors and radiation weighting factors are those as recommended by the ICRP as given in Chap. 2.

6.3.4 China[3]

China has adopted all ICRP and ICRU regulations/recommendations.

6.3.5 India

AERB

The Atomic Energy Regulatory Board (AERB) in India has defined the rules for radiation protection in the Atomic Energy Act. A comprehensive paper describing the regulations in India is given in S.B. Grover, J. Kumar, A. Gupta, and L. Khanna "Protection against radiation hazards: Regulatory bodies, safety norms, dose limits and

[3] I thank Prof. Dr. Yuanning Gao form the Centre for High Energy Physics, Tsinghua University, Beijing, China, for providing this information.

protection devices", published in the Indian Journal of Radiology and Imaging (Volume 12, Issue No. 2, 2002). The rules are very similar to other countries.

general principles

The radiation-protection standards are based on three general principles:

* Justification of a practice, i.e., no practice involving exposures to radiation should be adopted unless it provides sufficient benefit to offset the detrimental effects of radiation.
* Protection should be optimized in relation to the magnitude of doses and number of people exposed.
* Dose limitation deals with the idea of establishing annual dose limits for occupational exposures, public exposures, and exposures to the embryo and fetus.

radiation-exposed workers

The main annual dose limits are:

* for radiation-exposed workers: 30 mSv/yr and 100 mSv for a five-year period;
* for radiation-exposed workers: 150 mSv/yr for the lens of the eye and 500 mSv/yr for the skin, hands, and feet;
* for the public: 1 mSv/yr.

More details can be found on the web page of the Atomic Energy Regulatory Board of India `www.aerb.gov.in/`.

6.3.6 Japan[4]

dose limit for 5 years

The general dose limits are:

women

* 100 mSv/5 years with a maximum of 50 mSv per single year. The same dose limit applies for women with the additional constraint of 5 mSv/3 months.

pregnancy

* Exceptions for women who are pregnant: 1 mSv due to internal exposure (from the moment when the employer knows of the pregnancy).

modified rules for large installations

For large nuclear physics and particle physics installations these general rules can be modified. For the large High Energy accelerator research organization KEK at Tsukuba the following regulations apply:

[4] I am grateful to Dr. Syuichi Ban from the High Energy Accelerator Research Organisation KEK in Tsukuba, Japan, for providing this information; see also his presentation "Personnel exposure control in KEK" given at the "Workshop on Operational Radiation Protection at High-Energy Accelerators"; `http://proj-orpw05.web.cern.ch/proj-orpw05/`.

* dose limit for man 20 mSv/year,
* dose limit for woman 6 mSv/year,

with the necessity to record the exposures

recording

* if the gamma dose exceeds 0.1 mSv/month,
* if the neutron dose exceeds 0.2 mSv/month.

Further constraints for the working levels for daily and weekly control are defined such that

working levels

* daily control level for man 0.5 mSv/day,
* daily control level for woman 0.3 mSv/day,
* weekly control level for man 1.0 mSv/week,
* weekly control level for woman 0.5 mSv/week.

It is remarkable that the dose limits are different for women and men.

If exposures larger than 7 mSv/yr are recorded, the reason must be found, and the fact must be reported to the radiation safety supervisor.

6.3.7 Mexico[5]

The regulations in Mexico are to a certain extent similar to the ones defined in the US, but in some cases much more liberal. They are written down in `www.cnsns.gob.mx/radiolo/reglamentos/rgsrweb.htm`. The dose limits are given in sievert and in rem and the units of activity are given both in becquerel and in curie. For ion doses even the unit 'roentgen' is in use.

The general limit for the annual whole-body dose for radiation-exposed workers is 50 mSv (5 rem), and the limit for the lens of the eye is 150 mSv (15 rem). The regulation differentiates between stochastic and non-stochastic doses. The annual limit for stochastic doses is given above, but for non-stochastic doses the limit is 500 mSv (50 rem) with the exception for the lens of the eye, which is still 150 mSv (15 rem).

radiation-exposed workers

Young people aged between 16 and 18 are not supposed to work in radiation areas. However, if education e.g. for students, requires the handling of radioactive material, an annual limit for the whole body of 15 mSv (1.5 rem) applies. The annual dose limit for the general public is 1 mSv (0.1 rem).

young people

general public

To handle emergency situations, e.g. preventing the risk of fire or contamination of valuable equipment, a singular dose up to 250 mSv

emergency situations

[5] I am grateful to Prof. Dr. Jürgen Engelfried, Universidad Autonoma de San Luis Potosi, Mexico, for providing this information.

(25 rem) is acceptable. For the hands or the forearm even 1 Sv (100 rem) can be tolerated in such a situation. In case of severe accidents all necessary steps must be taken to mitigate danger to life and health, and to prevent exposure of many workers to high-level radiation. Under these exceptional circumstances even doses of up to 1 Sv (100 rem) for the whole body and for hands and forearms of 3 Sv (300 rem) are permitted. It is also recommended that persons exposed to high-level radiation in a radiation accident should not father a child within six months after having received a high dose.

singular doses

Furthermore, it is recommended that for women in childbearing years a possible exposure to radiation should be evenly distributed in time. This also applies for pregnant women with the additional recommendation that the probability to receive a dose of more than 15 mSv (1.5 rem) should be very small.

pregnancy

In analogy to the US and Europe also different radiation areas are defined. A 'radiation area' is a zone where a dose rate of more than 0.05 mSv/h (5 mrem/h) can occur or a dose of more than 1 mSv (100 mrem) in five consecutive days might be received. In a 'high-radiation area' exposures of more than 1 mSv/h (100 mrem/h) are possible. Special precautions have to be taken for areas where gaseous radioactive substances are handled to limit the intake of radioactive material into the body.

radiation area

6.3.8 Russia[6]

Russia has also adopted the general framework of the ICRP and ICRU regulations/recommendations. The limit on the equivalent dose is 20 mSv per year on the average during any five consecutive years, but not larger than 50 mSv per year. For the normal population the limit is 1 mSv/yr on average during any five consecutive years, but less than 5 mSv in any single year.

normal population

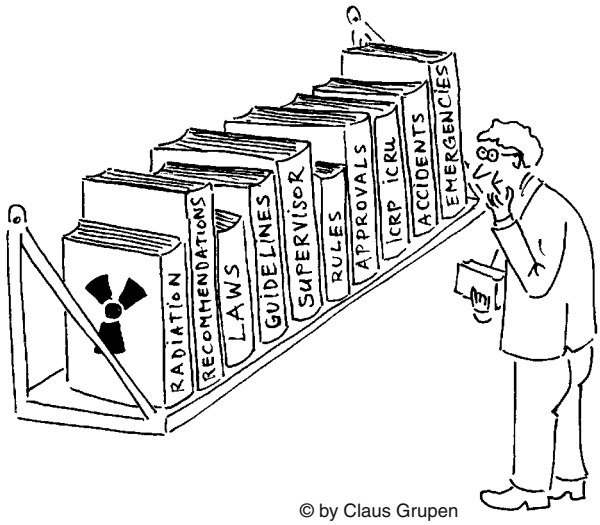
For women below the age of 45, working with radiation sources, there are additional requirements: a dose on the surface of the lower part of the belly should be less than 1 mSv/month and the total amount of radionuclides entering the organism should be $< 1/20$ of that for male personnel. Under these conditions the dose of a possible fetus irradiation is < 1 mSv during two months of unregistered pregnancy.

possible fetus irradiation

Pregnant women, starting from the day when a woman claims pregnancy, should be moved to a job not related to radiation sources or radiation exposures for the whole period of pregnancy and feeding.

pregnant women

[6] I am grateful to Prof. Dr. Simon Eidelman, Budker Institute of Nuclear Physics, Novosibirsk, Russia, and to Prof. Dr. Gerd Beyer, CERN, Geneva, Switzerland, for providing this information.



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6.3.9 South Africa

The radiation-protection regulations in South Africa have been published in the Government Gazette Staatskoerant; Regulation Gazette No. 8454, Vol. 490 in Pretoria 2006. The regulations follow closely the ICRP recommendations. The essential points are:

radiation-exposed workers

The occupational exposure of radiation workers shall be so controlled that the following limits are not exceeded:

* an average effective dose of 20 mSv per year averaged over five consecutive years,
* a maximum effective dose of 50 mSv in any single year,
* an equivalent dose to the lens of the eye of 150 mSv in a year, and
* an equivalent dose to the hands and feet or the skin of 500 mSv in a year;
* in special circumstances a temporarily changed increased dose limit may be approved subject to the agreement of the affected employees, provided that all reasonable efforts are being made to improve the working conditions to the point where compliance with the above dose limits can be achieved.

apprentices and students

For apprentices and students aged between 16 and 18 years the dose limit is 6 mSv in a year and, correspondingly, 50 mSv for the lens of the eye and 150 mSv for the extremities or the skin.

pregnancy

The dose limit for women is generally the same as for men. However, following the declaration of a pregnancy, a dose limit of 2 mSv to the abdomen for the remainder of the pregnancy applies.

emergency situations

In case of emergency situations the following increased dose limits apply: For actions intended to avert a large collective dose

exceptional doses

or to prevent the development of catastrophic conditions, all reasonable efforts must be made to keep doses to the worker below twice the maximum annual dose limit as given above. For the purpose of saving life or preventing serious injury every effort shall be made to keep the doses below ten times the maximum annual dose limit. Interventions, which may result in their doses approaching or exceeding ten times the annual dose limit, may only be performed when the benefits to others clearly outweigh the risk of the workers undertaking the interventions.

general public

The annual effective dose limit for members of the public is 1 mSv. This limit also applies for visitors to the sites, where radiation sources are handled or ionizing radiation (e.g. by accelerators) is produced.

In the detailed document mentioned above the exclusion of actions, the exemptions with and without further consideration, the exemption for the transport of radioactive material, the licensing, and the clearance are also defined. In the annex to the regulations the exempt radioactivity concentrations and exempt total radioactivities are given for all radioactive isotopes.

6.4 Supplementary Information

Example 1

exemption limits
clearance levels

The various national regulations on radiation protection define limits on the activity of radioactive material that can be handled without restrictions (*exemption limits*), and limits on the specific activity of radioactive waste (*clearance levels*). For the exemption limits values for the maximum allowed specific activity below which no special regulations apply are also defined. For the clearance levels one has to distinguish between the 'normal' clearance levels and the levels for unconditional clearance. Levels for unconditional clearance concern, for example, contaminated scrap or soil. If the activity per gram falls below the unconditioned clearance level, the material is considered no longer to be radioactive.

unconditional clearance

A dose of 10 µSv per year has been widely considered to be a reasonable basis for the exemption and clearance levels, i.e., an exposure to such material should not lead to an annual dose of more than 10 µSv for an individual.

Consider e.g. the unconditioned clearance level of soil contaminated by ^{137}Cs. According to many national radiation-protection regulations the clearance level for ^{137}Cs is 60 Bq/kg. If one is exposed to such contaminated soil, one will be exposed mainly to the γ rays from the excited decay product, namely ^{137}Ba*. This isotope emits 662-keV γ rays. For an exposure from the soil one would get a dose rate of

$$\dot{H} = \Gamma_\gamma \frac{A}{r^2} \ , \tag{6.1}$$

where $\Gamma_\gamma = 8.46 \times 10^{-14} \frac{\mathrm{Sv\,m^2}}{\mathrm{Bq\,h}}$ (see Table 2.3). For a clearance level of $A = 60\,\mathrm{Bq/kg}$ and a typical distance from the soil of $r = 1$ meter the annual dose can be worked out if a reasonable exposure time and an amount of 'effective' soil is assumed. For an irradiation from 1000 kg of soil over a period of 8 hours a day in 241 days (365 minus weekends and holidays) one arrives at an annual dose of

annual dose

$$H = 10\,\mu\mathrm{Sv} \ . \tag{6.2}$$

This example just serves to demonstrate the chosen unconditioned clearance level which might lead to an annual dose of 10 µSv for individuals.

unconditioned clearance level

Example 2

Tritium is an isotope of hydrogen. It has a half-life of 12.3 years and decays by β-ray emission. Tritium will equilibrate after intake into the human body and will consequently deliver a dose to the whole body. According to the National Council on Radiation Protection (NCRP) in the United States the Annual Limit on Intake (ALI) is 80 mCi ($\approx$ 3 GBq) corresponding to a Committed Effective Dose Equivalent (CEDE) of about 5 rem (50 mSv) whole-body dose. This corresponds to the maximum permitted dose per year for a worker in a radiation area in the United States. Translated into European safety regulations the associated ALI level would be $\frac{20}{50} \times 3\,\mathrm{GBq} = 1.2\,\mathrm{GBq}$.

ALI level

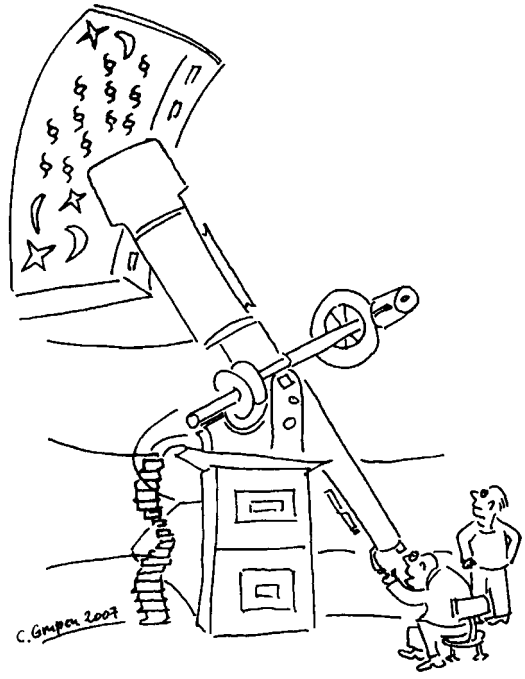
Example 3

The International Commission on Radiological Protection (ICRP) has also calculated the relationship between the activity taken into the body (intake) and the committed effective dose equivalent from intake. The corresponding ALI levels include the type of radiation, its energy, a possible selective deposition in the human body, and the effective half-life, which can be worked out from the physical and biological half-life.

intake

^{131}I is a typical radioisotope which could be inhaled after radiation accidents in nuclear power plants, or which has frequently been used in the past for the diagnosis of functional problems of the thyroid gland. The thyroid gland is also the critical organ for ^{131}I, i.e., it will accumulate predominantly in this gland. The ICRP has worked out that an inhalation of 200 kBq of ^{131}I will lead to a selective deposition in the thyroid gland of 50 mSv. If the tissue weighting factor for the thyroid gland (0.05) is taken into consideration, this gives an effective whole-body dose equivalent of $H_{\mathrm{eff}} = 50\,\mathrm{mSv} \times 0.05 = 2.5\,\mathrm{mSv}$, which would be in accordance with the dose limits of a category-B worker in a radiation-controlled area.

critical organ



"This regulation jungle is even harder to interpret than black holes!"

Summary

Most countries follow the recommendations of the International Commission on Radiological Protection when the safety standards for radiation protection have to be defined and regulated. The details are very complicated, but some general guide marks can be outlined. The dose limits for radiation workers in most cases are at 20 mSv per year. The corresponding limits for the general public is at 1 mSv per year. As a rule the ALARA principle, to keep the doses as low as reasonably achievable, can be considered as a sound guideline for radiation protection. One must always keep in mind that additional doses must be compared to the environmental radiation of about 2 mSv per year present nearly all over the world. It is impossible to present all regulations for every country in this book. A convenient compilation which lists useful radiation-safety references and web sites for the whole world can be found under `www.radiation.org.uk/`. A helpful summary for the European regulations is also found under `http://irpall.irpa.net/pdfs/KL-5a.pdf`.

6.5 Problems

Problem 1

krypton load

With the help of a chemical separation technique the noble gas krypton is to be extracted form the normal air. The krypton concentration for ground-level air is 1.1 ppm. The air activity that can be traced back to the radioactive krypton isotope ^{85}Kr presently amounts to 1.1 Bq/m^3. The radioisotope ^{85}Kr originates mainly from nuclear power plants. This isotope is a typical fission fragment and can easily be released into the environment. How many cubic meters of krypton in the present isotopic abundance in air corresponds to an exemption limit of 1×10^4 Bq?

Problem 2

isotope ratios

A mineral hunter has found a lump of uranium ore of natural isotopic abundance, whose total activity corresponds to 1×10^4 Bq. The isotopic abundance of natural uranium is ^{238}U : ^{235}U : ^{234}U = 99.275% : 0.7195% : 0.0055%, and the half-lives of the isotopes are
$T_{1/2}(^{238}\mathrm{U}) = 4.5 \times 10^9$ yrs,
$T_{1/2}(^{235}\mathrm{U}) = 7 \times 10^8$ yrs,
$T_{1/2}(^{234}\mathrm{U}) = 2.4 \times 10^5$ yrs.
How many kilograms of natural uranium are contained in the lump of uranium ore?

Problem 3

dose limits

A category-A worker in a fuel-reprocessing plant has received a whole-body dose of 12 mSv by external irradiation and a liver dose of 40 mSv by incorporating radioactive material in a controlled area. What kind of maximum extra annual whole-body dose is allowed for the worker, if no other exposures would occur? What would be the maximum allowable lung dose, if, apart from the 12 mSv whole-body dose and the 40 mSv liver dose, no other exposures would occur. Assume for the calculation that the total dose limit is given by the ICRP recommendation.

7 Organization of Radiation Protection

"My time inside there was very short compared to the amount of time it took to take on and take off this suit and to test me for how much radioactivity I have."

William Scranton
(after visiting the Three-Mile-Island reactor)

radiation-protection directive

The responsibility for the correct integration of the radiation-protection rules in a company, nuclear power plant, research center, or an university lies in the hands of the radiation-protection supervisor. The radiation-protection supervisor has to appoint in a radiation-protection directive an appropriate number of radiation-protection officers for the control and surveillance of the work in question. The radiation-protection officer or, for short, the radiation officer has to be qualified for his work in the field of radiation protection. In contrast to this the radiation-protection supervisor need not be an expert in the field of radiation protection. He transfers the duty to respect the regulations of radiation protection to the radiation officer.

radiation officer

Usually the handling of radioactive material requires a license from the relevant authority. It is the duty of the radiation officer to arrange the necessary licenses for the handling of radioactive material. When the radiation-protection supervisor has appointed a radiation officer, the terms and conditions of his responsibility must be well-defined in writing. If there is more than one radiation officer in a company, it must be ensured that the terms and conditions of their responsibilities do not overlap.

qualification

The radiation-protection supervisor must notify the competent authority of the appointment of the radiation officer and define his or their responsibility in matters of radiation protection. The notification of such an appointment is considered to be evidence of the qualification of the radiation officer in the field of radiation protection. Since the position of a radiation officer is associated with high responsibility, only persons may be appointed if no facts are known which could cast doubt on their reliability. A necessary ingredient, of course, is that they possess the required qualification for the field of radiation protection. The radiation officer is responsible for the correct handling of the radioactive material in a company, in a power plant, or a research center. He must inform the radiation-protection supervisor immediately, if there are deficiencies affecting the safety in the field of radiation protection. Conflicts may arise from the fact that the radiation officer might propose alterations in

C. Grupen, *Introduction to Radiation Protection*,
Graduate Texts in Physics, DOI 10.1007/978-3-642-02586-0_7,

the handling of the safety regulations which the radiation-protection supervisor does not agree to. However, the radiation officer must not be hindered in any way in performing his duties and he should not be put at a disadvantage due to his activities even if they do not find the full support of the radiation-protection supervisor. The radiation-protection supervisor and the radiation officer must assure that in the event of danger to life, health, or property adequate measures are taken immediately. For example, if there is a danger of the dispersion of radioactive substances this risk must be kept as low as practicable so that the danger of incorporation into the human body is kept at a reasonably low level. Also steps must be taken to assure that accidental criticality of nuclear fuel cannot occur.

radiation accidents

The regulations in the field of radiation protection require that persons who will handle radioactive material, e.g. students in a nuclear physics lab at a university, are instructed about the possible dangers of handling radioactive sources. This instruction must be done annually and has to cover a number of aspects which are:

instruction

- introduction into the local laboratory safety rules,
- introduction into the standard working procedures with radioactive sources,
- information with respect to possible dangers,
- information about radiation exposures,
- description of the safety rules and possible protection techniques,
- accurate information about the relevant radiation-protection safety rules,
- instructions about the organization of radiation protection, and the responsibility of the radiation officer. The workers perform their tasks under the guidance of the radiation officer and they are bound to follow his instructions.

The radiation officer has to ensure that radioactive materials possessed under license conform to the materials which are included in the license. Also the radioactive materials should only be handled by individuals which are authorized to do so as stated in the license. It goes without saying that all users have to carry the required monitoring equipment such as film badges or electronic dosimeters.

film badges
electronic dosimeters

An important aspect is also that the radiation officer has to ensure that all radioactive material under the license is properly secured against unauthorized removal and against theft. Special care has to be taken in the handling of unsealed radioactive sources, because there is the danger of incorporation of radioactive material. On the other hand, the radiation officer has to perform periodic leak tests of sealed sources. If an originally sealed source is found to be leaky, then it takes on the character of an unsealed source. Normally

sealed sources
unsealed sources

such a leaking source has to be stored away, because the handling of this leaky source will usually not be covered by the license.

accounting

One of the most important tasks of a radiation officer is a painstakingly correct and clear accounting. The competent authority has to be informed about the acquisition and disposal of radioactive material. It is evident that acquisition and disposal has to be well documented. It must be clear at any time which radioactive material is used or stored. For this purpose the radioactive material has to be described accurately. The list containing the used material has to contain the following items:

- radioisotope (e.g. $^{137}_{55}$Cs),
- activity and type of radiation (e.g. 10^6 Bq; β, γ),
- physical property (e.g. solid or liquid),
- sealed or unsealed source,
- date of the acquisition of the source or the radioactive material,
- address of the supplier and addressee.

Figure 7.1
Design-approved radioactive sources for demonstration experiments (QSA Global GmbH)

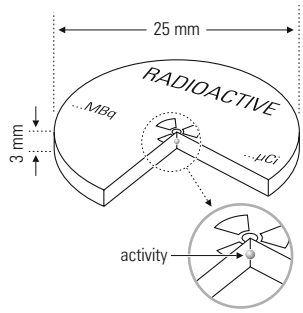


Figure 7.2
Pointlike emitter, in this case 3.7 MBq ^{57}Co, for use in the field of radiography (type 25/3, AEA Technology QSA GmbH)

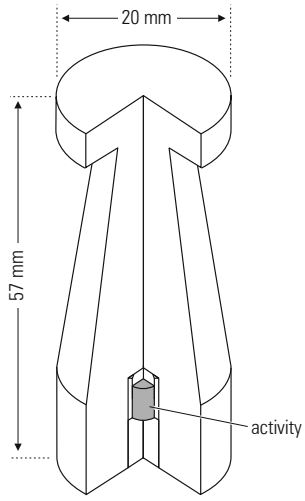


Figure 7.3
^{137}Cs calibration source for function control of detectors for activity measurements (type CDRB 1548, 3.7 MBq, AEA Technology QSA GmbH)

documentation

The written documentation about special instructions, area monitoring, body doses, contamination measurements, possession, and disposal of radioactive material have to be stored over a long period of time. Body doses have to be kept up to the age of 75 of the monitored person, but at least 30 years.

radiation passport

Radiation doses have to be documented in a radiation passport for the radiation workers. The purpose of this is to prevent to exceed the dose limits, in particular, if radiation workers are active in different companies and places. The radiation passport shows whether the owner of the passport fulfills the conditions for the envisaged activity, e.g. in an exclusion area or radiation-controlled area. The radiation officer of a plant is supposed to allow only activities for those people not belonging to the company, if they can provide an uninterrupted, complete radiation passport. This radiation passport should contain the following information:

- personal data and employer;
- information about external and internal radiation exposures;
- body doses, possibly exceeding the annual limits;
- result of the medical checkup;
- possible respiratory protection instruction and training;
- accounting of radiation exposures in the occupational life.

Radioactive materials, containers, and rooms, in which radioactive material is being used or stored, just as instruments for the production of ionizing radiation and devices with design qualification approval have to be properly labeled. Also the different radiation areas (exclusion areas, controlled areas, surveyed areas) and contaminated areas have to be marked as such.

Workers have to be alerted of possible dangers. The characterization or warning of relevant radiation areas must be done with the official warning labels (see Fig. 7.4) with the following indications

- ATTENTION – RADIATION,
- RADIOACTIVE,
- NUCLEAR FUEL,
- EXCLUSION AREA – NO ADMITTANCE,
- CONTROLLED AREA,
- CONTAMINATION.

In addition, the labeling must contain information about the radioisotope, its activity, and the responsible radiation officer. Labels which are no longer valid ***have to be removed***.

The radiation officer has to perform a number of measurements in those areas for which he is responsible. These measurements serve the purpose of radiation-protection monitoring and control. These measurements include the following items:

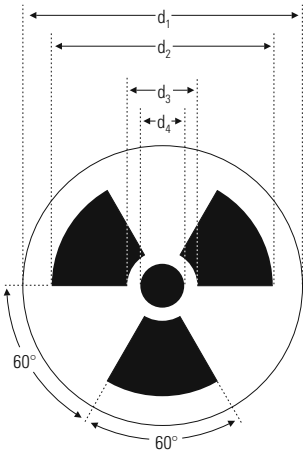


Figure 7.4
Radiation warning label. For different sizes of this label the values d_2, d_3, and d_4 have to be properly scaled for the allowed set of parameters d_1 (20, 40, 80, 160, 250 mm). The black areas are imaged on a yellow background. In most cases this label is framed by a black triangle the apex of which points to the top (see Fig. 7.5)

monitoring

- measurement of dose values,
- monitoring of the amount of activity,
- admission control,
- control of correct storage,
- leak tests,
- checkup on the safety measures,
- monitoring of unusual radiation exposures,
- check on the dose limits for radiation-exposed workers and non-radiation-exposed persons,
- measurement of incorporations,
- measurement of contaminations,
- monitoring of the environmental radiation,
- monitoring of possible contaminations of air, water, and ground.

The radiation officer can hire staff to help him to fulfill his duties. Their field of activity must be clearly defined in writing in the form of a radiation-protection directive.

Occasionally there will certainly be incidents in the practical work of radiation protection where it is the duty of the radiation officer to inform the competent authority about these incidents, e.g.

exceeding dose limits

loss of radioactive sources

finding of radioactive substances and acquisition of actual control

- exceeding the allowed dose limits,
- loss and acquisition of radioactive material,
- deficiencies and problems with safety systems.

In case of accidents in radiation-protection areas the following priority always has to be respected, namely, rescue – alert – secure – inform the competent authority.

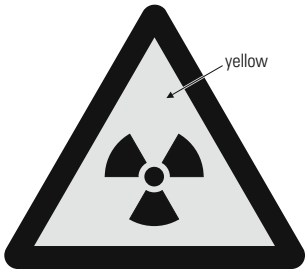


Figure 7.5
Frequently used form of the radiation warning label

medical examination

limitation of activities

The aim of the medical examination which is compulsory for radiation workers of category A is not primarily to diagnose radiation damages but rather the purpose of these examinations is to check the state of health of the worker before he starts his activity and while he is working in these radiation areas. For persons which become active in a controlled area a medical examination is compulsory before they start to work in the controlled area. For persons of category A in Europe the medical examination has to be repeated annually.

restricted activities

In case of health risks as diagnosed in a medical examination the activities of the worker can be limited (e.g., if there is a problem with carrying respiratory equipment, only the handling of sealed radioactive sources may be allowed). It is even possible to exclude certain workers from working in a radiation-exposed area, e.g. pregnant women. The restriction or reduction of tasks for persons in controlled areas can also be the consequence of exceeding the allowed annual whole-body dose. The purpose of these restrictive procedures is to limit further radiation exposures so that the dose over a period of several years stays within the allowed dose limits.

radiation accidents
emergency situations

An important aspect in the field of practical radiation protection is the handling of incidents and accidents. One has to distinguish between minor incidents, accidents, large serious accidents, and emergency situations. In such cases the permitted dose for radiation workers may be exceeded. A situation is already called an accident, if the continuation of a plant has to be interrupted for safety reasons. When designing an installation or plant, one has to take care that accidental doses may not exceed the values given in the respective radiation-protection regulations. For the European Union this accidental dose is 50 mSv/yr which must not be exceeded.

minor radiation incidents

Radiation accidents and emergency situations are quite rare. But also minor radiation incidents below the threshold for emergency situations just as accidents or severe accidents have to be handled with great care to ensure a maximum of safety for the radiation workers.

The handling of radiation accidents requires to consider the following items:

alarm planning

- provision for accidents (e.g. first aid, adequate training),
- activate the procedure for an emergency situation (limit or reduce the amount of the damage, prepare the fire fighting, medical treatment of persons involved in the accident),
- report to the radiation-protection supervisor, radiation officer, and information of relatives of persons involved in the radiation accident,
- analysis and reconstruction of the accident,
- duty of disclosure of the accident at the competent authority.

duty of disclosure

information for the fire brigade

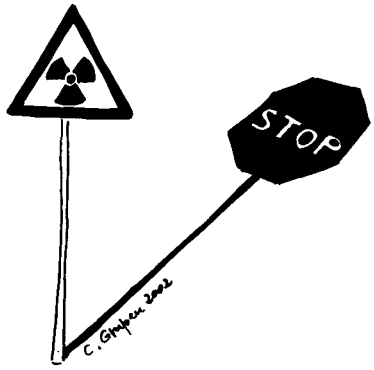
The radiation-protection regulation classifies three categories of accidents, if fires are involved. These different categories are related to the amount of activity concerned in the various parts of the installation or plant. Depending on the amount of radioactive material these areas have to be properly labeled as an information for the fire brigade.

Procedures to dispose of radioactive waste are defined in the radiation-protection regulations. The following requirements have to be considered for the adequate disposal of radioactive waste:

- correct labeling of the radioactive waste (e.g. identification of the radioisotope, recycled material);
- labeling of the waste container with detailed information on the amount of radioactive waste, total activity, dose rate at a distance of 1 m, date of storage, ...;
- possibility of preliminary storage of radioactive waste.

forbidden dispersal of radioactive waste

It is important to note that it is not permitted to subdivide the radioactive waste into quantities which fall below the exemption limits



or clearance levels. Also the dilution and dispersal of radioactive waste or radioactive materials into the environment is forbidden.

7.1 Supplementary Information

Example 1

radium mineral springs

In so-called radium mineral springs concentrations of radon including the decay products in the decay chain of 4000 Bq/l can occur. Radon is produced in radium decays. The radium concentration, however, in the water is relatively low, in most cases with levels of about 1 Bq/l. One frequently talks about radium springs and radium baths, even though the correct denomination would have been radon springs and radon baths.[1] In earlier times these kinds of treatment were prescribed. It is known now that swimming in these mineral springs or drinking the radium water can lead to considerable radiation exposures.[2] A famous victim of such a radium treatment was the American golfer Eben Byers, who died 1932, because he had drunken every day twelve bottles of radium water to relieve the pain after an arm injury.

radon inhalations

Similar considerations also hold for radon inhalations. According to the recommendation of the ICRP, radon concentrations in houses should not exceed 200 $\mathrm{Bq/m^3}$. Typical values in most apartments and houses are on the order of 30 $\mathrm{Bq/m^3}$. Record values for radon concentrations in houses were found in the small city St. Joachimstal in Bohemia. This town was famous for uranium mining with the consequence that in some places radon concentrations up to

[1] I thank Prof. Dr. H. von Philipsborn for pointing this out to me.

[2] The spas actually advertize these treatments by indicating that the α rays emitted form the radium effectively massage the cell membranes, thereby improving the patient's health!

10^6 Bq/m^3 inside houses were measured. The basement of some of the houses essentially consisted of uranium-containing waste from the uranium mines. In the decay chain of uranium also the radioactive noble gas radon occurs and by leaking through the basement radon can reach the living rooms of the houses.

Example 2

The maximum permitted surface contaminations for working areas are different for α emitters on the one side and β and γ emitters on the other side. Typically, because of the high radiation weighting factor for α emitters, the limits are different by a factor of 10 for α-ray emitters on the one hand and β and γ emitters on the other hand.

effect of α rays

α rays are connected with a very high biological effectiveness. This is the reason why the exemption limits for α-radiating isotopes, or dose limits for possible contaminations, are much more stringent compared to β and γ emitters. The external radiation with α rays does not present a problem because in most cases α rays are already absorbed in air (a typical range is about 4 cm) and in any case even if α rays reach humans these α rays will be absorbed in the surface layers of the tissue or in the clothing. In contrast to that α-emitting radioisotopes become extremely dangerous, if they are incorporated, because in that case the full effect of the high relative biological effectiveness comes into play.

Summary

The radiation-protection supervisor of an installation or a nuclear power plant defines in the radiation-protection directive the area of competence for the radiation officers. For this particular area only the radiation officer is responsible. The radiation officer has to be qualified in the field of radiation protection and he has to fulfill the duties as they are laid down in the radiation-protection directive. The radiation officer's qualification in the field of radiation protection has to be updated in regular intervals by attending relevant courses on radiation protection.

7.2 Problems

Problem 1

The dose rate at a work place is assumed to be 4 µSv/h. For a person who works on a regular basis 40 hours per week over the whole year in this area, this room must be associated with a radiation area. Will this room be a radiation-controlled zone or just a radiation-surveyed area according to the European regulations?

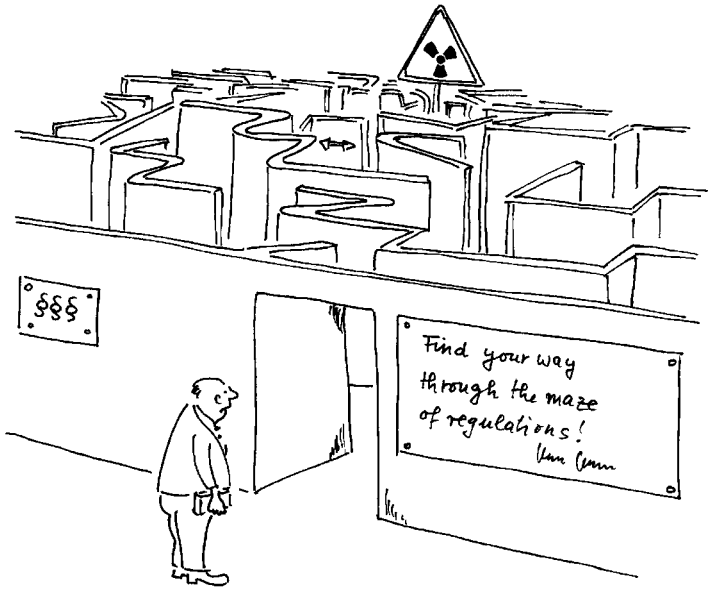
Problem 2

In a container surrounding the reactor in a nuclear power plant (volume $V_1 = 4000\,\mathrm{m}^3$) a tritium concentration of $100\,\mathrm{Bq/m}^3$ is measured. This tritium originated from a containment area in the inner reactor core of a volume of $500\,\mathrm{m}^3$. Work out the original tritium concentration. What was the total activity?

Problem 3

inhalations

In a working area a ^{60}Co concentration in the air of $1\,\mathrm{Bq/m}^3$ is found. For an annual breathing volume of $8000\,\mathrm{m}^3$ one will incorporate about 8000 Bq. Work out the amount of ^{60}Co corresponding to this activity ($T_{1/2}(^{60}\mathrm{Co}) = 5.24$ yrs, mass of a ^{60}Co nucleus $m_{\mathrm{Co}} = 1 \times 10^{-22}$ g)!



8 Practical Safety Measures[1]

"The only real security that a man can have in this world is a reserve of knowledge, experience, and ability."

Henry Ford

radiation-protection principles

It is the aim of safety measures in the field of radiation protection to avoid unnecessary radiation exposures, contaminations, and ingestion and inhalation of radioactive material ('incorporations'). To a certain extent, of course, there are radiation exposures which are unavoidable, but it is the aim to reduce these unavoidable radiation exposures, contaminations, or incorporations to a level as low as reasonably achievable. This is the so-called ALARA principle. There are, however, national radiation-protection regulations which require the radiation exposure to be kept as low as possible. Of course, it must be ensured that the exposures stay within the limits given by the regulations. To fulfill these requirements is the main task of the radiation-protection officer.[2]

practical aspects of radiation protection

In the following some practical aspects of radiation protection will be covered, namely,

- licensing,
- installations,
- external facilities,
- design approval,
- fire fighting,
- arrangements for mitigating the consequences of a severe accident,
- training of radiation workers,

Figure 8.1
Rugged instrument with GM counter designed for quick and reliable measurement of the gamma dose rate (RadEye G-10 counter, Thermo Scientific)

[1] The information presented in this chapter are based in part on the "Ordinance of the Protection against Damage and Injuries Caused by Ionising Radiation (Radiation Protection Ordinance)" as issued by the Bundesamt für Strahlenschutz, Salzgitter, Germany, edition 6/98.

[2] In the early days of the study of radioactivity the concept of 'radiation protection' did not even exist and there was no 'radiation officer'. Physicists like Becquerel, Curie, and Hahn handled relatively large quantities of radioactive substances with their bare hands. In addition to this, any radioactive material given off as gas or airborne dust was frequently inhaled. Even today the logbooks of Marie and Pierre Curie are contaminated by radium (half-life 1600 years) and their decay products, and they are on loan in the Bibliothèque Nationale only with special restrictions.

C. Grupen, *Introduction to Radiation Protection*,
Graduate Texts in Physics, DOI 10.1007/978-3-642-02586-0_8,

Figure 8.2
New generation pocket meter with NaI(Tl) crystal detector and sophisticated low-power technology components (RadEye PRD, Thermo Scientific)

- protection of air, water, and soil,
- radiation exposure from specific causes or unforeseen circumstances,
- handling of unsealed radioactive sources,
- contamination and decontamination,
- medical supervision,
- storage and security of radioactive substances,
- bookkeeping and declaration, and
- treatment of radioactive waste.

8.1 Licensing

The handling of radioactive substances exceeding the exemption limit or the clearance level requires a license. A license will be granted to individuals or companies if there is no evidence casting doubt on the reliability of the applicant or his legal representative. It must also be ensured that no facts are known which could cast doubt on the reliability of the radiation officers. They must also possess the required qualification in radiation protection. For larger companies or institutions there may be too much work for one member of staff to handle, so that more than one radiation officer is required for safe operation. Their fields of responsibility, however, have to be clearly established. It must be ensured that all other individuals engaged in the handling of radioactive material have the necessary knowledge concerning possible radiation hazards and that they are familiar with possible protective measures to avoid unnecessary exposure.

qualification as radiation officer

transportation of radioactive material

The transportation of radioactive substances or of waste containing nuclear fuel on public traffic routes requires a license from the relevant authority. The persons involved in this transportation have to make sure that possible radiation hazards to the public are kept at a level as low as possible, and they have to make sure that protective measures are taken.

import and export of radioactive material

The import or export of radioactive substances or waste containing nuclear fuel also requires a special license. For imports or exports it must be ensured that the radioactive substances or the radioactive waste is received only by persons who are in the possession of the requisite license for handling them.

One might assume that the licenses are mainly meant for radioactive sources, radioactive substances, and nuclear waste, but there are also other applications which require a special license, e.g.,

accelerators for charged particles

- accelerator or plasma facilities generating more than a given number of neutrons per second;

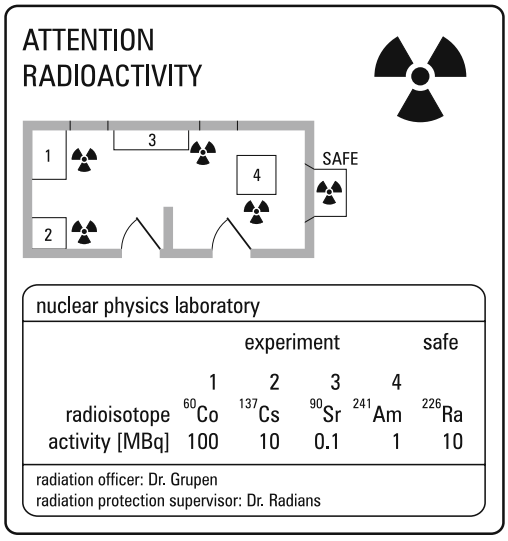


Figure 8.3
Example of the labeling of a nuclear laboratory in which radioactive substances are handled

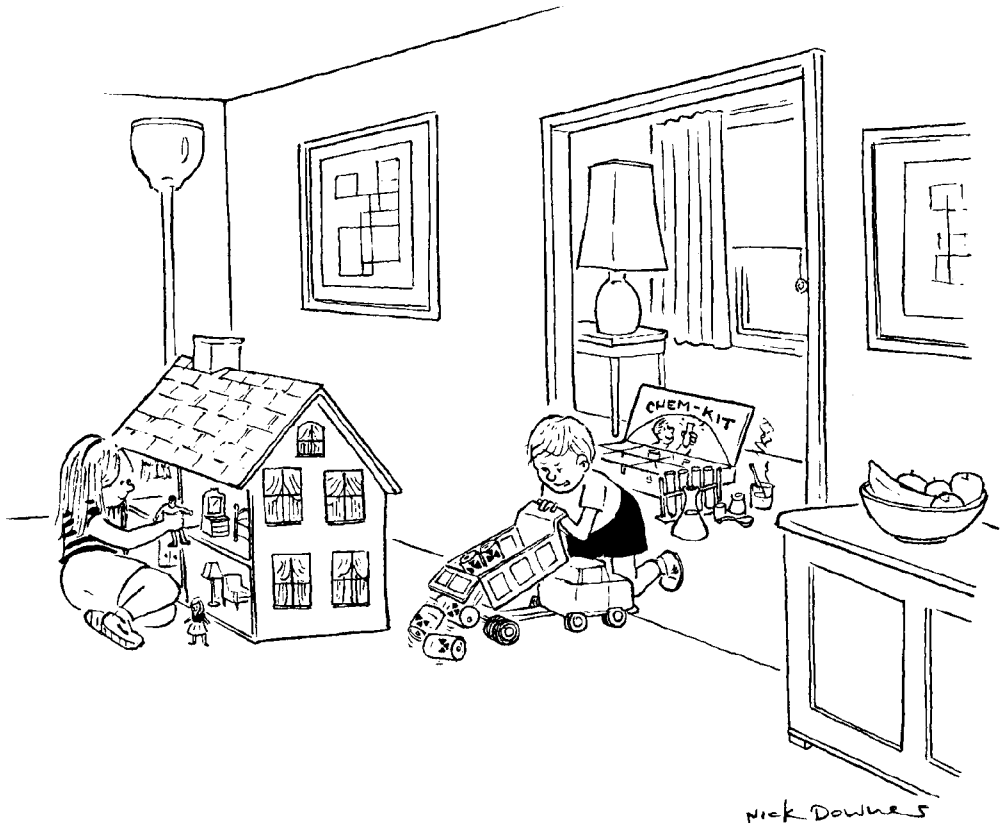
- electron accelerators, mainly used in radiology, providing an electron energy of more than 10 MeV, if the mean radiation power can exceed 1 kW;
- any electron accelerator having an energy of more than 150 MeV, even if the radiation power is much less than 1 kW;
- ion accelerators with ions of more than 10 MeV per nucleon, if the radiation power can exceed 50 W or, correspondingly, ion accelerators with ion energies of more than 150 MeV.

If an installation such as an accelerator for the generation of ionizing radiation is being modified, or if the operation is modified in such a way that the aspects of radiation protection are affected, then also a new license is required.

It goes without saying that the construction of installations can only be licensed if there is no evidence casting doubt on the reliability of the applicant. It is also necessary that the applicant possesses the requisite qualification in the field of radiation protection. The licensing for installations also requires a safety-analysis report which describes the installation and its operation. It should also describe the effects and possible hazards connected with the installation and its operation, as well as the facilities and measures to mitigate or limit possible hazards due to ionizing radiation.

safety-analysis report

Radiation workers are often required to work in other installations of their company or even those of other companies. A license is required for a company to send workers to external installations or facilities. The exposures in the home company and the external installations have to be documented.



8.2 Design Approval

The design of installations, devices, or any equipment which contains radioactive substances or produces ionizing radiation can be approved upon application, if the radiation-protection regulations are respected. The application has to be made by the manufacturer or importer of the equipment and it has to be directed to the competent authority according to the relevant state law. It is important for the application that the intended use of the installation or device has to be described in detail.

approving authority

The approving authority will base its decision on design tests, carried out by the authority itself. For this purpose the manufacturer has to supply design specimens for testing. If the instruments are found to be safe according to the radiation-protection regulations, the design approval will be granted for a period of up to 10 years. It is even possible to extend this period on request, if according to

any new regulations the approving authority comes to the conclusion that the instruments are still considered safe.

The approval for the design of installations and devices can be withdrawn if the competent authority finds out that the adequate protection against radiation damage is not provided.

The approval certificate includes the following information:

- the essential radiation-protection features of the device,
- the approved use of the device,
- any restrictions or conditions of use for the owner of the device, including time restrictions,
- the date of the design-approval certificate and the period of validity,
- and, finally, an indication concerning the duties of the owner of the device in accordance with the radiation-protection regulations.

attention: no alterations to design-approved devices

Modifications of the device may not be performed if these alter its essential radiation-protection characteristics. An instrument or device may no longer be used if, because of wear or damage, it no longer complies with the provisions given in the design approval, or if the fundamental radiation-protection characteristics as specified in the approval certificate have been modified. The owner of the device must immediately take the necessary steps to prevent radiation damage if any problem or irregularity occurs. He must also notify the competent authority immediately in this case.

Figure 8.4
Workplace equipment: radiation protection by lead-glass windows and lead shielding with lead-glass windows (JL Goslar)

8.3 Arrangements for Fire Fighting

Appropriate fire-fighting arrangements must be planned in conjunction and cooperation with the competent authority. These agreements must, in particular, specify

Hazard-Class-1,2,3 areas

- those areas where the fire brigade can work without special protection from the hazards of radioactive material (Hazard Class 1);
- those areas in which the fire brigade can only work with special equipment (Hazard Class 2); and, finally,
- those areas where the fire brigades can only work with special equipment such as respiratory protection and in the presence of an expert who can assess the radiation hazard while the fire fighting is in progress (Hazard Class 3). This expert also has to decide which preventive measures are to be taken to reduce the exposures to limits given by the fire brigades.

Figure 8.5
Fireman with protective clothing and respiratory equipment (`www.ffwessfeld.de`)

As an example, firemen in Germany are only allowed to receive once in their lifetime a radiation exposure corresponding to a dose of 250 mSv in a radiological emergency situation. This dose must stay within a limit of 400 mSv over the total working life of a fireman.

8.4 Arrangements for Mitigating the Consequences of Severe or Design-Basis Accidents

public safety

The necessary number of staff and the required equipment for localizing and eliminating the dangers connected with severe or design-basis accidents within restricted areas must be maintained at all times and proof of the readiness must be furnished to the responsible authority. All the information and the necessary advice required to eliminate or to mitigate the consequences of severe accidents must be provided to the authority responsible for public safety. Additionally, a plan to mitigate and eliminate the consequences of radiation accidents must be provided. It is also important that specific plans for a radiological emergency situation are available.

information policy

In such an emergency, the population which may be affected by the emergency situation must be informed in an appropriate way. The information given to the population should be coordinated with the competent authority for public safety. The information for the public must be repeated and updated if this is required by the emergency situation. The threshold level for a radiological emergency situation varies from country to country. Exposures of more than 50 mSv for the public certainly call for such an emergency situation.

8.5 Instruction and Training

exclusion area, restricted area

Individuals authorized to enter exclusion areas or restricted areas must receive appropriate instructions before entering these areas for the first time. The training to enter such areas has to include aspects

of the working procedures and the mention of possible dangers, possible radiation exposures, the safety aspects, and protective measures to be taken, and the license which governs their work. Persons handling radioactive material or using ionizing radiation outside restricted areas must also receive such training, if the work requires a license. These briefings have to be provided in fine detail before the radiation workers actually do their work in the exclusion area or restricted area. The training must be repeated every six months or even at shorter intervals, if this is requested by the competent authority or if a change in working procedure or possible dangers makes it necessary. The contents of the instructions must be documented and be signed by the individuals who have received the training.

Figure 8.6
Environmental monitor with a portable proportional-chamber detector; measurement range 5 nSv/h to > 1 Sv/h (VacuTec Meßtechnik GmbH)

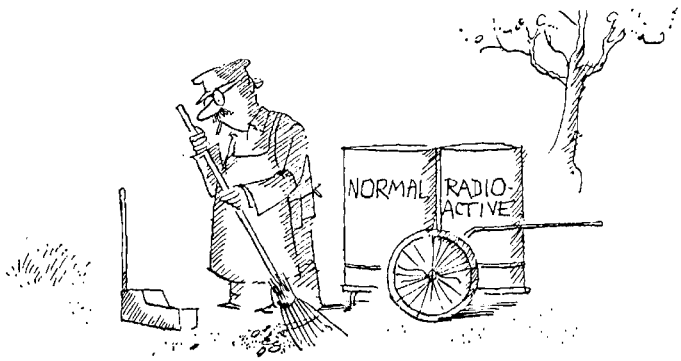
8.6 Protection of Air, Water, and Soil

clearance levels

Nuclear installations, nuclear hospitals, and nuclear power plants will very likely discharge certain amounts of radioactive substances into air, water, or soil. The national regulations will give clearance levels for possible contaminations of the environment. In addition to clearance levels there are limits for the inhalation of gaseous radioactive substances and ingestions of radioactive material which might find its way into food or drink, for example.

concentration limits

The limits on the concentration in air, water, and soil are defined by the competent authority. If the maximum values given by these authorities is exceeded, then it must be ensured that subsequent exposure is limited so that for a period of any three successive months the body doses will be smaller than the limits specified by the authority. These limits are provided for all radioisotopes, separately for possible discharges into air, water, and soil. These limits are guided



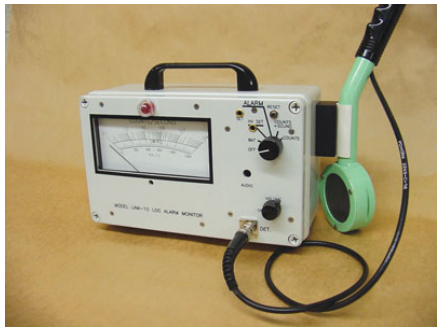


Figure 8.7
Versatile monitor with scintillation probe for both laboratory and field applications (Cole-Parmer Instrument Company, Vernon Hills, Illinois 60061; model EW-86551-22)

by the fact that any individual in the population may not get more than 10 µSv per year from such discharges (see also Appendix C).

8.7 Special Reasons for Radiation Exposure

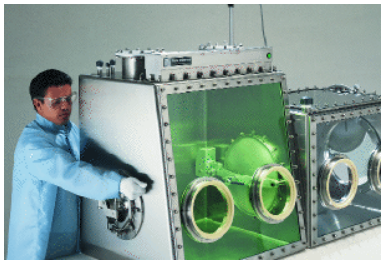
special incidents

In the case of an accident or in an emergency situation there may be urgent need to remedy the effects of the accident or to remove danger from people. In these cases the limits for radiation exposures may be exceeded. Only category-A workers (see Sect. 8.9) over 18 may be subject to these additional radiation exposures due to special events. However, the body doses received as a result of this special situation must not exceed twice the limits normally given by the radiation-protection regulations. These body doses from radiation exposure due to particular circumstances must be added to the body doses already received in the same year. The additional doses received in such situations must be compensated for in the subsequent years so that, e.g. over a period of five years, the dose limits are again respected.

8.8 Handling of Unsealed Radioactive Sources

protection against contamination and incorporation

If unsealed radioactive sources whose activity exceeds the limits given in the radiation-protection regulations are handled, one has to make sure that procedures are adopted so that the incorporation of radioactive substances and contamination of individuals involved are kept as low as reasonably achievable. If necessary, the persons handling unsealed sources have to wear protective clothing, use protective equipment, and use respiratory protection. It goes without saying that they must avoid incorporating radioactive substances or bringing them dangerously near to the body. In particular, eating, drinking, and smoking is forbidden if unsealed radioactive substances are being handled.



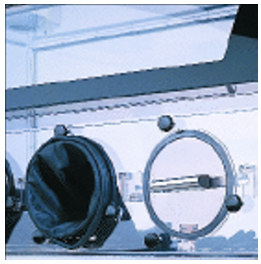


Figure 8.8
Glove box for the safe handling of radioactive substances (Terra Universal, Inc.)
www.terrauniversal.com

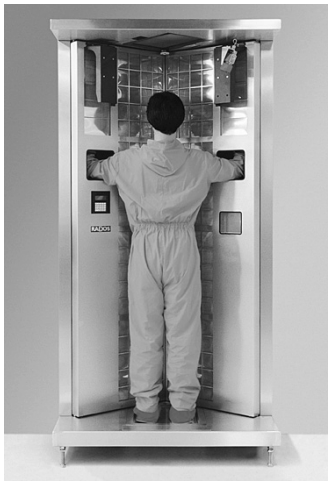


Figure 8.9
Whole-body contamination monitor for the measurement of α, β, and γ contaminations with a system of large-area counters (type RADOS RTM860TS, RADOS Technology GmbH)

Figure 8.10
Hand–foot monitor for the measurement of α and β rays with large-area counters (model LB 145, BERTHOLD TECHNOLOGIES GmbH & Co. KG)

Unsealed sources may only be left in the working area as long as they are actually being used. Otherwise they have to be locked up in a safe so that incorporation or contamination is impossible.

During the handling of unsealed radioactive substances some contamination may not be completely avoidable. It must be checked whether people have been contaminated while working with these unsealed substances. This has to be done when they leave the restricted areas in which these unsealed substances have been handled. If contamination of the skin is detected then appropriate steps have to be taken immediately to prevent a danger of further dispersion or incorporation.

contamination checks

The decontamination must be performed only by qualified personnel who possess the appropriate knowledge. Items of clothing which may be dangerously contaminated must be kept in the restricted area. Safe storage of these objects has to be guaranteed or they may even have to be treated as radioactive waste. Workplaces which have been contaminated during the handling of unsealed radioactive substances can only be used for other purposes if they

decontamination

have been thoroughly decontaminated. Usually the relevant authority must be notified if such a decontaminated area is to be used for other purposes.

8.9 Medical Supervision

medical examinations of workers

Category-A workers are those who are approved to work in restricted areas and category-B workers are those who are allowed to handle unsealed radioactive substances but both are permitted to do so only if they have been examined by an authorized physician prior to the commencement of the work in question. Also the radiation-protection supervisor has to be given a certificate issued by the physician stating that there are no medical objections carrying out this kind of work. The medical examination has to be repeated annually for category-A workers. These medical checkups are compulsory and those persons who are subject to such medical supervision must tolerate these examinations.

purpose of examinations

The purpose of the annually repeated medical examinations for category-A workers is not to find or to detect possible hazards due to the ionizing radiation but to ensure that these workers are still able to fulfill their job in restricted areas. If radiation workers receive doses more than twice the body doses specified in the radiation-protection regulations, they must immediately be sent to an authorized physician and the competent authority has to be notified of the high radiation exposure.

Biological effects due to radiation doses below approximately 100 mSv cannot be identified in blood samples. It may, however, happen that, as a result of the special medical supervision, there is reason to fear that the health of the supervised person might be in danger if he continues to perform his work in the restricted areas. In that case the competent authority may order that the person concerned may no longer perform it or may only perform it on a restricted basis.

authorized physicians

This medical supervision must only be undertaken by physicians who are authorized to do so, and who have proven that they have the necessary qualifications. The authorized physicians are responsible for the first examinations and later re-assessments. The results of the medical examinations have to be documented. The physician has to keep a medical file on persons who are subject to medical supervision even it they are exposed only on certain occasions. This file has to contain information concerning the working conditions, and the result of the medical supervision, as well as the total of the body doses which the supervised person has received during his work.

medical files

Such a medical file must be kept for at least 30 years from the date of the last medical examination.

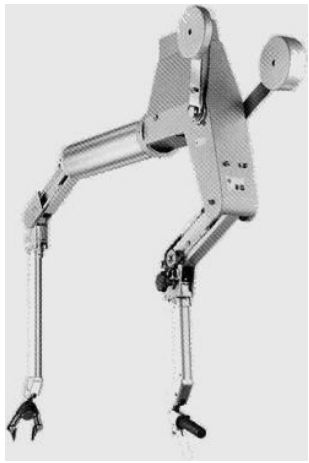


Figure 8.11
Manipulator for the handling of radioactive sources (Oxford Technologies) `www.oxford technologies.co.uk`

8.10 Storage and Security of Radioactive Substances

Radioactive substances exceeding the exemption limits must be stored in protected rooms or containers or safes while they are not being handled, processed, or otherwise used. Particular care has to be taken against loss and theft. The radioactive material should not be stored with other non-active material.

A very important point in the storage of nuclear fuel is that the vessel containing the radioactive material must be made in such a way that it is totally impossible to reach a critical state while being stored. From nuclear physics it is known that in the fission process about two or three neutrons are liberated per fission. This is used in a reactor to operate the plant with constant power. For this purpose at least one of these liberated neutrons has to initiate further fission reactions, i.e., the neutron amplification factor must be equal to unity. In this case the reactor is said to be in critical state. Such a state must be prevented under all circumstances when nuclear fuel is being stored. If a certain quantity of nuclear fuel is already stored in a protected room or a container, and if additional nuclear fuel is added to this amount of nuclear material, it may reach a critical state with the danger of causing uncontrolled fission. In the case of storage of nuclear fuel, it is advisable to have radiation monitors measuring the dose rate and, in particular, the dose rate due to neutrons.

prevention of criticality

8.11 Bookkeeping

It is very important to keep a file concerning the extraction, production, acquisition, delivery, and handling of radioactive substances stating their type, activity, and identity. The documentation also has to indicate if the substances are to be used by other individuals or organizations: and when, it has to be ensured that at any moment the whereabouts of the substances are known. A loss of substances has to be immediately reported to the nuclear supervisory authority.

loss of substances

On the other hand, not only losing but also finding radioactive substances might create problems. In any case of discovery the competent authorities have to be notified of the find. Even if one unintentionally acquires control over radioactive substances, this has to be reported. It can also happen that one receives radioactive substances

finding of substances

Figure 8.12
Fiber-reinforced concrete container with excellent radionuclide containment properties and resistance to aging caused by irradiation and external forces (AREVA; Saint-Quentin-Yvelines Cedex, France)

Figure 8.13
Lead safe for the storage of radioactive samples (JL Goslar)

Figure 8.14
Release monitor for the measurement of the specific activity of tools and parts of mechanical machinery (type FHT 3035 CCM release monitor, ESM Eberline Instruments GmbH)

without knowing that they are radioactive. In such cases a measurement of the activity will clarify whether the competent authority has to be notified of this discovery.

8.12 Waste Treatment and Storage of Radioactive Waste

re-use

If possible, radioactive waste should be re-used. This might seem odd, but, for example, steel, which cannot be further decontaminated, could be re-used to fabricate containers for waste of very high

disposal of waste

activity. If it is impossible to re-use some waste, it must be disposed of once and for all. The correct disposal of radioactive waste is a very important matter. Uncontrolled dumps are not acceptable.

short-lived radioactive material

Radioactive waste originates mainly from the process of recycling of used fuel rods. The problem of short-lived radioactive material is essentially solved by waiting until these substances have decayed. It must be considered that radioactive waste will produce quite a substantial amount of heat. This heat emission must be taken into account and, if necessary, cooling must be provided.

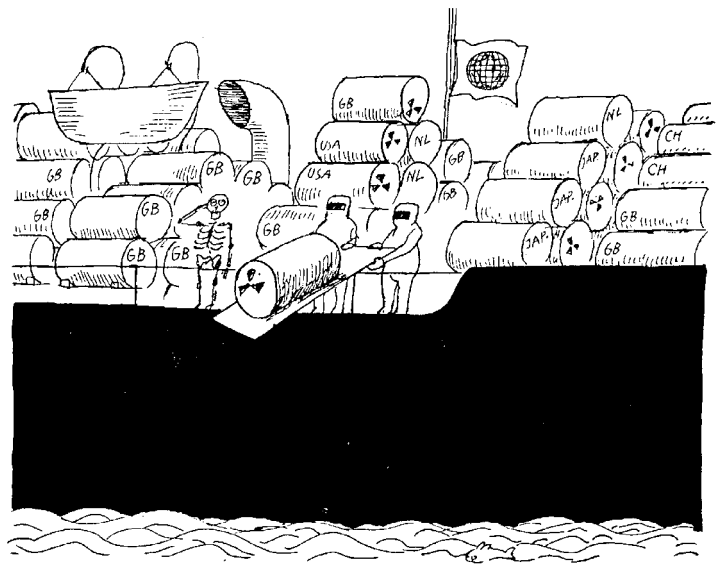
storage in underground cavities

Storage of radioactive waste in underground cavities is possible. There are, however, substantial requirements for such cavities, namely: geological stability, a high plasticity, and impermeability for liquids and gases. In addition, good heat-conducting properties must be ensured.

To get an idea of the storage problems, the amount of radioactive waste from the former Soviet Union is about 610 million m^3 with a total activity of 10^{20} Bq.

transmutation

In principle a more elegant way for the handling of radioactive waste can be envisaged, namely, the transmutation of long-lived radioactive isotopes by neutron or proton irradiation. This transmutation would allow the transformation of long-lived radioisotopes into short-lived ones or even stable isotopes. The cross sections for such reactions are normally quite small so that relatively long irradiation times and high particles fluxes are required. For example, the



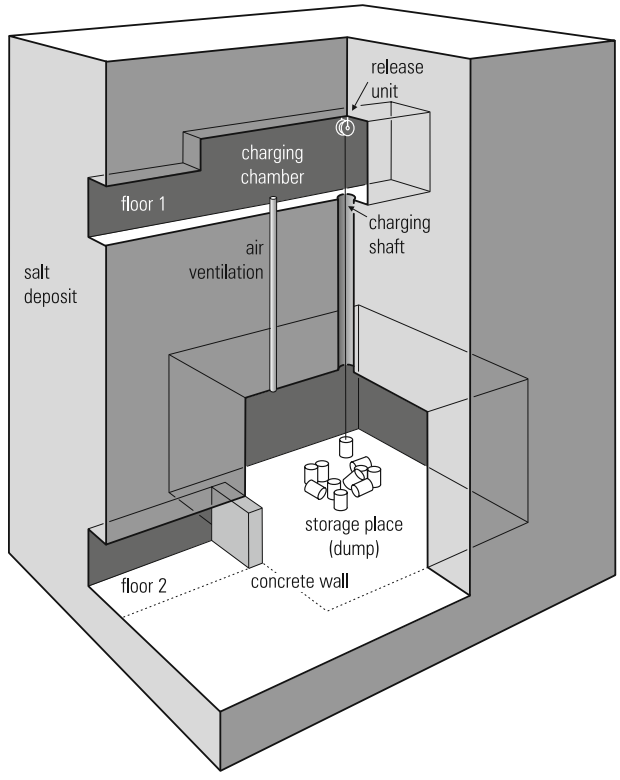


Figure 8.15
Illustration of the possibilities of storage of nuclear waste in a salt deposit

'bone seeker'

dangerous 'bone seeker' ^{90}Sr could be transformed by proton irradiation via

$$p + {}^{90}_{38}\mathrm{Sr} \rightarrow n + {}^{90}_{39}\mathrm{Y} \tag{8.1}$$

into a short-lived β-emitting yttrium isotope ($T_{1/2} = 64\,\mathrm{h}$), which in turn would decay within a few weeks into stable zirconium $^{90}_{40}$Zr.

In nuclear-fission reactors one of the important isotopes, which may be dangerous for the biosphere, is ^{137}Cs (half-life 30 years). The cesium isotope could be transformed, using protons, into stable ^{137}Ba in the reaction

$$p + {}^{137}_{55}\mathrm{Cs} \rightarrow n + {}^{137}_{56}\mathrm{Ba}\ . \tag{8.2}$$

Recently, physicists have succeeded in transforming long-lived radioactive waste by neutron bombardment into short-lived radioisotopes. Using a proton accelerator many neutrons could be produced by spallation[3] if suitable targets are used. Moderators for these

spallation

[3] Spallation is the process in which a heavy nucleus emits a large number of nucleons as a result of being hit by a high-energy particle.

neutrons produced by proton interactions could smear the production energy spectrum over a wide energy range: this would allow all resonances for the neutron-capture processes necessary for the transmutation to be covered. In this way the long-lived technetium isotope ^{99}Tc ($T_{1/2} = 210\,000$ years) could be transformed into ^{100}Tc ($T_{1/2} = 15.8$ seconds) and the fission product ^{129}I ($T_{1/2} = 15.7$ million years) into ^{130}I ($T_{1/2} = 12.36$ hours). Presently, these techniques are not performed on a large scale because for the production of the necessary neutron fluxes a proton accelerator in the GeV region is required and this is very expensive (see also Example 3 in this chapter).

transformation of long-lived radioisotopes

For safe storage of nuclear waste one also has to consider that radiation emerging from the waste could change the properties of the material of containers. Substances exposed to radiation can develop

- brittleness,
- corrosion,
- a reduction of stability,
- a change of color,
- an increase of hardness, and
- activation.

The radiation damage of material can be traced back to physical changes like the production of lattice defects, vacancies, or occupation of interstitials. Furthermore, helium and hydrogen produced by $n\alpha$ and np reactions due to neutron irradiation can modify the mechanical properties of materials significantly. Plastics can be damaged by the breakup of molecular bonds. All these effects have to be considered when containers and cavities for final disposal of nuclear waste are being designed and planned.

8.13 Packaging and Transport

It is mandatory to ensure safe transport of radioactive material by an appropriate container. The transport of radioactive material has to be accompanied by documentation in which the radioisotope, its activity, and the type of the material (sealed or unsealed) is stated. The material is classified by a transport class number, which depends on the maximum dose rate $\dot{D}$ over the outside surface of the container. Figure 8.16 shows typical lead containers for the transport of radioactive samples. An example for the label for the contents in such a container is illustrated in Fig. 8.17.

Figure 8.16
Lead containers for the transport of radioactive samples (JL Goslar)

transport class number

The transport index of 2.0 indicates that the dose rate $\dot{D}$ at a distance of one meter takes on a maximum value of 20 µSv/h (2 mrem/h). At the surface of the container the dose rate may vary

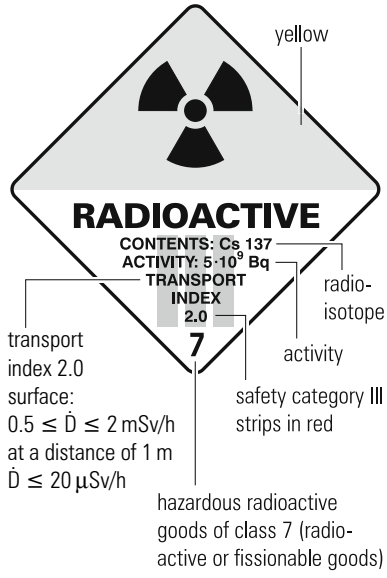


Figure 8.17
Example of the labeling of a transport container with a radioactive inventory

between 0.5 and 2 mSv/h. Also it has to be considered whether insurance needs to be taken against the possible risk associated with the transport of nuclear material.

Containers are subdivided into different categories, which are defined in Table 8.1.

Table 8.1
Definition of transport categories

transport index t	**max.** $\dot{D}$ **(mSv/h) on every point of the outer surface**	**category**
0	< 0.005	I–white
$0 \leq t \leq 1$	$0.005 \leq \dot{D} \leq 0.5$	II–yellow
$1 < t \leq 10$	$0.5 < \dot{D} \leq 2$	III–yellow
$t > 10$	$2 < \dot{D} \leq 10$	III–yellow (especially labeled for special agreements)

CASTOR container

The transport of CASTOR containers from nuclear power plants to recycling facilities has gained a lot of publicity. CASTOR is an abbreviation for CAsk for Storage and Transport Of Radioactive material. CASTOR containers for fuel elements are typically 6 m long and they have a wall thickness of 450 mm. The ribbed exterior of the container allows excellent heat emission. CASTOR containers are

thoroughly tested for all kinds of accidents possible during road or rail transportation. For example, the CASTOR container must withstand a fall from large height (9 m) onto a concrete floor. It must resist a fire at 800 degrees centigrade, and must remain intact after a collision with a train, a truck or a concrete wall, or even the impact of a projectile.

construction and test of CASTOR containers

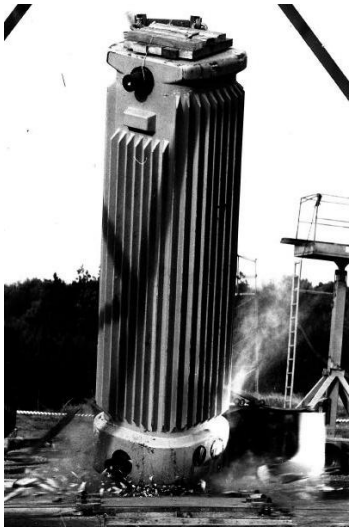


Figure 8.18
CASTOR container in a drop test (`www.tes.bam.de/e_ram/pdf/BAM-PM_16-78.pdf`)

Figure 8.19
CASTOR V/19 with fuel element carrier (`www.tes.bam.de/ram/bauart/bauart-2.htm`)

Normally, CASTOR containers contain radioactive material with an activity of several 10^{17} Bq, corresponding to 16 fuel rods. The dose rate at the surface of a CASTOR container is limited to 10 mSv/h and to 2 mSv/h at the outer envelope on the transport vehicle. At a distance of 2 m the dose rate must be smaller than 100 μSv/h. In practical cases the measured dose rates fall significantly below these legal limits.

exposition by CASTOR transports

The surface of some CASTOR containers can have substantial contamination from the under-water loading process. This contamination can come about in the following way: Inside the core of a nuclear reactor, cooling water acts as shield for the radiation emerging from the fuel rods. It is inevitable that in this process the water will be contaminated. During the loading procedure of spent fuel, which is done under water for shielding reasons, the outside of the CASTOR container must be protected from contamination by the contaminated water. Therefore it is enclosed by a protective cover which is filled with pure, uncontaminated water. After the CASTOR container has been loaded, it is closed while still under water. After retrieving the container from the water pool the contaminated

water still inside the CASTOR container is drained. Subsequently the container is cleaned with uncontaminated pure water and dried. A following wipe test ensures that the surface contamination of the container does not exceed the allowed limits. The average surface contamination of the containers is normally around or below $0.4\,\mathrm{Bq/cm^2}$, and it is forbidden that any single point should exceed an activity limit of $4\,\mathrm{Bq/cm^2}$.

exudation of contaminations

Surface contaminations in specific parts of the container exceeding these limits can easily originate from contaminated water having penetrated into cavities or closed leakage bolts. The contamination may spread over larger areas during the transport. Such a situation has happened in reality, and it was suspected that the containers were not tight. However, the containers were actually watertight and residual contaminations originated from contaminated water not being completely wiped off.

Even including such minor incidents, the dose limits have been respected in all cases. A direct measurement of the dose rate due to surface contaminations is impossible because the dose rate at a certain distance from the container mainly comes from the stored nuclear fuels inside the container. It has been calculated that the dose rates at a distance of 2 m from the container, due to surface contaminations, are on the order of 2 nSv/h. This has to be compared with

Figure 8.20
Stationary radioactivity-measurement equipment with plastic scintillation counters for the checkup of lorries (type FZM 700, mab STRAHLENMESSTECHNIK)

"The duck-pond could use some attention!"

a dose rate originating from the CASTOR container of 100 µSv/h, which is permitted by the regulations. Also the dose rate of 2 nSv/h from the surface contaminations has to be compared with the environmental radiation from natural sources on the order of 0.2 µSv/h.

Still, one has to consider possible problems due to the surface contaminations through incorporation of material from the surface of the container. However, the containers are enclosed in a casing for the transport so that a direct access to the contamination is extremely improbable. Only when these containers are loaded, or when they reach their final destination, is the casing removed from the containers, but this procedure is performed by qualified personnel who are trained to respect the corresponding safety rules.

danger of incorporations

8.14 Supplementary Information

Example 1[1]

Let us assume that in a nuclear physics laboratory of volume $V = 20\,\mathrm{m}^3$, a rate of $n = 10^{10}$ radioactive nuclei of a certain radioisotope (^{238}U) is introduced per hour. The rate at which air is exchanged between the laboratory and the surroundings is assumed to be $p = 20\,\mathrm{m}^3/\mathrm{h}$. Work out the time dependence of the activity concentration in such a laboratory. What is the activity in the equilibrium state?

time dependence of activity

The decay constant of ^{238}U is $\lambda = \frac{\ln 2}{T_{1/2}} = 4.88 \times 10^{-18}\,\mathrm{s}^{-1}$. The rate of change of the radioactive isotopes in the laboratory is composed of the rate of introduced radio isotopes n, the rate of decaying nuclei $\lambda\, N$, and the loss due to air exchange $\frac{N}{V}\, p$:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = n - \lambda\, N - \frac{N}{V}\, p \ .$$

The solution of this (non-trivial) differential equation is performed by separating the variables:

$$\frac{\mathrm{d}N}{n - \lambda\, N - \frac{N}{V}\, p} = \frac{\mathrm{d}N}{a\, N + n} = \mathrm{d}t, \ \text{ where } \ a = -\left(\lambda + \frac{p}{V}\right) \ .$$

By integration one obtains

$$\int_0^t \mathrm{d}t' = \int_0^N \frac{\mathrm{d}N'}{a\, N' + n} \ ,$$

$$t = \frac{1}{a}\, \ln\left(a\, N' + n\right)\Big|_0^N \ ,$$

[1] This example is mathematically demanding and therefore reserved for advanced readers.

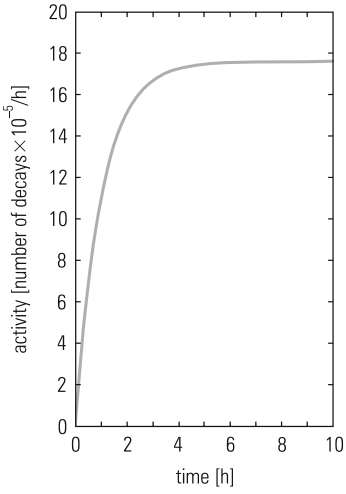


Figure 8.21
Time dependence of the activity of ^{238}U by decay and air exchange

$$a\,t = \ln\left(\frac{a\,N + n}{n}\right) ,$$

$$N = \frac{n}{a}\left(\mathrm{e}^{a\,t} - 1\right) = \frac{n}{\lambda + \frac{p}{V}}\left\{1 - \mathrm{e}^{-(\lambda + p/V)\,t}\right\} ,$$

$$\frac{N}{V} = \frac{n}{\lambda\,V + p}\left\{1 - \mathrm{e}^{-(\lambda + p/V)\,t}\right\} .$$

equilibrium activity

The solution of this differential equation shows that the initial activity $A = \lambda\,N$ (for $t = 0$) is zero, then it rises as $1 - \mathrm{e}^{a\,t}$, and reaches an equilibrium activity for infinitely long times. Since the exponential approaches zero for $t \to \infty$, one obtains for the activity in the equilibrium state

$$A = \lambda\,N = \frac{\lambda\,n\,V}{\lambda\,V + p} = \frac{4.88 \times 10^{-18}\,\mathrm{s}^{-1} \times 10^{10}\,\mathrm{h}^{-1} \times 20\,\mathrm{m}^3}{4.88 \times 10^{-18}\,\mathrm{s}^{-1} \times 20\,\mathrm{m}^3 + \frac{20\,\mathrm{m}^3}{3600}\,\mathrm{s}^{-1}}$$
$$= 1.76 \times 10^{-4}\,\mathrm{h}^{-1}$$
$$= 4.88 \times 10^{-8}\,\mathrm{Bq} .$$

One might be surprised that the activity is so small, but this is related to the large half-life of the ^{238}U isotope. Figure 8.21 shows the time dependence of the activity. We see that an equilibrium state is reached after about 4 hours. For ^{90}Sr ($T_{1/2} = 28.5$ years corresponding to $\lambda = 7.7 \times 10^{-10}\,\mathrm{s}^{-1}$), under otherwise equal conditions,

$$A = 27\,720\,\mathrm{h}^{-1} = 7.7\,\mathrm{Bq} ,$$

corresponding to an activity concentration in the equilibrium state of $0.385\,\mathrm{Bq/m}^3$.

Example 2

The long-term storage of highly radioactive nuclear waste in containers involves a number of problems. Take as an example storage in steel containers: Problems may occur over a period of several decades or centuries. The ionizing radiation from the radioactive waste will interact with the steel container, and this irradiation will modify the container's properties in the course of time. Due to the continuous bombardment of the steel lattice by ionizing radiation, some iron atoms will be displaced from their original position and lattice defects will occur. Since the normal regular structure of the steel lattice is associated with a low-energy state, the creation of vacancies and lattice defects is accompanied by an increase of the internal energy of the material. This increasing energy level can reach quite substantial values so that the irradiation could result in brittleness or loss of stability of the steel. It is generally believed that the common method of storage in steel containers, due to the expected changes in the material properties, guarantees safe storage only over a period of about 100 years.

storage of radioactive waste

There is, however, a solution to this. If instead of the standard container materials like steel, another material is used, which has a disordered structure from the start, one can hope that the atomic displacements due to irradiation will not reduce the durability of this material. The idea of increased radiation hardness in disordered compounds could be verified on an example of ceramic material like erbium zirconate. Such radiation-resistant compounds could lead the way to safe storage of highly radioactive nuclear waste.

radiation hardness

Example 3

Transmutation: an attractive alternative for final disposal?

In recent years significant progress in the field of transmutation of long-lived radioisotopes into short-lived or even stable ones has been achieved. The amount of nuclear waste from nuclear power plants and recycling facilities worldwide is estimated to be about 10 000 tons annually. It is known how to handle typical fission products like cesium or strontium. However, the storage of transuranium elements such as plutonium, neptunium, americium, and curium appears to be rather problematic. These transuranium isotopes are created from the original nuclear fuel (mostly ^{235}U) by neutron attachment with subsequent β decays. Actually, this was the original idea of Otto Hahn and Fritz Straßmann to produce elements beyond uranium by neutron bombardment. As it is known their experiments eventually resulted in the discovery of fission.

neutron bombardment

Even though the transuranium elements represent only about one per cent of the total radioactive waste, the problem arises because of their extremely long half-lives (e.g. $T_{1/2}(^{237}\mathrm{Np}) = 2.1 \times 10^6$ yrs). It is conceivable to separate the transuranium elements from the nuclear waste and bombard them with fast neutrons. This would

either fission these nuclei or transform them into short-lived isotopes. Typical transmutation products are isotopes of ruthenium and zirconium, which are either stable or relatively short-lived on the scale of 100 years. The safe storage of these isotopes only has to be guaranteed for a period of several hundred years. Is is believed that salt domes could ensure this. A safe storage of transuranium elements with half-lives of millions of years is hard to demonstrate.

neutron generation by spallation

Fast neutrons can be generated by spallation. Energetic protons from an accelerator colliding with a heavy target (e.g. lead) will produce a large number of fragments, among others also many neutrons. In this way a single proton can liberate 30 to 50 neutrons in a collision. This technique requires, however, a proton accelerator. Already in 1984 this method has been demonstrated to work at the European Center for Particle Physics CERN in Geneva, Switzerland. In this experiment small quantities of plutonium had been converted by transmutation to short-lived fragments.

transmutation by proton accelerators

Transmutation by protons from an accelerator is relatively simple, at least in principle. The process of transmutation cannot get out of control, because neutrons have to be continuously delivered. Without proton beam the transmutation stops immediately. However, one has to admit, that there are some disadvantages and a number of unsolved problems, such as:

- One needs an expensive, high-power proton accelerator.
- A high purity of the transuranium elements is required (99.99%).
- The production of high-purity transuranium elements is not yet mastered technologically.
- It is foreseen to use a liquid lead–bismuth mixture as coolant. This is complicated to handle.
- The efficiency of transmutation is only about 20% to 25%. Therefore the transmutation procedure has to be iterated with repeated steps of separating and irradiating the material, such that all transuranium isotopes are successfully transformed into fragments.

heat production by transmutation

As an interesting side effect it would be profitable to use the heat generated in the process of transmutation as energy source. To cover the world energy supply by burning fossil materials like coal, gas, or oil is not a good idea in the long run, because of the expected adverse effects on the climate. The present availability of alternative energy resources (solar power, wind, geothermal power, ...) needs to be improved. Considering that at the moment 439 nuclear power plants worldwide are in operation, and will continue to do so for a while, a technologically tested method to transform nuclear waste into material which can be safely stored would certainly be a good

argument to convince the population of the necessity and practicability for nuclear energy with inherently safe nuclear reactors.

A large-scale implementation of this new transmutation technique requires a considerable instrumental and energetic effort. Therefore is is probably a long way before such a concept can be realized on an industrial basis.

Summary

Practical aspects of radiation protection require the existence of suitable safety techniques. These safety measures include the design of working procedures and the handling of radioactive substances itself. Also the use of tested laboratory procedures is recommended, and the safe disposal of radioactive waste has to be allowed for. Some very simple rules can be identified: keep distance from the radioactive material, use appropriate shielding, restrict the working time in the presence of nuclear material, limit the activity of radioactive substances, and, if possible, exclude any ingestion and inhalation or at least reduce them to a level that is unavoidable.

8.15 Problems

Problem 1

A wipe test on an ^{241}Am radioactive source with a contamination monitor leads to a count rate of 20 counts per second. The effectiveness of the wipe test is assumed to be 80% and the efficiency of the monitor can be assumed to be 10%. Can the source still be considered 'tight', i.e., is the surface activity below the recommended value of 200 Bq?

Problem 2

During a contamination measurement with a wipe test a count rate of $R = 1000\,\text{Bq}$ is measured (decontaminated area $F = 900\,\text{cm}^2$, effectiveness of the wipe test $\eta_1 = 20\%$). The detection efficiency of the contamination monitor is assumed to be $\eta_2 = 1\%$ and the background rate $R_0 = 10\,\text{Bq}$. What is the true activity per cm^2?

Problem 3

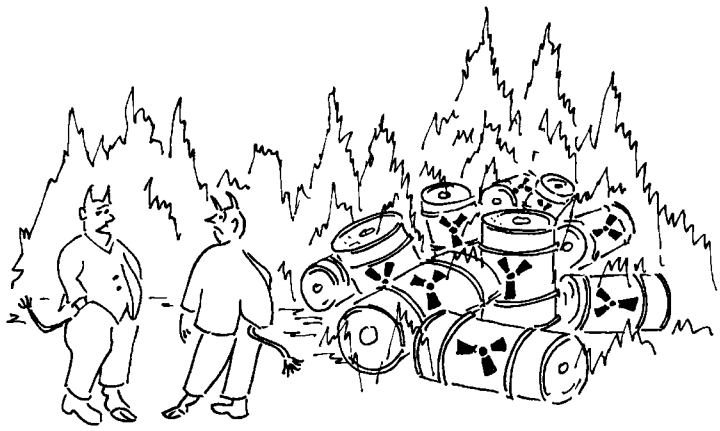
A large transport container (mass $m = 120$ tons) with a radioactive inventory of 10^{17} Bq will heat up due to the ionizing radiation. Let us assume that per decay 10 MeV is liberated and this energy will be completely transferred to the container over a period of 24 hours without any loss. Estimate the temperature that the container will attain, if made from iron with an initial temperature of 20°C (specific heat of iron: $c = 0.452\,\text{kJ}/(\text{kg K})$).

Problem 4 In a large nuclear physics laboratory a pointlike ^{60}Co emitter with an activity of 0.1 GBq has been lost. It is necessary to search the laboratory for this radioactive source. What is the maximum distance at which the source can be detected if the dose-rate meter used has a detection threshold of 10 µSv/h?

Problem 5 After a fire in a nuclear physics laboratory the expert adviser from the fire department or the radiation officer of the laboratory has to decide on where to put the safety boundary, which is normally defined by a dose-rate limit of 25 µSv/h. At a distance of 100 m from the radioactive source, which is involved in the accident, an ambient-dose rate of 1 µSv/h is recorded. Where should the boundary for safe operations be placed under the assumption that the radioactive source is pointlike?

Problem 6 The efficiency of a filter for radioactive dust and gases is assumed to be $\eta = 30\%$. Uranium-containing radioactive gas with a concentration of $\kappa = 40\,\mathrm{kBq/m^3}$ flowing through this filter will deposit a certain amount of activity in it. Work out the activity of the filter after one week of operation ($t = 7 \times 24\,\mathrm{h} = 168$ operating hours) if the average gas throughput is $m = 20\,\mathrm{m^3/h}$!

Problem 7 A strong 10-Ci ^{137}Cs source for applications in nuclear medicine is packaged in such a way that it corresponds to a transport number II–yellow and a transport index $t = 0.3$. What is the associated range of the dose rate $\dot{D}$ covering every point of the outside container, and what is the dose rate at a distance of one meter from the cargo?



"This stuff stinks like hell!"

9 Radiation Sources

"Radioactive sources are used throughout the world for a wide variety of peaceful and productive purposes in industry, medicine, research and education, and in military applications."

International Atomic Energy Agency

One might assume that only radioisotopes are significant sources of radiation. The rapid development in basic physics research and its technical applications have created a variety of possibilities for producing nearly all sufficiently long-lived elementary particles and photons in the form of radiation sources. The energy range from ultracold particles ($\ll 25$ meV) up to energies of 1 TeV can be covered. If, in addition, cosmic rays are considered, also particles and photons with energies in excess of 1 TeV are available albeit at low intensity. In the following sections the main methods of production of ionizing radiation are described. Nuclear fission and fusion plants as sources of neutrons and electron antineutrinos will be dealt with in a separate chapter.

9.1 Particle Radiation

All charged particles can be accelerated and stored up to very high energies in accelerators. Most accelerators are circular installations in which the particles to be accelerated are kept in a vacuum beam pipe by magnetic dipole fields. The particles are then accelerated by high-frequency alternating electromagnetic fields in so-called cavities, which are fed by klystrons[1]. For beam focusing quadrupole magnets and magnetic correction lenses are used. Figure 9.1 is a sketch of the standard equipment of a circular accelerator. The magnetic guiding field has to be increased in a synchronous fashion with increasing momentum of the particles (synchrotron) so that the particles will be kept on a fixed orbit in the vacuum pipe.

accelerator

synchrotron

Typically electrons, positrons, protons, and antiprotons are accelerated, e^+ and e^- to, say, 100 GeV in electron synchrotrons and

[1] A klystron is an electron tube that generates microwaves by velocity modulation. Usually a beam of electrons is passed through a resonant cavity where it interacts with high-frequency radio waves, in the course of which a bunched beam is produced. At accelerators klystrons are used as amplifiers at microwave and radio frequencies to produce high-power driving forces for the particle beams.

C. Grupen, *Introduction to Radiation Protection*,
Graduate Texts in Physics, DOI 10.1007/978-3-642-02586-0_9,

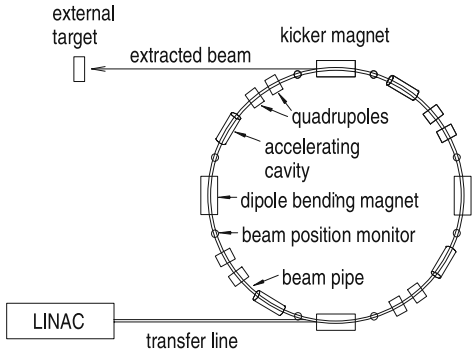


Figure 9.1
Synchrotron accelerator

Figure 9.2
Dual-energy linear electron accelerator. (Source: RadiologyInfo^{TM}, `www.radiologyinfo.org/`)

p and $\bar{p}$ to a maximum of 7 TeV (p) in proton synchrotrons. By extracting the accelerated particles a large number of secondary particles can be produced by collisions with an external target, which then can also be stored themselves. In the field of experimental high energy physics mainly pion, kaon, muon, and neutrino beams are produced for this purpose. Beams of negative pions have also been used in the field of medicine for tumor treatment. Heavy ions, which can also be accelerated in synchrotrons up to high energies, are also an excellent tool for tumor treatment in the framework of hadron and heavy-ion therapy, see also Sect. 4.1.

hadron therapy
heavy-ion therapy

Even though charged pions, kaons, and muons are relatively short-lived ($\tau_\pi^0 = 26\,\text{ns}$, $\tau_K^0 = 12\,\text{ns}$, $\tau_\mu^0 = 2.2\,\mu\text{s}$), they can still be used at high energies as secondary radiation because of the relativistic time dilatation. Muons can even be stored in circular accelerators. For energies of about 10 GeV the lifetimes of charged pions, kaons, and muons are given by (γ is the Lorentz factor)

$$\tau_\pi = \gamma\,\tau_\pi^0 = \frac{E}{m_\pi c^2}\,\tau_\pi^0 \approx 1.9\,\mu\text{s}\ , \tag{9.1}$$

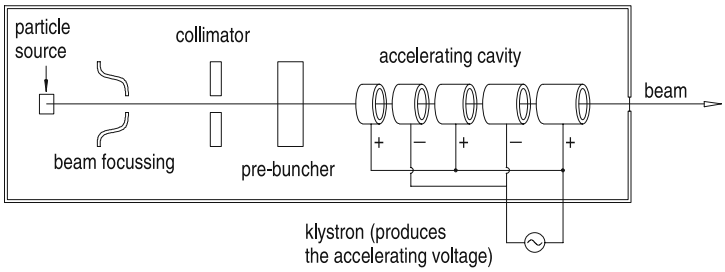


Figure 9.3
Linear accelerator

$$\tau_K = \gamma \tau_K^0 \approx 240\,\text{ns} \ , \tag{9.2}$$

$$\tau_\mu = \gamma \tau_\mu^0 \approx 210\,\mu\text{s} \ . \tag{9.3}$$

Muons of this energy can travel a distance of about 60 km before they decay.

linear accelerator

A linear accelerator usually serves as injector for a circular accelerator. Figure 9.3 shows the main components of such a linear accelerator. This type of accelerator is also frequently used in medicine. In linear accelerators particles (mostly electrons and positrons) can be accelerated up to energies of 1 TeV.

synchrotron radiation

At high energies it makes sense – at least for electrons – to use linear accelerators. A circular movement represents an accelerated motion and accelerated charged particles suffer an energy loss by synchrotron radiation. The time-dependent emission of radiation of a charged particle of energy E in a synchrotron with bending radius r is

$$\frac{\mathrm{d}W}{\mathrm{d}t} \approx \left(\frac{E}{m_0 c^2}\right)^4 \frac{1}{r^2} \ , \tag{9.4}$$

where m_0 is the rest mass of the accelerated particle. Because of the low electron mass compared to that of a proton ($m_e/m_p \approx 1/2000$) the energy loss of electrons in circular accelerators at high energies can be considerable. For example, the energy loss of 100-GeV electrons in the Large Electron–Positron collider LEP at CERN (circumference 27 km, bending radius $r = 3100\,\text{m}$) per revolution was

circular accelerators

$$W \sim \frac{\mathrm{d}W}{\mathrm{d}t}\, 2\pi r = C\, \frac{E^4}{r} \ , \tag{9.5}$$

$$W = 8.85 \times 10^{-5}\,\text{GeV}^{-3}\,\text{m}\, \frac{(100\,\text{GeV})^4}{3100\,\text{m}} \tag{9.6}$$

$$= 2.85\,\text{GeV} \ , \tag{9.7}$$

so that electron accelerators at high energies can practically only be operated as linear accelerators. Because of the high proton mass the synchrotron radiation loss for these particles does not currently limit their energies in synchrotrons.

energy loss by synchrotron radiation

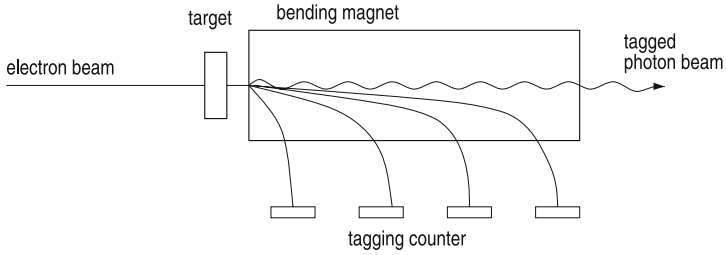


Figure 9.4
Tagging system

wiggler magnets
undulators
photon beams

The production of synchrotron light at circular electron accelerators is certainly of disadvantage for particle physicists. On the other hand, it represents a brilliant source of photons with energies up to the X-ray range. By special magnetic structures (wiggler magnets for intense incoherent and broadband photons, undulators for coherent radiation) highly intense X rays can be generated, for example, for structure analysis in solid state physics or biology. With the help of electron beams also photons in the high-energy domain can be generated. This works along the following lines: electrons of high energy produce bremsstrahlung in a target (e.g. lead or tungsten). If the electron momentum is measured before and after the interaction, the photon energy is obtained as energy difference between the incoming and outgoing electron. Such a tagging system is sketched in Fig. 9.4.

continuous bremsstrahlung spectrum

Altogether the produced photon beam consists of a superposition of different energies, which overall represent a continuous bremsstrahlung spectrum, but for individual events the photon energy is given by the tagging system.

neutrino beams
neutrino factories

The production of neutrino beams is also worth mentioning. Neutrino beams play a dominant role in particle physics when the validity of the standard model of particle physics is to be tested. Since the interaction cross section of neutrinos (ν) is exceedingly small, neutrino beams of high intensity have to be generated so that statistically significant interaction rates are achieved. Normally muon neutrinos are used for this purpose, where these neutrinos are produced in pion or muon decays ($\pi^+ \to \mu^+ + \nu_\mu$, $\pi^- \to \mu^- + \overline{\nu}_\mu$, $\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu$, $\mu^- \to e^- + \overline{\nu}_e + \nu_\mu$). In planned so-called 'neutrino factories' the neutrino fluxes will be very high: high enough for aspects of radiation protection to play an important role.

9.2 Photon Sources

X-ray tubes

X-ray tubes represent a classical photon source. This energetic electromagnetic radiation was discovered by Wilhelm Conrad Röntgen

in 1895 (see Chap. 10 on X rays). In typical X-ray tubes photons with energies up to several hundred keV can be produced, even the MeV range is accessible. The X-ray spectrum is continuous since it is created by electron bremsstrahlung. It is, however, superimposed by discrete X-ray lines, which are characteristic for the used anode material. The energies of characteristic X rays can be determined using Moseley's law:

X-ray spectrum

characteristic X rays

Moseley's law

$$E(\mathrm{K}_\alpha) = Ry\,(Z-1)^2\left(\frac{1}{n^2}-\frac{1}{m^2}\right)\ . \tag{9.8}$$

In this equation n and m are the principal quantum numbers and Ry is the Rydberg constant (13.6 eV). E.g., for K_α radiation on lead ($n=1, m=2$) one obtains $E(\mathrm{K}_\alpha^{\mathrm{Pb}}) = 66.9\,\mathrm{keV}$.

Rydberg constant

The photon energy range which is classically covered by X-ray tubes, is also obtained by synchrotron-radiation sources. However, the photon flux of synchrotron-radiation sources is higher by many orders of magnitude. The synchrotron-photon spectrum is continuous just like the bremsstrahlung spectrum of X-ray tubes. Because of the high intensity of the synchrotron-photon spectrum intense monoenergetic photon beams can be produced by monochromators[2]. Such monochromatic X rays from electron synchrotrons are, for example, used in diagnostics in the field of non-invasive coronary angiography. The coronary arteries are marked with stable iodine as contrast agent. Two digital images, one below and one above the K absorption edge, are taken (see Fig. 4.12), and subtracted in a computer. This allows to suppress the absorption in the surrounding tissue thereby yielding an image of the blood vessels of high contrast ('dual-energy technique' or 'K-edge subtraction technique'). Figure 9.5 shows a subtraction image of the human aorta and neighboring coronary arteries after an injection with stable iodine.[3]

synchrotron-radiation sources

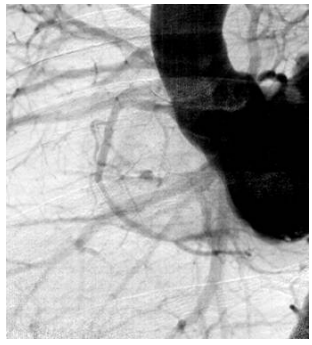


Figure 9.5
Subtraction image of the human aorta and neighboring coronary arteries after an injection with stable iodine

In the previously mentioned tagging systems high-energy photons in the GeV range can be generated according to the X-ray production principle. At the same time decays of neutral pions ($\pi^0 \rightarrow \gamma+\gamma$) or annihilations of electrons and positrons ($e^+ + e^- \rightarrow \gamma+\gamma$,

annihilations

[2] A device that produces monochromatic radiation from a polychromatic source. For X rays normally diffraction by crystals, which act like an optical grating, is used.

[3] S. Fiedler, Synchrotron Radiation Angiography: Dead Ends and Perspectives; `www.lightsource.ca/bioimaging/Saskatoon_2004_sf.pdf` and H. Elleaume, S. Fiedler, F. Estève, B. Bertrand, A. M. Charvet, P. Berkvens, G. Berruyer, T. Brochard, G. Le Duc, C. Nemoz, M. Renier, P. Suortti, W. Thomlinson, and J. F. Le Bas, First Human Transvenous Coronary Angiography at the European Synchrotron Radiation Facility, Phys. Med. Biol. 45 (2000) L39–L43.

used in positron-emission tomography (PET)) are sources of energetic photons. For completeness also decays of radioisotopes have to be mentioned, which – after α or β activity – decay frequently by γ emission into the ground state. In these decays photons with energies up to several MeV can be produced. As a consequence of nuclear transformation also excitations in the electron shell can occur leading to characteristic X rays.

Furthermore, also the thermal production of X rays from hot particle plasmas must be considered. In a fusion reactor with temperatures of up to 200 million degrees the energy of the thermal radiation is estimated to be $E_X = kT = 8.617 \times 10^{-5}\,\mathrm{eV\,K^{-1}} \times T = 17\,\mathrm{keV}$.

inverse Compton effect

In electron–photon interactions energetic electrons can produce high-energy photons by the inverse Compton effect. This process plays a dominant role in X-ray and gamma-ray astronomy.

9.3 Neutron Sources

spallation neutron sources

Neutrons are predominantly produced in strong interactions. In spallation neutron sources, energetic hadrons (mostly protons) produce a large number of neutrons in reactions with heavy nuclei. It is possible to create up to 30 neutrons per reaction by the bombardment of nuclei with hadrons. The spallation neutrons are created over a wide energy range and could ideally be used for the purpose of

transmutation

transmutation of nuclear waste. In such transmutations long-lived fission products from nuclear-fission reactors can be transformed by neutron interactions into short-lived or even stable isotopes. This technique, if being used on a large scale, could represent an attrac-

disposal of radioactive waste

tive alternative to the disposal of radioactive waste in underground cavities or other deposits. In dedicated neutron generators single neutrons can be produced by the bombardment of special targets with protons, deuterons, or alpha particles. In this way neutrons in the MeV range are obtained.

Otherwise neutrons can be produced in photonuclear interactions such as

$$\gamma + d \;\rightarrow\; p + n \;,$$
$$\gamma + {}^{9}\mathrm{Be} \;\rightarrow\; {}^{8}\mathrm{Be} + n \;.$$

radium–beryllium sources

A classical technique is the neutron production in (α, n) reactions. α-ray-emitting radioisotopes are mixed with a beryllium isotope. The α rays interact with ^{9}Be to produce neutrons of around 5 MeV according to the reaction

$$\alpha + {}^{9}\mathrm{Be} \;\rightarrow\; {}^{12}\mathrm{C} + n \;. \tag{9.9}$$

As α emitter one can use radium (^{226}Ra), americium (^{241}Am), plutonium (^{239}Pu), polonium (^{210}Po), or curium (^{242}Cm, ^{244}Cm). The neutron yield for these (α, n) reactions is of the order 10^{-4} per α particle.

neutron yield

In fission reactors highly radioactive fission products are generated. Since the fission materials, e.g. ^{235}U, are relatively neutron rich, the fission products contain too many neutrons. The neutron excess can be decreased by the emission of prompt or delayed neutrons. Nuclear-fission reactors are therefore a rich source of neutrons. The fission products can also try to reach a stable final state by successive β^- decays. In the Sun, which is a fusion reactor, globally four protons are fused into helium. In a fusion power plant (see Chap. 12 on nuclear power plants) deuterium and tritium will be fused to helium:

highly radioactive fission products

nuclear fusion

$$d + t \rightarrow {}^4\mathrm{He} + n \ . \tag{9.10}$$

In this reaction an energetic neutron is generated ($E_n = 14.1$ MeV). The original hope that fusion power plants would be completely clean from the point of view of radiation protection is not fully tenable. These energetic neutrons are very difficult to shield. They will activate the reactor materials and produce radioisotopes, so that a fusion reactor also represents a potential danger from the point of view of radiation protection. On the other hand, it is desirable that energetic neutrons are produced, despite their disadvantageous effects on the materials, as they are the source of power of fusion reactors. It has to be mentioned, however, that the big advantage of fusion reactors is that uncontrolled chain reactions cannot occur, which is definitely a possible problem with nuclear-fission reactors.

Finally it should be mentioned that under extreme conditions – as can be found, e.g. in supernova explosions – the pressure in the hydrogen plasma can be so high that electrons are merged with protons. In such a deleptonization process

deleptonization process

$$p + e^- \rightarrow n + \nu_e \tag{9.11}$$

neutrons are produced. Because of the average lifetime of neutrons of 886 s, these neutrons – even at very high energies – will decay long before reaching Earth, if traveling in that direction. In most cases, however, they do not escape from the supernova but are rather caught in a neutron star after a gravitational collapse.

9.4 Cosmic-Ray Sources

Cosmic rays may present a radiation hazard, in particular, for flight personnel. Radiation-relevant aspects concerning cosmic rays will

primary cosmic radiation

secondary cosmic radiation

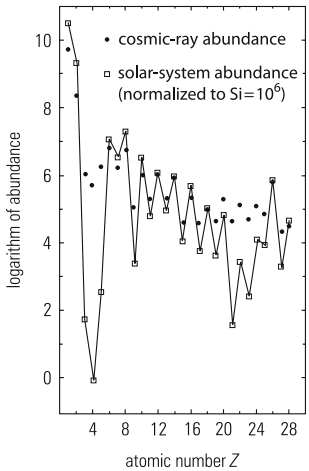


Figure 9.6
Elemental abundance of primary cosmic rays for $1 \leq Z \leq 28$

be presented in more detail in Chap. 11 on environmental radioactivity. In this chapter only the potential of cosmic rays as sources of particles for measurement and calibration of detectors shall be mentioned. Primary cosmic rays consist mainly of protons (85%) with a fraction of 12% α particles and about 3% heavy nuclei ($Z \geq 3$). By interactions of primary cosmic rays with atomic nuclei of the atmosphere the initial primary particles initiate cascades of secondary and tertiary particles. In this way predominantly pions and kaons are generated. These mesons[4] can either induce further interactions or decay. The competition between interaction and decay depends on the local density of the atmosphere. The soft component of cosmic rays consisting of electrons, positrons, and photons (initiated by π^0 decay) will be absorbed relatively fast in the atmosphere. In contrast, the decay products of charged pions and kaons, namely, muons and neutrinos, can easily reach sea level. 80% of charged cosmic rays at sea level are composed of muons, which are mainly distributed over an energy range from about 1 GeV up to 1 TeV. Because of the low interaction probability cosmic neutrinos play almost no role for the purposes of radiation protection.

The omnidirectional muon flux at sea level through a horizontal area amounts to about 1 particle per cm^2 and minute, corresponding to a flux for near vertical directions per solid angle and area of

$$\phi(\mu^{\pm}) = 8 \times 10^{-3}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1} \quad . \tag{9.12}$$

omnidirectional muon flux

Because of their low energy loss ($\approx 2\,\mathrm{MeV}/(\mathrm{g/cm}^2)$) muons can also reach large depths underground.

In the field of radiation protection cosmic-ray muons will lead to a background in all radiation monitors, in addition to that from terrestrial radiation. A contamination monitor with a horizontal area of $15 \times 10\,\mathrm{cm}^2$ will measure a background rate of ≈ 150 particles per minute purely due to cosmic rays. This result should not only be considered as a disadvantage since it represents at the same time a function test of the measurement devices. For such a test no artificial radiation sources are required. For measurements on radioactive materials this background rate has to be considered in any case. Because of the high penetration power of muons, they are also ideal

function test of the measurement devices

[4] Pions and kaons are mesons which belong to the group of strongly interacting particles ('hadrons'). These hadrons include baryons and mesons. Protons, neutrons, and their excitations are baryons. In the naïve quark model baryons are composed of three quarks. For example, the proton (uud) is a bound state consisting of two up quarks (electric charge $+2/3$ of an elementary charge) and a down quark (electric charge $-1/3$ of an elementary charge), while the neutron is a udd state. In contrast, mesons are bound states of a quark and an antiquark. For example, the positively charged pion (π^+) is a $u\bar{d}$ state.

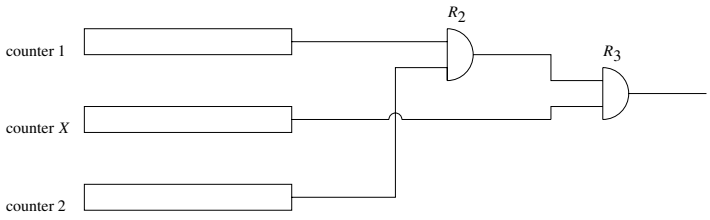


Figure 9.7
Coincidence arrangement for the determination of the detection efficiency of a detector

candidates for coincidence measurements which can determine the detection efficiency of particle detectors for charged particles. In a coincidence arrangement consisting of three detectors placed on top of one another (see Fig. 9.7) the count rates in the three counters are N_1, N_2, and N_X. If the true particle rate is N and the counters 1 and 2 have an efficiency of ε_1 and ε_2, the two-fold coincidence rate is

coincidence arrangement

$$R_2 = \varepsilon_1 \varepsilon_2 N \ . \tag{9.13}$$

The three-fold coincidence rate with the counter X of unknown efficiency is then

$$R_3 = \varepsilon_1 \varepsilon_2 \varepsilon_X N \ . \tag{9.14}$$

Thus the ratio of three-fold to two-fold coincidences,

efficiency test

$$\frac{R_3}{R_2} = \varepsilon_X \ , \tag{9.15}$$

fixes the unknown detection efficiency of the counter X.

9.5 Supplementary Information

Example 1

In the field of nuclear medicine certain radioisotopes are often needed for diagnosis and therapy. Short-lived radioisotopes, which are sometimes preferred in the field of radiotherapy, have to be produced in situ. For example, the ^{131}I isotope, frequently used in the past, is replaced more and more by the short-lived ^{99m}Tc isotope. This is because ^{131}I has a relatively long half-life of 8 days. The half-life of ^{99m}Tc is only 6 hours and allows therefore an ambulant diagnosis of the thyroid gland. ^{99m}Tc is obtained by β^- decay from ^{99}Mo. The branching fraction to the metastable level of ^{99m}Tc is about 86%. This metastable level then decays by γ emission (140 keV) into the ground state of ^{99}Tc. ^{99}Tc decays after that with a half-life of 214 000 years into the stable ^{99}Ru isotope. Because of the long half-life of the ground state ^{99}Tc this level can be considered as quasi-stable. Figure 9.8 shows the simplified decay-level scheme of the molybdenum–technetium generator. In Fig. 9.9 the setup of a 'radioisotope cow' for the production of ^{99m}Tc is sketched.

diagnosis of the thyroid gland

technetium generator

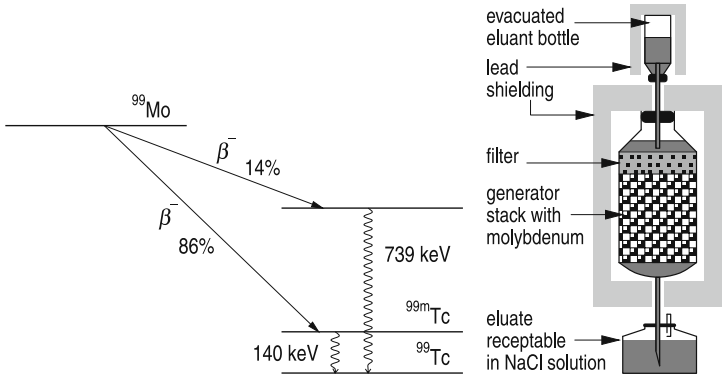


Figure 9.8
Simplified decay-level scheme of the molybdenum–technetium generator

Figure 9.9
The decay products of ^{99}Mo generated in the reactor are almost completely washed out by an appropriate eluant (elution substance, e.g. physiological saline). Then the technetium isotope is available as a radioactive tracer in the lower eluate container

"That's our radioisotope cow. We feed her with ^{99}Mo and then milk the short-lived ^{99m}Tc isotope for clinical applications." © by Claus Grupen

Example 2

'radioisotope cow'

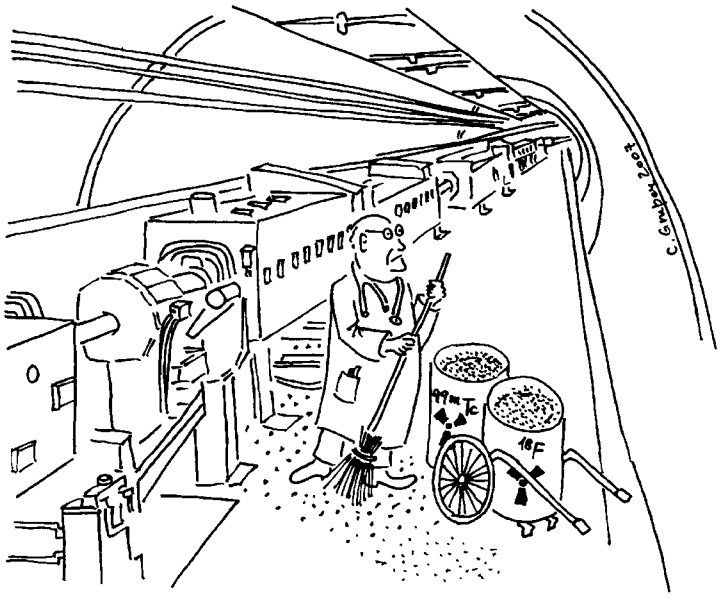
calibration radiation

Short-lived radioisotopes can also be 'milked' from long-lived isotopes. For example, the long-lived radioisotope ^{137}Cs (half-life 30.2 years) decays by β^- emission to the metastable state ^{137m}Ba with a probability of 94.4%. ^{137m}Ba is obtained after a short time with sufficient yield. This metastable state of barium decays with a half-life of 2.55 min by γ emission with an energy of 662 keV into the ground state ^{137}Ba. The γ rays from the decay of ^{137m}Ba are frequently used as calibration radiation. The nuclear excitation energy, however, can also be transferred directly onto an atomic-shell electron so that this source also emits monoenergetic conversion electrons. The K-conversion probability is 7.7% and leads to electron energies of

$$E_e = 662\,\text{keV} - B_\text{K} = 622\,\text{keV}\ , \tag{9.16}$$

where the binding energy in the K shell is calculated to be

$$B_\text{K} = Ry\,(Z-1)^2 = 39.66\,\text{keV}\quad . \tag{9.17}$$



"Radioisotopes for nuclear medicine are created as waste product at accelerators."
© by Claus Grupen

Example 3

radioisotope batteries

Radioisotope batteries provide energy over a long period of time. They are used if an energy supply is needed over a long time and if the charging of batteries is difficult or impossible, e.g. in space missions. Radioisotope batteries also are functional under extreme external conditions like very high or very low temperatures. The working principle of radioisotope batteries is the production of energy from radioactive decays. There are different methods to convert the decay energy into electrical energy, such as

conversion principle

- direct charge collection,
- indirect conversion via scintillation processes,
- thermoelectric energy generation.

For comparison, a normal lithium-ion battery, as it is used in many devices in household equipment, has an energy content of about 0.3 mW h. In contrast to that a radioisotope battery based on ^{210}Po has an energy content of 3 W h. Table 9.1 compiles some radioisotopes which are frequently used for radioisotope batteries.

conversion methods

In the direct conversion method, the charge produced by radioactive decay is collected on a spherical capacitor which surrounds the source symmetrically. In this way voltages $U = Q/C$ of 10 to 100 kV can be obtained. A 3-Ci ^{238}Pu source, which is typically used for pacemakers, produces a power of several mW. The patient

Table 9.1
Table of frequently used isotopes for radioisotope batteries

isotope	$\langle E \rangle$ [keV]	$T_{1/2}$ [yrs]	specific power [W/g]	type of radiation
^{63}Ni	17	100	0.0067	β^-
^{3}H	5.7	12.3	0.33	β^-
^{90}Sr/^{90}Y	200/930	29	0.98	β^-
^{210}Po	5300	0.38	140	α
^{238}Pu	5500	88	0.56	α
^{244}Cm	5810	18	2.8	α

receives a radiation-dose rate of 1 mSv/yr. From the point of view of radiation protection it is important to dispose of sources, e.g. after the death of the patient, in a controlled way.

RTG: radioisotope thermoelectric generator

Many radioisotope batteries are also used for NASA missions. In this case the electrical energy is produced via the thermoelectric effect (RTG: radioisotope thermoelectric generator). The α particles, which are emitted in ^{238}Pu decay, will produce heat in an absorber as they slow down and stop. The heat is then converted into electrical power. A typical ^{238}Pu battery has a weight of 3 kg and contains an activity of 100 kCi. This type of source provides a power of 300 W over a lifetime of more than 20 years. The launch of rockets carrying radioisotope thermoelectric generators of such high radioactivity presents a certain risk. If the launch of the rocket fails or if the rocket explodes in the atmosphere, there is a clear danger that the atmosphere might be polluted with the ^{238}Pu isotope. If the rocket were to explode at high altitudes in the atmosphere, a very large part of the planet Earth could be contaminated with ^{238}Pu.

betavoltaic microbatteries

A very different technique can be used in betavoltaic microbatteries, where in a silicon counter – using a similar method to photovoltaic devices – a continuous current can be produced. However, the conversion efficiency for such betavoltaic microbatteries is only about 1%. Higher yields can be obtained if the electrons from the beta decay are converted into light in a scintillation counter. This scintillation light is processed in a normal photoelectric cell whose photocurrent provides the energy supply.

Example 4

radiation protection at accelerators

Radiation protection at accelerators is an important issue. Prompt radiation escaping from the beam and the shielding structures, and residual activity in the beam lines, targets, and collimators has to be carefully investigated.[5]

The main reason for external radiation at properly shielded accelerators is induced radioactivity. It depends on

[5] The following information is essentially extracted from the written radiation-protection instructions given to CERN personnel by Dr. Marco Silari and Dr. Marilena Streit-Bianchi since January 2008.

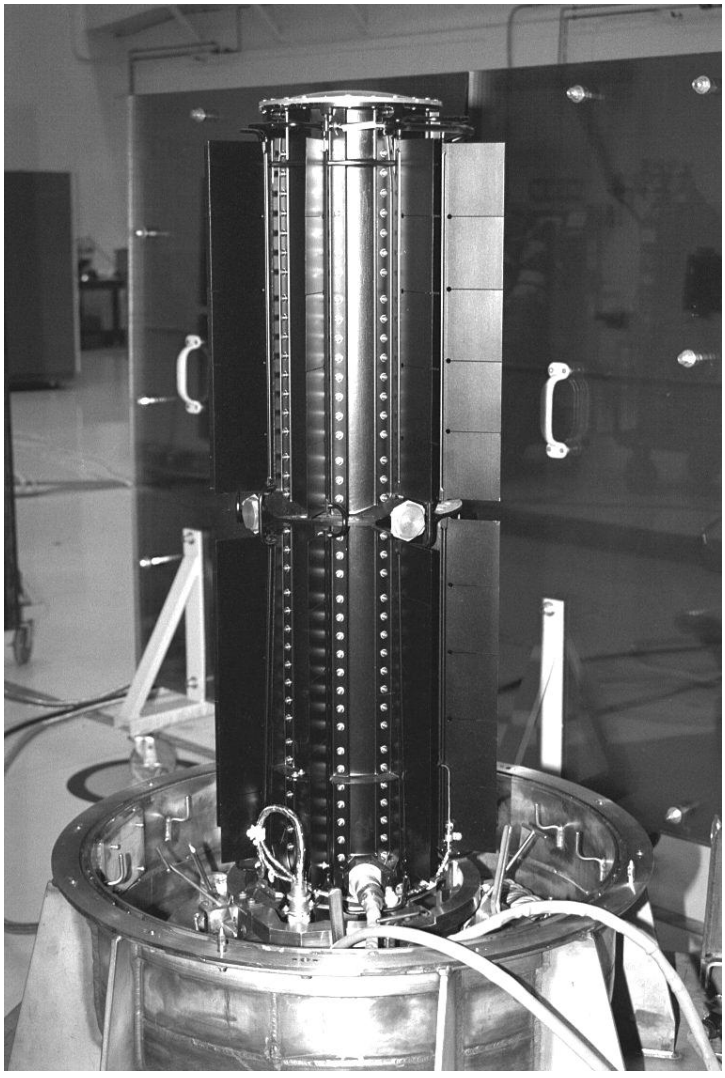
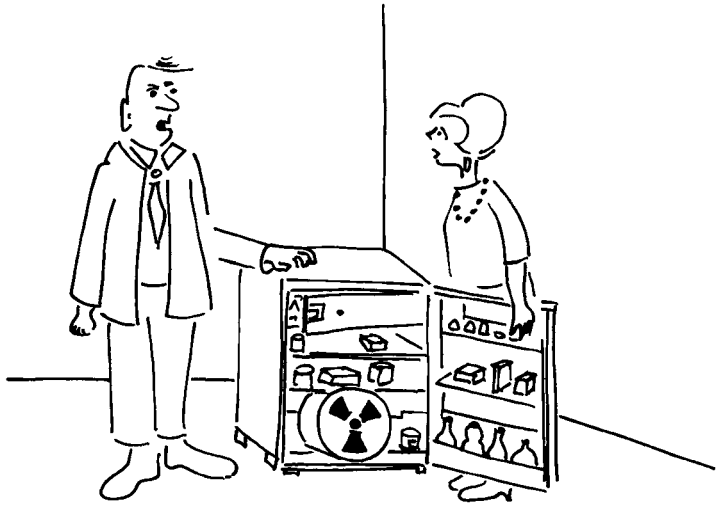


Figure 9.10
Radioisotope thermoelectric generator (RTG) on board of the Cassini probe to Saturn. This RTG contains three units of 12.2 kg pluotoniumoxide each, corresponding to a total of 29.1 kg metallic plutonium. The plutonium is a mixture of ^{238}Pu ($\approx$ 84%, half-life 87.7 years) and ^{239}Pu ($\approx$ 14%, half-life 24110 years) and some other isotopes. Its total activity is 14 PBq. The RTG produces a thermal power of 4400 W. Source: `http://en.wikipedia.org/wiki/Radioisotope_thermoelectric_generator` and `www.bernd-leitenberger.de/cassini_rtg.shtml`

* type and energy of the accelerated particles,
* beam intensity,
* materials irradiated by the primary beam,
* lifetime of the produced isotopes.

The radiological hazard may also result from inhalation and ingestion of radioactive material. Contamination risks have to be encountered when surfaces of activated components are dusty or have become corroded.



"The radioisotope battery not only supplies the refrigerator with electricity but at the same time provides sterility." © by Claus Grupen

The binding energy per nucleon in almost any material is on the order of 7 to 8 MeV. Therefore particle accelerators with beam energies of more than 10 MeV will produce some induced radioactivity. Neutrons may also activate materials if their energy is somewhat below this value. Proton beams are by a factor of about 100 more powerful to produce induced radioactivity compared to electron beams.

proton beams

electron beam

Many activation products are short-lived. In metallic components (e.g. magnets, targets, collimators, ...) medium- or even long-lived isotopes are also formed. Among those are, for example,

* the electron-capture emitter ^{54}Mn with a half-life of 312 days, which is produced in a (p, n) reaction from ^{54}Cr, and decays back into an excited state of ^{54}Cr, which emits γ rays of 835 keV.
* the isotope ^{57}Co ($T_{1/2} = 272$ days), produced in (p, γ) reactions from ^{56}Fe or (γ, p) reactions from ^{58}Ni, which decays by electron capture into excited states of ^{57}Fe ($E_{\gamma_1} = 122$ keV, $E_{\gamma_2} = 137$ keV, and $E_{\gamma_3} = 14.4$ keV). In the course of this transition also conversion electrons are emitted.
* the isotope ^{60}Co ($T_{1/2} = 5.27$ years, produced in (n, γ) reactions from ^{59}Co), which is a source of energetic and penetrating γ rays (1.17 MeV and 1.33 MeV) after a β decay into excited ^{60}Ni states.

Typical activation products in shielding concrete are the dominant β^+ emitter ^{152}Eu ($T_{1/2} = 13.5$ years) and the β^- emitter ^{154}Eu ($T_{1/2} = 8.8$ years). These isotopes are created either by (γ, n) or (n, γ) reactions from ^{153}Eu. ^{154}Eu decays into ^{154}Gd which is

a rich source of γ rays with energies of up to 1.27 MeV. ^{152}Eu decays either by electron capture into ^{152}Sm (with subsequent γ transitions) or by β^- decay into the long-lived α emitter ^{152}Gd ($T_{1/2} = 1.1 \times 10^{14}$ years, $E_\alpha = 2.2$ MeV). In iron-loaded concrete also ^{60}Co is produced.

Maximum values of specific activities obtained in activation processes on metallic components or shielding concrete typically range from a fraction of a Bq/g up to a few Bq/g.

The main components with high induced radioactivity are those elements which are directly hit by primary beams: collimators and beam dumps, and places where substantial beam losses can occur. Also the residual gas in the beam pipe can be activated.

Dose rates at collimators can reach rather high values, so that certain areas must be classified as protected areas, even if the accelerator is shut down. For the Large Hadron Collider at CERN typical dose rates like

* $\approx$ 100 Sv/h at the collimators inside the tunnel during normal operation,
* $\approx$ 5 mSv/h due to beam-gas interactions during operation, and
* a few μSv/h in accessible experimental areas outside the accelerator shielding

are expected.

Figure 9.11
Collimator used in the Intersecting Storage Ring (ISR) at CERN (photo credit: CERN photo archives)

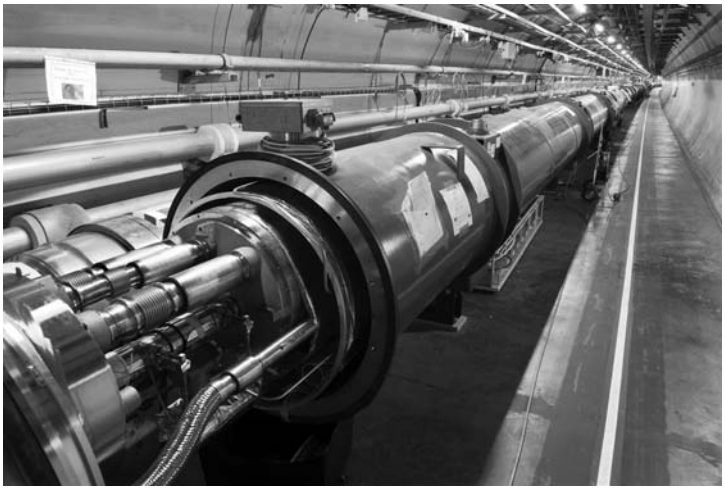


Figure 9.12
View into the ring of the Large Hadron Collider at CERN showing a section of superconducting dipole magnets for the bending of the proton beams. Photo credit: CERN photo archive

Summary

It is possible to provide a large variety of radiation sources for radiological applications. Linear and circular accelerators enable us to produce nearly all kinds of charged particles; even unstable elementary particles can be produced as secondary beams, or they can also be accelerated after they have been produced in interactions or decays. Photons, on the other hand, are usually generated in a rather indirect way. In X-ray tubes the bremsstrahlung process provides photons over a wide range of energies. With synchrotron-radiation sources photon beams of very high intensity up to the X-ray regime can be provided. The MeV energy range can be covered by γ rays from radioisotope decays. Like photons, also neutrons need to be produced indirectly in interactions. In this field radium–beryllium or americium–beryllium sources are of particular importance.
The highest energies available are supplied by the omnipresent cosmic radiation, which can be adequately used for calibrations or background measurements of radiation monitors. Hadron beams (protons and heavy ions (e.g. ^{12}C)) can be taken advantage of in the field of proton and heavy-ion therapy of tumors in radiology.

9.6 Problems

Problem 1

Neutrons can be produced by (α, n) reactions in ^{9}Be. α particles from ^{226}Ra decays have energies of typically 5 MeV. The average energy loss of α particles of this energy is about 1.37 MeV/(mg/cm^2). Work out the neutron yield on a thick beryllium target, if the (α, n) cross section is 3×10^{-25} cm^2.

Problem 2

A low-level counter for the measurement of the ^{14}C activity of some old wooden material is placed between two scintillation counters (area of 100 cm^2 each, distance 50 cm). Because of the short range of low-energy electrons ($E_{\max} = 0.157$ MeV) from β^- decay of ^{14}C, the wooden sample has to be arranged inside the low-level counter; e.g. in the form of $^{14}CO_2$ gas. A coincidence of the two scintillation counters, signaled by the passage of a cosmic-ray muon, is used as a veto for the output of the low-level counter. Work out the dead time created by cosmic-ray muons, if the signal width of the coincidence circuitry is 100 µs and if the low-level measurement extends over a period of 24 hours.

Problem 3

The neutron flux is – quite analogously to the photon flux – attenuated exponentially in matter:

$$I(x) = I_0 \, \mathrm{e}^{-\mu x} \ ,$$

where $\mu = N \, \sigma$, and N is the number of target atoms per cm^3 and σ is the absorption cross section. The dimension of μ is cm^{-1}. The mass absorption coefficient is defined in an analogous way as for photons,

$$\mu^*(\mathrm{cm}^2/\mathrm{g}) = \frac{\mu}{\rho} \ .$$

If neutrons interact in tissue, they mainly transfer their energy to protons. The cross section for 5-MeV neutrons in tissue is $\sigma \approx 1 \times 10^{-24} \, \mathrm{cm}^2$. Work out the equivalent dose for a neutron flux of $10^6/\mathrm{cm}^2$.

10 X Rays and X-Ray Regulations

"In the end, the public's health is at stake. An underexposed chest x-ray cannot reveal pneumonia, and an inaccurate radiation therapy treatment cannot stop the spread of cancer."

Charles W. Pickering

X-ray installations

The regulations on the handling of X rays are very similar to the regulations on standard radiation protection. The X-ray regulations in the European Union apply to those X-ray tubes and X-ray installations in which electrons are accelerated at least to 5 keV and in which they are limited to a maximum energy of 1 MeV. All installations in which electrons can be accelerated to energies beyond 1 MeV are subject to the regulations of standard radiation protection.

stray radiation

Devices and installations that produce unwanted radiation, like old-fashioned TV screens, where electrons are accelerated up to energies of something like 20 keV, do not require a license if a dose rate of 1 μSv/h at a distance of 10 cm from the surface is not exceeded or if they are approved by the competent authority by way of a design approval.

design approval

The X-ray regulations, of course, mainly concern X-ray tubes used for X-ray diagnosis and X-ray therapy on humans. It is desirable to obtain the best X-ray image available for a particular radiation exposure. At the same time one should try to reduce the radiation exposure by improving the X-ray detection system and image reconstruction without affecting the image quality. The radiation dose of the patient has to be documented. If the patient wants a copy of the documentation about the received X-ray doses, it has to be provided to the patient.

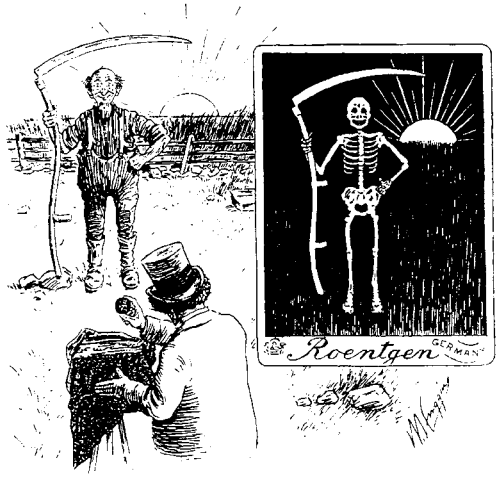
radiation exposures for patients

X-ray passport

Documents containing the information about the received X-ray doses have to be kept over a period of at least 30 years. Typical limits on the ambient-dose rate of X-ray tubes at a distance of 1 m from the focal point for a closed beam port would be 2.5 mSv/h for X-ray examinations and treatments using X-ray tubes with an accelerating voltage of up to 200 kV. The corresponding dose limit for X-ray tubes with voltages of more than 200 kV is 10 mSv/h.

In medical examinations with X rays those parts of the human body which are not examined must be shielded by a lead–rubber apron. A lead–rubber apron of 0.3 mm thickness reduces the intensity of 30-keV X rays already by a factor of 1000. For higher energies correspondingly lead–rubber aprons of higher thickness are

C. Grupen, *Introduction to Radiation Protection*,
Graduate Texts in Physics, DOI 10.1007/978-3-642-02586-0_10,



"Smile!" Cartoon from the Journal 'Life' 1896

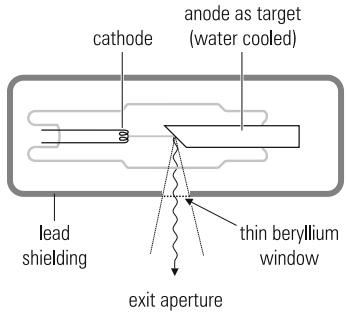


Figure 10.1
Sketch of an X-ray tube

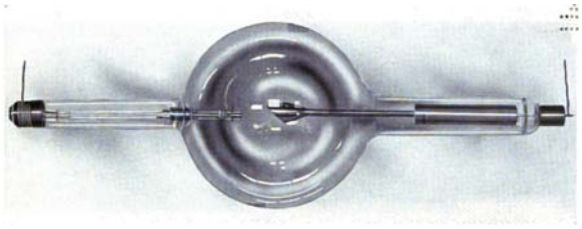


Figure 10.2
X-ray tube, from early 1900. The heated cathode is on the left, and the anode is on the right. The X rays are emitted downwards (The Coolidge X-ray tube: `http://commons.wikimedia.org/wiki/Image:Coolidge_xray_tube.jpg`; see also "The Cathode Ray Tube site": `http://members.chello.nl/~h.dijkstra19/page5.html`)

required. For example, a lead shield of 1 mm thickness reduces the intensity of 50-keV X rays by a factor of 1000.

Figure 10.1 sketches the operation principle of an X-ray tube. Electrons from the cathode are accelerated onto a target (frequently tungsten) and produce bremsstrahlung X rays when they are decelerated in the anode. This continuous X-ray spectrum has discrete lines superimposed on it, which are characteristic for the target material.

X-ray bremsstrahlung

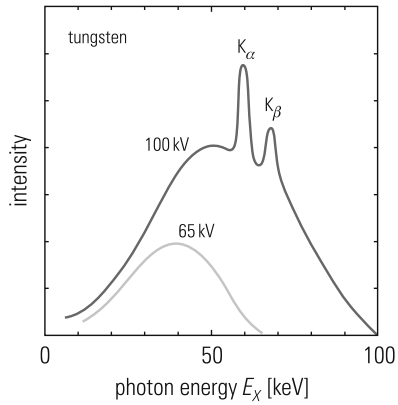


Figure 10.3
Energy spectra of an X-ray tube operated with voltages of 65 kV and 100 kV. The characteristic X rays of the tungsten anode are not excited for 65 kV

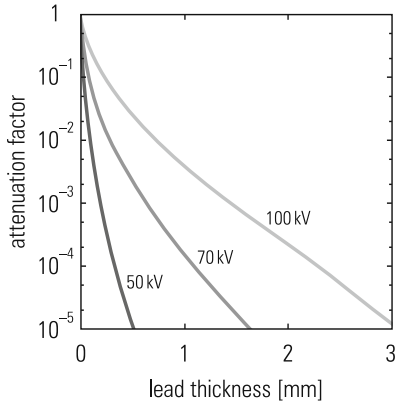


Figure 10.4
Attenuation factors of X rays in lead for three different operating voltages

characteristic X rays

Figure 10.3 shows the spectra of an X-ray tube with a tungsten anode for acceleration voltages of 65 kV and 100 kV. At the acceleration voltage of 65 kV the characteristic X-ray lines (K_α and K_β) of tungsten are not excited.[1]

shielding against X rays

Figure 10.4 shows the attenuation factors for X rays, produced by accelerating voltages of 50 kV, 70 kV, and 100 kV, and then filtered with 0.5 mm of aluminum. The attenuation curves are not perfect exponential functions because the X-ray spectra are continuous and the attenuation coefficients depend on the X-ray energy. In contrast to an attenuation factor of 1000 for monoenergetic X rays of 50 keV for a shielding of 1 mm of lead, the X rays generated by an

[1] The characteristic X rays are called K, L, M, ... lines. These lines are characterized by electron transitions from higher shells to lower ones. The K series provides short-wave X rays. K_α corresponds to a transition from the L to the K shell and K_β to a transition from the M to the K shell (see Fig. 3.12). Consequently, K_β X rays are more energetic than K_α rays.

X-ray tube operated with an accelerating voltage of 50 kV are attenuated by a factor of about 100 000 in a shielding of only 0.5 mm of lead. The reason for this is that the average energy of X rays for an accelerating voltage of 50 kV is only 30 keV and the absorption coefficient is a very steep function of the photon energy ($\sim 1/E_\gamma^{3.5}$).

documentation
storage of data

The radiation exposure of X-ray personnel has to be measured, documented, and stored for a period of 30 years. The definition of radiation areas follows that of the radiation-protection regulation exactly.[2] Just as in the field of radiation protection the radiation officer for X rays has to label the different areas correctly. Also it is the duty of the radiation officer to try to limit the exposure by X-ray examinations to a value as low as reasonably achievable. The radiation supervisor for X rays has to make sure that, for examinations on humans, a medical expert is consulted regarding the optimization of X-ray doses in the framework of patient dosimetry and quality control. The medical expert has to be a trained physicist or a scientist who is qualified also in the field of radiation protection.

radiation areas

patient dosimetry

It is highly desirable that the personnel operating the X-ray installations and also the medical doctors have the necessary qualifications and experience in the field of radiation protection with X rays.

qualified
X-ray-radiation personnel

10.1 Supplementary Information

A chest X-ray in the 1980s was usually performed at an anode voltage of $U = 80\,\mathrm{kV}$. In medicine you will find it difficult to get the information from the doctor about the X-ray exposure in terms of µGy or µSv. They normally give information in terms of the product of the exposure time and the electron current in the X-ray tube. Typical values are around $I\,t = 2\,\mathrm{mA\,s}$. Let us assume that the X-ray beam has a divergence of about 60° and the patient (area of the chest $A = 30 \times 30\,\mathrm{cm}^2$) is at a distance of 1 m from the X-ray focus.

Example 1
chest X-ray

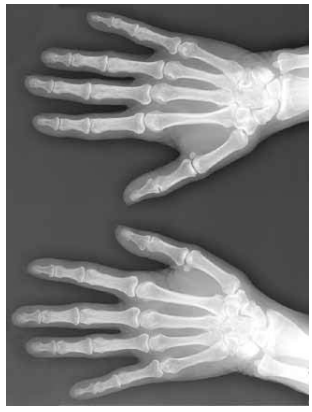


Figure 10.5
X-ray showing a frontal view of the hands (Source: RadiologyInfo™ www.radiologyinfo.org/)

[2] As a reminder: limits on the effective doses in the European Union

surveyed area	$1\,\mathrm{mSv/yr} < \dot{D} \leq 6\,\mathrm{mSv/yr}$
controlled area	$6\,\mathrm{mSv/yr} < \dot{D} \leq 20\,\mathrm{mSv/yr}$
excluded area	$\dot{D} > 3\,\mathrm{mSv/h}$
radiation-exposed persons category A	$6\,\mathrm{mSv/yr} < \dot{D} \leq 20\,\mathrm{mSv/yr}$
radiation-exposed persons category B	$1\,\mathrm{mSv/yr} < \dot{D} \leq 6\,\mathrm{mSv/yr}$
maximum occupational exposure over the whole life	$D \leq 400\,\mathrm{mSv}$

Figure 10.6
Siemens MAMMOMAT 1000 for analog mammography. This X-ray system is optimized for high-volume screening and regular mammographic views with high image quality at short exposure times

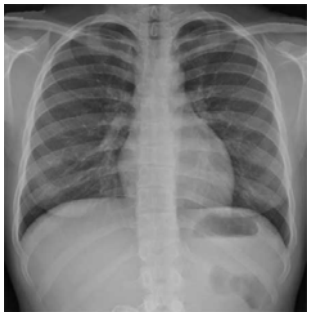


Figure 10.7
Normal posterior-to-anterior (PA) chest X-ray (source: RadiologyInfo^{TM} `www.radiologyinfo.org/`)

This information allows to estimate the X-ray exposure for a chest examination.

For an accelerating voltage of 80 kV the maximum photon energy is 80 keV and the average energy only 65 keV. A large fraction of the electron energy is lost as heat in the anode, so, the anode has to be cooled. Only a small fraction is emitted in the form X rays. This fraction can be described by

$$\eta_1 = 10^{-6} \times U\ Z\ ,$$

where U is the X-ray accelerating voltage in kV and Z the atomic number of the target. For $U = 80\,\mathrm{kV}$ and $Z = 74$ (tungsten) one obtains

$$\eta_1 = 6 \times 10^{-3}\ .$$

From the product $I\ t$ the number of electrons N_e hitting the anode can be worked out:

$$N_e = \frac{I\ t}{e} = \frac{2 \times 10^{-3}\,\mathrm{A\,s}}{1.602 \times 10^{-19}\,\mathrm{A\,s}} = 1.25 \times 10^{16}\ .$$

This yields a number of X-ray photons of

$$N_\gamma = \eta_1\ N_e = 7.4 \times 10^{13}\ .$$

Assuming that this fraction η_1 is completely emitted into the opening angle of 60°, and the distance to the patient is 1 m, and the illuminated area of the chest is $30 \times 30\,\mathrm{cm}^2$, the solid-angle fraction η_2 under which the X-ray tube 'sees' the patient can be worked out. One finds $\eta_2 = 8\%$. Therefore, the chest of the patient is hit by

$$N^*_\gamma = \eta_2\ N_\gamma = 5.9 \times 10^{12}$$

photons. Of these only

$$N^*_\gamma\ \left(1 - \mathrm{e}^{-\mu\,x}\right) = 2.7 \times 10^{12}$$

are absorbed in the patient, where $\mu = 0.03\,\mathrm{cm}^{-1}$ is the mass absorption coefficient and $x = 20\,\mathrm{cm}$ the assumed depth of the chest.

solid-angle fraction

absorption probability

For an average photon energy of 65 keV this corresponds to a deposited energy of

$$E = 1.74 \times 10^{17}\,\mathrm{eV} = 0.028\,\mathrm{J}\ .$$

partial-body dose

whole-body dose

This energy is deposited in a volume of $30 \times 30 \times 20\,\mathrm{cm}^3$ corresponding to a mass of 18 kg. This leads to a dose of 1.55 mGy. Converted to an effective whole-body dose (the tissue weighting factor for the chest is $w_i = 0.05$) leads to a dose of

$$H_{\text{eff}} = 0.078\,\text{mSv}$$

(the radiation weighting factor for X rays is 1, therefore, in this case, $1\,\text{Gy} = 1\,\text{Sv}$).

In daily medical work it is, of course, impossible to perform these calculations for each individual case. Therefore, usually, the accelerating voltage, the product of exposure time and X-ray-tube current, and the tissue equivalent dose measured at the typical distance of the patient are given. Modern X-ray tubes use 120 kV and 5.6 mA s for a frontal chest examination. The patient usually is positioned at a distance of 150 cm from the focus and a field of view of $35 \times 43\,\text{cm}^2$ is defined. Under these conditions a dose–area product of $0.4\,\text{Sv}\,\text{cm}^2$, i.e. 0.27 mSv chest dose, corresponding to a 13.5 µSv whole-body dose for the patient is obtained. If the chest of the patient is X-rayed from the side, a typical voltage of 110 kV is selected, with a product of exposure time and current of 11 mA s for the same size of the image area at the same distance. A typical area-dose figure under this condition is $0.6\,\text{Sv}\,\text{cm}^2$ corresponding to a whole-body dose of 35 µSv.

direct chest X-ray

dose–area product

lateral chest X-ray

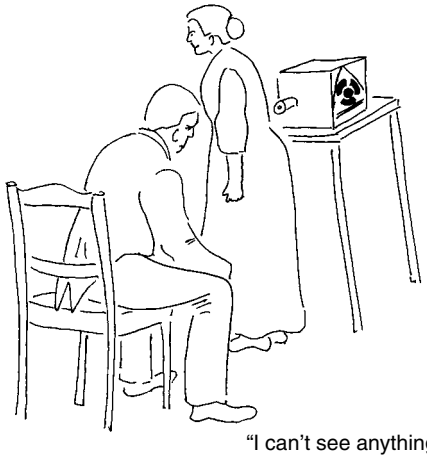
Example 2

Installations and equipments which produce unwanted X rays are also subject to the X-ray regulations. Some of these installations even require a license. This is true e.g. for electron microscopes or microwave klystrons.

electron microscope

microwave klystron

Even the old-fashioned TV sets using a vacuum tube for the TV screen generate soft X rays. In the European Union a limit is defined on the dose rate from such a device. This limit is given by the dose rate of 1 µSv/h to be measured at a distance of 10 cm from the



"I can't see anything!"

TV sets

surface of the device. Exposures from a standard color TV set fall significantly below this limit. Also one has to consider that soft X rays are easily absorbed in air so that for typical distances from the TV set values of about 1 nSv per hour are obtained. This may lead to an annual dose in the µSv range for typical exposure times when watching TV. It is interesting to note that a low amount of radiation exposure watching TV can be traced back partially to the radioisotopes ^{40}K and uranium and its decay products, which are present in the glass of the TV tube. Modern TV sets with plasma or LCD screens (Liquid Crystal Display) do not create any X rays at all.

stray radiation

Unwanted X rays are also produced by old-fashioned monitors for computers. For long working hours at a short distance from the computer display, higher annual doses might be expected. However, most displays are well shielded against low-energy X rays and also against low-frequency electromagnetic radiation and, therefore, cause only a very small radiation exposure. This only applies to the old-fashioned displays using a vacuum tube for the display. The radiation exposure using flat screens is, of course, zero.

low-radiation displays

Example 3

In the year 2001 high exposures of soldiers operating radar equipment were reported. Radar stations, of course, generate radar radiation which is a non-ionizing electromagnetic high-frequency radiation with frequencies in the gigahertz range. This microwave radiation can, of course – in a similar way as for microwave ovens or mobile phones – create a certain biological risk on humans ('electrosmog'[3]). This potential danger is not discussed here (see Chap. 15 on non-ionizing radiation), however, it has to be mentioned that the generation of radar rays is unavoidably accompanied by the creation of X rays. Radar equipment, therefore, produces X rays even though it is not its purpose to do so. In this case radar equipment is a typical generator of unwanted X rays.

microwave radiation

'electrosmog'

radar equipment

X rays in radar equipment are produced by the use of certain electronic components. Depending on the type of radar equipment klystrons or magnetrons are used to accelerate electrons with voltages of 20 to 100 kV. The deceleration of electrons creates X-ray bremsstrahlung in the energy range up to the maximum electron energy (i.e. up to a maximum of 20 keV or 100 keV, respectively).

klystron

magnetron

In various newspapers conflicting information was given about the received doses. If the radar equipment is properly shielded, typical dose rates between 0.06 and 0.07 mSv/h are expected. However, occasionally the radar equipment was not shielded properly or was even unshielded. In such a situation maximum values of 10 mSv/h

[3] a technical term constructed from the words 'electromagnetic', 'smoke', and 'fog' describing pollution by high-frequency non-ionizing electromagnetic radiation

have been measured which would correspond to an excluded area. Other estimations obtain exposures of up to 120 mSv per year: even in these cases, additional exposures by unshielded equipment during maintenance or calibration works were not considered.

radium dust

An additional risk originates from the use of radium-containing material for displays of the radar equipment. During maintenance and repairs the radium-containing consoles were cleaned and partially machined. In this way highly toxic, α-emitting radium dust was very likely released into the breathing air. It is estimated that 20 000 people have operated such radar devices over a period of 25 years. Out of these 2000 cases of cancer have been reported, of which 200 were fatal, as reported by 'Medical Wordwide'[4]. Using the standard risk factor for lethal cancer incidence of 0.5% for the given age group and period, one would have expected about 100 fatal cases. It appears that the exposures during the running of radar equipment significantly increased the cancer-incidence rate.

cancer incidence

Example 4

exposure due to X rays

An X-ray tube is operated in a laboratory at a voltage of 100 kV at 220 mA over a time of 600 seconds per week. A corridor passing at a distance of 5 m from the X-ray machine has to be shielded in such a way that it does not count as surveyed area. The X-ray machine is oriented towards this wall for 30% of the time. People passing through the corridor spend less than 25% of their time there.

workload mA min

The manufacturer of the X-ray tube has given an exposure of $K = 5\,\mathrm{mSv/(mA\,min)}$ at a distance of 1 m without shielding. A surveyed area is defined by a maximum dose limit of 1 mSv/yr for permanent residence.

The dose rate in front of the shielding wall at 5 m distance is

$$\begin{aligned}\dot{D} &= 5\,\frac{\mathrm{mSv}}{\mathrm{mA\,min}} \times 220\,\mathrm{mA} \times 10\,\frac{\mathrm{min}}{\mathrm{week}} \times 52\,\frac{\mathrm{weeks}}{\mathrm{year}} \\ &\quad \times 0.3 \times 0.25 \times \frac{1}{25} \\ &= 1716\,\frac{\mathrm{mSv}}{\mathrm{yr}}\ .\end{aligned}$$

To reach the level of 1 mSv/yr the radiation has to be attenuated by a factor of 1716.

Figure 10.8
Diamond detector as solid-state ionization chamber for the relative dosimetry of X rays and beta rays; measurement range 80 keV–20 MeV for photons, 4–20 MeV for electrons (PTW–Freiburg, Germany)

X-ray shielding

For an average X-ray energy of about 70 keV and a mass absorption coefficient μ of about $0.15/(\mathrm{g/cm^2})$ corresponding to $0.375/\mathrm{cm}$ for concrete ($\rho_{\mathrm{concrete}} = 2.5\,\mathrm{g/cm^2}$) the required thickness is

[4] I am grateful to Dipl. Phys. Helmut Kowalewsky for providing this information. Further details can be found at `www.m-ww.de/enzyklopaedie/strahlenmedizin/radarstrahlung.html`.

$$I = I_0\,\mathrm{e}^{-\mu x} = \frac{I_0}{1716}\ , \quad \mathrm{e}^{\mu x} = 1716\ ,$$
$$x = \frac{1}{\mu}\ln(1716) \approx 20\,\mathrm{cm}\ .$$

Summary

The X-ray regulations are independent of the regulation concerning the handling of radioactive sources. The X-ray regulations concern X-ray equipment and installations in which electrons are accelerated to a minimum energy of 5 keV and a maximum energy of 1 MeV. The limits given by the X-ray regulations are defined in a similar way to those of the radiation-protection regulations.

10.2 Problems

Problem 1

X-ray diffraction

X rays are used in the field of solid state physics for the determination of lattice constants (the spacing of atoms or ions in a regular crystal lattice). It is, however, only possible to resolve the lattice structures if they are larger than the wavelength of the electromagnetic radiation used. The question is, what kind of voltage has to be used for an X-ray tube, if structures on the order of magnitude of 0.5 Å need to be resolved?

To solve this problem one must consider that the maximum energy of photons ($h\nu$) is given by the accelerating voltage (eU). The frequency ν of the X-ray radiation is related to the wavelength λ via $\lambda\,\nu = c$ (h – Planck constant, c – velocity of light in vacuum).

Problem 2

The absorption coefficient for 50-keV X rays in aluminum is $\mu = 0.3\,(\mathrm{g/cm^2})^{-1}$. What is the required thickness of a wall made of aluminum to reduce the X rays by a factor of 10 000?

Problem 3

Let us assume that an X-ray tube operated with a voltage of 200 kV produces a dose rate of 0.7 mSv/h behind a concrete wall of thickness 20 cm. By an additional lead shielding on the outside of the concrete wall the dose rate should be reduced to a level of 1 µSv/h.

protective barrier against X rays

1. Work out the thickness of this additional lead shield.
2. What would have been the thickness of the shielding if one had wanted to reduce the dose rate to a level of 1 µSv/h by a lead shielding alone?

($\mu_{\mathrm{concrete}} = 0.3\,\mathrm{cm^{-1}}$ and $\mu_{\mathrm{lead}} = 11\,\mathrm{cm^{-1}}$ for an X-ray tube operated with an accelerating voltage of 200 kV.)

11 Environmental Radioactivity

"For a successful technology, reality must take precedence over public relations, for Nature cannot be fooled."

Richard Feynman

Natural radioactivity from the environment has three components:

- cosmic rays,
- terrestrial radiation,
- ingestion (eating, drinking, and breathing).

Cosmic rays from our Sun and our galaxy and terrestrial radiation from the Earth crust as well as incorporations of radioisotopes from the biosphere represent whole-body exposures. A special role is played by the inhalation of the radioactive noble gas radon which, in particular, represents an exposure for the lungs and the bronchi. In addition to these natural sources further exposures due to technical, scientific, and medical installations developed by modern society occur. The existence of natural radioactive substances, however, demonstrates that radioactivity and the development of life coexisted since the very earliest times on our planet.

coexistence of life and radioactivity

11.1 Cosmic Rays

Our Milky Way is the dominant source of high-energy cosmic rays. The low-energy particles predominantly originate from our Sun. Primary cosmic rays consist largely of protons ($\approx$ 85%) and helium nuclei ($\approx$ 12%). Only 3% of primary nuclei are heavier than helium. Nevertheless all elements of the periodic table occur as particles in primary cosmic rays (see also Fig. 9.6). Apart from these baryonic, strongly interacting components of cosmic rays, there are also electromagnetically interacting electrons and photons in primary cosmic rays as well as weakly interacting neutrinos. Even though the flux of neutrinos – particularly from the Sun – is extremely high, neutrinos play only a minor role in the field of radiation protection due to their low interaction probability.

cosmic rays

Primary cosmic rays interact with atoms or, more precisely, with atomic nuclei of the atmospheric gas and produce a large variety of elementary particles. Because of the high energies of primary

C. Grupen, *Introduction to Radiation Protection*,
Graduate Texts in Physics, DOI 10.1007/978-3-642-02586-0_11,

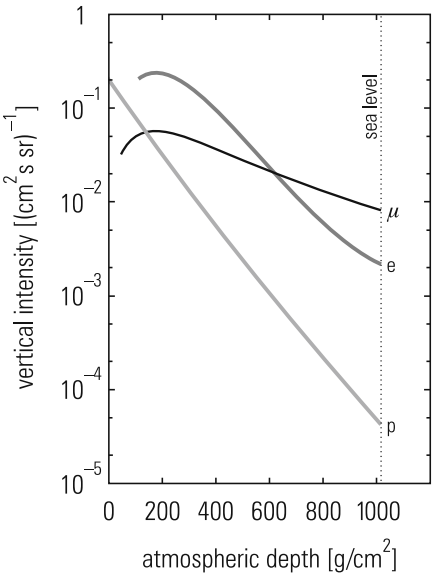


Figure 11.1
Altitude dependence of proton, electron, and muon fluxes in the atmosphere

muon component

proton component
electron component

cosmic rays, cascades of secondary and tertiary particles will develop in the atmosphere. The dominant component reaching the surface of the Earth consists of so-called muons. Muons are particles which have similar properties to electrons with the difference that they are about 200 times heavier and are unstable. The flux of these muons at sea level amounts to about one particle per cm^2 and minute through a horizontal area, see also Sect. 9.4. Figure 11.1 shows the proton, electron, and muon components as function of the atmospheric depth.

The secondary electron flux is relatively strongly attenuated in the atmosphere. However, muons are very penetrating particles, which can even be measured at great depths underground.

The exposure due to cosmic rays of a person in Western Europe and in the United States amounts to about 0.3 mSv/yr. It varies with geomagnetic latitude because the Earth's magnetic field shields charged primary cosmic rays to a certain extent. At the North Pole the radiation exposure is somewhat higher ($\approx$ 0.4 mSv/yr) while it is less at the equator ($\approx$ 0.2 mSv/yr). This is related to the different geomagnetic cutoff[1]. The exposure also varies strongly with

[1] Due to the magnetic dipole field of the Earth the cutoff momentum for primary cosmic radiation varies as $\cos^4 \lambda$, where λ is the geomagnetic latitude; the cutoff momentum is about 15 GeV/c at the equator (λ = 0 deg) and zero at the magnetic poles (λ = 90 deg). The atmospheric cutoff momentum due to the absorption of secondary cosmic rays in air amounts to about 2 GeV/c.

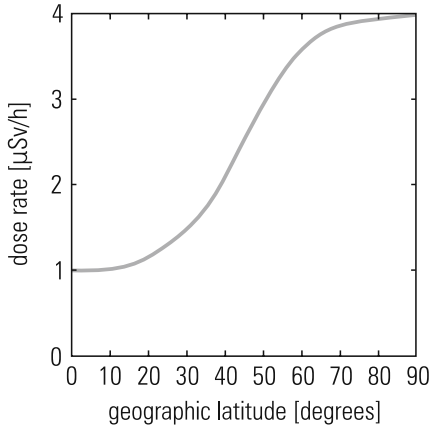


Figure 11.2
Average dose rate for flights at 10 km altitude as a function of the geographic latitude

altitude in the atmosphere since with increasing height the shielding effect of the air is reduced. For example, the exposure on Mt. Everest is 20 mSv/yr while it is about 1.2 mSv/yr in the Alps. At the altitudes of normal passenger flights (10–14 km), the dose rate is about 3 to 5 µSv per hour. For passengers in high-altitude research aircraft ($\approx$ 20 km altitude) the dose rate is about 20 µSv per hour, although this does depend on the geomagnetic latitude. Figure 11.2 shows the dependence of the radiation exposure on the geographic latitude at flight altitudes of around 10 km.

The radiation exposure of astronauts has been measured with dosimetry telescopes on board the Russian Space Station MIR and the International Space Station (ISS). The exposures vary typically between 300 and 500 µSv per day inside the station and are around 500 µSv for an eight-hour space-walk of an astronaut. About 70% of this dose originates from the galactic cosmic-ray component and 30% from protons trapped in the radiation belt.[2]

Paleomagnetic investigations on rocks have shown that reversals of the magnetic polarity of the Earth have occurred at irregular intervals, ranging from tens of thousands to many millions of years, with an average interval of approximately 250 000 years. In these periods of magnetic field reversal, in particular, when the field is zero, our planet was exposed to an increased radiation by cosmic rays by a factor of about 3 to 5. Even so, no particular negative effects on the development of life on our planet have been observed at these times.

The dependence of the radiation exposure as a function of height in the atmosphere for average geographic latitudes is shown in Fig. 11.3.

[2] I am grateful to S. Burmeister, University of Kiel, for providing this information.

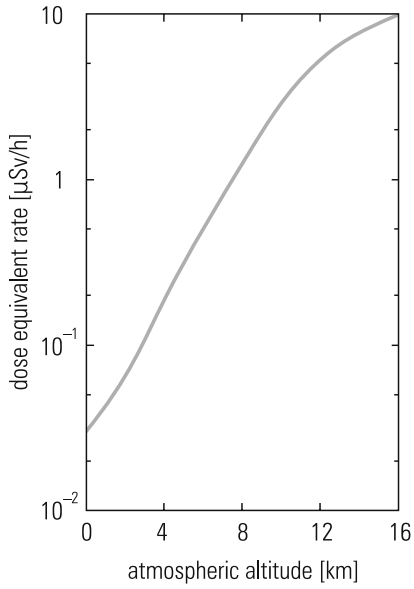
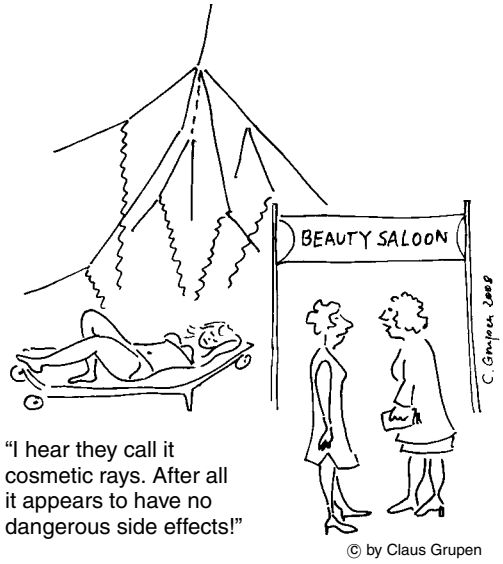


Figure 11.3
Variation of the dose rate with altitude in the atmosphere for average geographic latitudes (≈ 50 degrees)



11.2 Terrestrial Radiation

The soil of the planet Earth contains substances which are naturally radioactive and provide natural radiation exposures. The most important radioactive elements which occur in the soil and in rocks are the long-lived primordial isotopes potassium (^{40}K), radium (^{226}Ra),

natural radioactivity

and thorium (^{232}Th). The radioisotopes ^{40}K, ^{226}Ra, and ^{232}Th also occur in many building materials (such as concrete and bricks). Naturally, the radiation exposure varies with the environment depending on the concentration of radioisotopes in the ground. An average exposure for Europe and the United States is about 0.5 mSv/yr. However, this dose may exhibit strong regional variations. For example, for the area around the Black Forest in Germany dose rates up to 18 mSv/yr have been recorded. The highest exposures on Earth occur in Kerala on the western coast of India with 26 mSv/yr, in Brazil on the Atlantic coast with up to 120 mSv/yr, and in Ramsar in Iran with the record value of 450 mSv/yr. These exposures can be predominantly traced back to high thorium concentrations (up to 10%) in the ground.[3]

radon and evolution

Our natural environment therefore contains a large number of radioactive substances. Large populations have lived already over many generations in regions where the exposure is a factor of 10 higher compared to the average value without any visible disadvantages. The natural radioactivity from the environment was also substantially higher in early geological times (by a factor of 3 to 5 compared to today). It is assumed that such relatively high radiation doses were necessary to initiate the development of life on our planet. In the same way it might be suggested that the radiation from the natural environment was essential to speed up evolution and to create the biodiversity we observe today.

natural plutonium

It is interesting to note that plutonium also occurs as a natural isotope in the Earth's crust. ^{239}Pu with a half-life of 24 300 years is prominently produced by cosmic rays via the reaction

$$n + {}^{238}\mathrm{U} \longrightarrow {}^{239}\mathrm{U} + \gamma \tag{11.1}$$

with two subsequent β^- decays via ^{239}Np:

$$^{239}\mathrm{U} \xrightarrow{\beta^-} {}^{239}\mathrm{Np} \xrightarrow{\beta^-} {}^{239}\mathrm{Pu}\ . \tag{11.2}$$

11.3 Incorporation of Radioisotopes

natural radioisotopes in air, in drinking water, and in food

The most important natural isotopes which occur in air, in drinking water, and in food, are the isotopes of hydrogen (tritium: ^{3}H), carbon (^{14}C), potassium (^{40}K), polonium (^{210}Po), radon (^{222}Rn), radium

[3] The mineral apatite occurring in the Brazilian state Minas Gerais contains large quantities of uranium and thorium in some places so that plants grown in these regions, which take up these radioactive isotopes from the soil, will produce an autoradiographic image if placed on a film.

(^{226}Ra), and uranium (^{238}U). These natural radioactive elements accumulate in the human body after being taken in with food, water, and air so that humans themselves become radioactive. The natural radioactivity of the human body is about 9000 Bq and originates predominantly from ^{40}K and ^{14}C. From this incorporation one can work out the average per capita exposure by incorporated natural radioactive substances to be about 0.4 mSv/yr. In addition to this, there is an exposure of the lungs due to the inhalation of the radioactive gas radon present in air. Figure 11.5 shows the production of ^{222}Rn in the uranium–radium chain and the release of this gas through cracks in rocks or ground into air.

natural radioactivity of humans

radiation exposure of the lungs

Figure 11.4
Low-level monitor system with dust sampler for the measurement of low beta activities, e.g. in radon-filter measurements (model LLM 500, mab Strahlenmesstechnik)

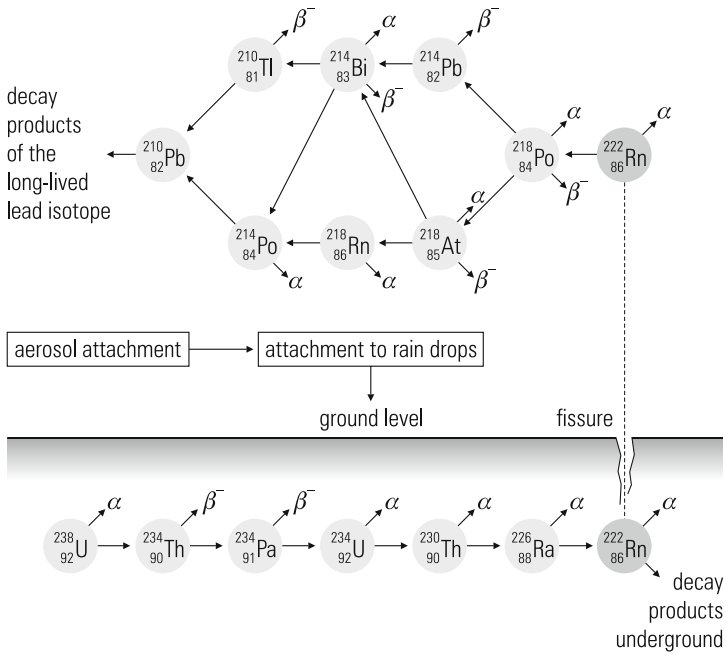


Figure 11.5
Production and release of ^{222}Rn

"10 000 nuclei decay per second in our bodies, and we worry about the price of petrol!"

radon inhalation

If the lung dose created by radon inhalation is converted into an equivalent whole-body dose, the result is an exposure of 1.1 mSv/yr, from the inhalation of this particular radon isotope alone.[4] However, it has not been demonstrated that low radon concentrations ($< 200\,\mathrm{Bq/m^3}$) might induce cancer. The total per capita exposure due to incorporations of natural radioactive substances from the environment amounts to approximately 1.5 mSv/yr.

In the same way as terrestrial radiation varies, also the radiation exposure by incorporation of radioisotopes from the biosphere is subject to substantial local variations. In badly ventilated houses the radon exposure alone can be a factor of 5 higher than the average. In poorly ventilated mines the radon exposure can even be higher than the average by factor of 100.[5]

radon exposure

In Table 11.1 the average per capita radiation exposures from natural sources are compiled. The average natural total radiation exposure amounts to about 2.3 mSv per year.

Figure 11.6 shows the fractions of radiation exposures by the different components from the environment in a graphical form.

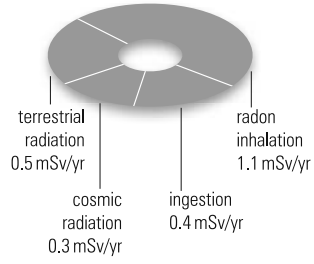


Figure 11.6
Breakdown of the exposures from the natural environment (2.3 mSv/yr)

[4] Snow samples e.g. from Mont Blanc exhibit a radioactivity which is 80 times higher compared to the snow on other mountains in the Alps. In contrast to other mountains in the Alps the granite rocks on Mt. Blanc have so many cracks that the noble gas radon can easily escape from the rocks. However, the radon concentration in the snow on Mt. Blanc is still quite harmless.

[5] In old Egyptian tombs and in pyramids radon concentrations of 6000 $\mathrm{Bq/m^3}$ have been found.

Table 11.1
Radioactive exposures of humans from natural sources

source	average exposure per year	highest values
cosmic radiation	≈ 0.3 mSv	10 mSv (at high altitudes)
terrestrial radiation	≈ 0.5 mSv	450 mSv (Ramsar, Iran)
incorporation of radioisotopes	≈ 1.5 mSv	5 mSv (extreme diet[6])

Humans cannot perceive ionizing radiation directly; and fortunately low-level radiation is mostly harmless. Nature possibly never saw the needs to equip humans with dedicated sensual organs for ionizing radiation, because such radiation does not present a hazard, and therefore does not require a warning.

11.4 Radiation Exposure by Technical Installations

The main usages of radioactive substances today are in scientific and technical installations. The dominant source for the per capita exposures, however, is the application of X, β, and γ rays in medicine in diagnostics and therapy. Some examples are given for illustration. Taking an X-ray image of the lungs gives a whole-body dose of about 0.1 mSv. An angiography of the arteries or an X-ray of a kidney represent an exposure of 10 mSv. In contrast, an X-ray image of the teeth leads to a dose of only 0.01 mSv.

X-ray diagnosis and therapy

therapy in nuclear medicine

The exposures by examination in nuclear medicine can, however, be quite substantial. The imaging of the thyroid gland with the iodine isotope ^{131}I leads to an equivalent whole-body dose of 33 mSv. In the past the liver was imaged with the gold isotope ^{198}Au corresponding to an equivalent whole-body dose of 3.6 mSv. These isotopes have now been mainly replaced by the short-lived ^{99m}Tc (a metastable state of ^{99}Tc). For example, myocardial perfusion scintigraphy nowadays frequently employs ^{99m}Tc. For a stress or resting examination of the heart an activity of 1 GBq is used which leads to an exposure of the patient of 7.6 mSv. Examinations using positron-emission tomography usually employ fluorine-18 de-

myocardial perfusion scintigraphy

positron-emission tomography

[6] This would include above-average concentration of radioisotopes in foodstuff, e.g. plants grown on soil with high levels of natural radioisotopes. In this context, even not counting as natural exposure, the high-level concentration of radioisotopes in mushrooms, venison, or reindeer steak after the Chernobyl accident has to be considered.

oxyglucose (^{18}F, half-life 110 minutes). For oncological investigations 400 MBq are usually injected corresponding to an exposure for patients of 7.6 mSv. ^{18}F is produced from ^{18}O by proton bombardment according to

$$p + {}^{18}\mathrm{O} \longrightarrow {}^{18}\mathrm{F} + n \ , \tag{11.3}$$

where the oxygen isotope is available in the form of $H_2{}^{18}O$. Since the half-life of the fluorine isotope is relatively long, it can be distributed locally after production at an accelerator. Short-lived positron emitters, such as ^{11}C ($T_{1/2} = 20$ min), ^{13}N ($T_{1/2} = 10$ min), ^{15}O ($T_{1/2} = 2$ min), ^{82}Rb ($T_{1/2} = 1.25$ min) can only be produced directly in hospitals which have a cyclotron in house.[7]

production of radioisotopes

In modern clinical practical work short-lived radioisotopes are predominantly used for diagnosis (e.g. ^{99m}Tc) to reduce the radiation exposure for the patient. Such radioisotopes can be produced e.g. by neutron bombardment. For example, ^{99m}Tc is obtained from neutron-activated molybdenum (see Chap. 9 on radiation sources). In the past short-lived isotopes were also created in the hospital with the help of so-called 'radioisotope cows'. For example, the short-lived γ-ray emitter ^{137m}Ba can be produced in the laboratory by milking the long-lived 'cow' ^{137}Cs (see Fig. 3.3, p. 22). Such a generator system is still used for calibration purposes in laboratories, but it is no longer used in nuclear medicine.[7]

radioisotope cow

surgery by robots

In many fields of diagnostics and surgery the experienced hand of the surgeon is replaced by the tremor-free movements of a robot. Miniature tools at the end of long catheters inserted into the femoral vein in the patient's thigh are frequently used for heart surgery. The tools can be controlled by robots, and this technique leads to better results in many cases. Such robots also spare the physicians many tiring hours of standing at an operation table wearing lead vests to limit the exposure to X rays or γ rays.

tumor therapy

It is obvious that the highest radiation exposures occur in the treatment of cancer. Here there is a compromise to be drawn between the expected therapeutical success and the radiation risk. In tumor therapy, maximum doses for single parts of the human body (i.e. not for the whole body) are extremely high: up to 100 Sv (!). A whole-body dose over a short period with such a dose would certainly lead to death from radiation sickness, since the lethal dose for the whole body amounts to about 4 Sv. A lethal dose is defined such that 50% of the exposed humans will die within 30 days without medical treatment. Cancer patients are able to survive a dose

[7] I am grateful to Dr. med. Oliver Lindner, physician at the heart and diabetes center of the university hospital of the Ruhr University Bochum, Germany, for this information.

of 100 Sv only because this dose is applied highly locally and, in general, only one organ is concerned. Furthermore, this high dose is applied in small sub-doses of several sievert with intervals thereby distributing the exposure over a number of days.

fractionated irradiation

per capita exposure

The average per capita exposure in Europe is currently somewhere around 1.9 mSv/yr from X-ray diagnosis and about 0.05 mSv/yr from other methods in nuclear medicine. This last average value is somewhat problematic since it relates to some very strong exposures received only by very few people. Other exposures from technical installations are almost negligible compared to the exposures due to medical diagnosis and treatment. In the 1960s, however, relatively large radiation exposures were observed from radioactive fallout after nuclear-weapons tests in the atmosphere, but these exposures have now faded away.

radioactive fallout

A large variety of nuclear isotopes is used in technical installations. For example, the isotopes tritium (^{3}H) and promethium (^{147}Pm) are used in phosphor screens, the α-ray emitter americium (^{241}Am) occurs in fire alarms of older types and plutonium (^{238}Pu), actinium (^{227}Ac), strontium (^{90}Sr), or cobalt (^{60}Co) are used in radioisotope batteries. In these batteries (see Chap. 9 on radiation sources) it is mainly the heat produced due to the absorption of radiation that is converted into electrical energy with the help of thermocouplers. Because of the long half-lives of certain radioisotopes ($T_{1/2}(^{238}\text{Pu}) = 88$ yrs, $T_{1/2}(^{227}\text{Ac}) = 22$ yrs, $T_{1/2}(^{90}\text{Sr}) = 28$ yrs) these radioisotope batteries represent maintenance-free long-lived energy sources. Therefore, they are ideally suited for long-term space missions.

phosphor screens

fire alarms containing radioactive substances

radioisotope batteries

Radioactive substances are also used as anti-static materials and filling-level indicators. Phosphate fertilizers contain not only ^{40}K, but also other natural radioactive substances like uranium and thorium including their decay products. Up to the 1950s uranium compounds were also used for the production of pigments (with the colors yellow, red, brown, and black), in particular, for the glass and ceramic industry. The production of such 'radiating colors' is no longer allowed.

anti-static materials

filling-level indicators

phosphate fertilizers

The exposure from smoothly running nuclear power plants is very low (< 0.01 mSv/yr).[8] In this context it has to be mentioned that coal plants – in addition to the CO_2 emission, which presents a

nuclear power plants

[8] It has, however, to be mentioned that in the vicinity of recycling plants elevated radiation levels have been measured. For example, close to the recycling plant in La Hague, France, ground contaminations of 100 Bq/m^2 of ^{137}Cs and 10 Bq/m^2 of ^{60}Co have been found. In the exhaust air of this plant ^{85}Kr activity concentrations of several 1000 Bq/m^3 have been observed.

Filling-level measurement

A test tube partially filled with lead shot is irradiated by γ rays from the radioisotope ^{226}Ra. It is important to keep the γ-ray source and the scintillation counter (see figure) at the same level. The system of source and detector is now moved parallel to the axis of the test tube and the count rate is monitored in the detector as a function of height. When the source/detector system is lowered and reaches the level of the lead shot, the count rate will decrease drastically and will stay at a constant low level for larger depths. The count-rate dependence on the height allows to read accurately the filling level of the lead shot in the test tube.

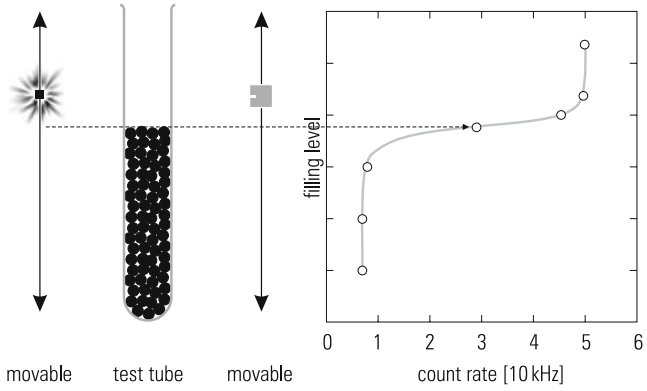


Figure 11.8
Filling-level measurement using a ^{226}Ra source

hazard for the Earth's climate – release more radioactive substances into the environment than nuclear power plants in normal operation conditions. The normal level of low-level radiation which is released by coal plants would provoke an outcry in the population if comparable quantities of radioactive substances were emitted by nuclear power plants. For example, in the United States about 800 tons of uranium are annually released into the air by coal plants. The use of effective filters, however, can reduce the emission of radioactive substances from coal plants quite substantially.

In Europe, a typical exposure of $\leq$ 0.01 mSv/yr is produced due to the use of radioactive substances and installations generating ionizing radiation in science and research.

An exception, of course, is the radiation exposure in 1986 after the reactor accident in Chernobyl in the former Soviet Union. In the year after the reactor catastrophe the average exposure in Western Europe may have been approximately 0.5 mSv. This exposure was mainly caused by the release of the radioactive isotopes ^{131}I, ^{137}Cs, ^{134}Cs, and ^{90}Sr, which entered into the food chain. The 50-years commitment dose of the reactor accident in Chernobyl can be esti-

Figure 11.7
Xenon/krypton ionization chambers for measuring the thickness and density of materials using radiation sources (VacuTec Meßtechnik GmbH)

Chernobyl accident

Gamma backscatter measurements

Filling-level measurements, i.e. absorption measurements, give information about the filling level and the absorber material. This type of measurement can only be done in the laboratory under well-controlled conditions. For applications in geology, e.g. in the investigation of boreholes, one is frequently interested in the chemical composition of the walls of the borehole to search for certain materials like oil, minerals, or heavy metals. The gamma backscatter method, as sketched in Fig. 11.9, is well-suited to this purpose. A γ-ray source (e.g. ^{226}Ra) emits γ rays of energy 186 keV isotropically. A detector records γ rays backscattered from the surrounding material. The detector itself is shielded from direct radiation from the source by a lead plate. The effectiveness of backscattering depends on the density and atomic number of the surrounding material. In Fig. 11.9, as well as a diagram of the apparatus, the count rate as a function of height in the borehole is plotted. The profile of the backscatter rate from layers of lead, water, and air clearly shows element-specific differences. The intensity of the backscatter rate permits to infer information on the density and the chemical composition of the surrounding layers. Measurements in a laboratory on air, water, aluminum, iron, and lead exhibit a clear correlation between the backscatter intensity R and the product of density ρ and the atomic number Z. Over a wide range, the backscatter rates can be approximated well by the empirical function $R \sim (\rho\, Z)^{0.2}$ (see Fig. 11.10).

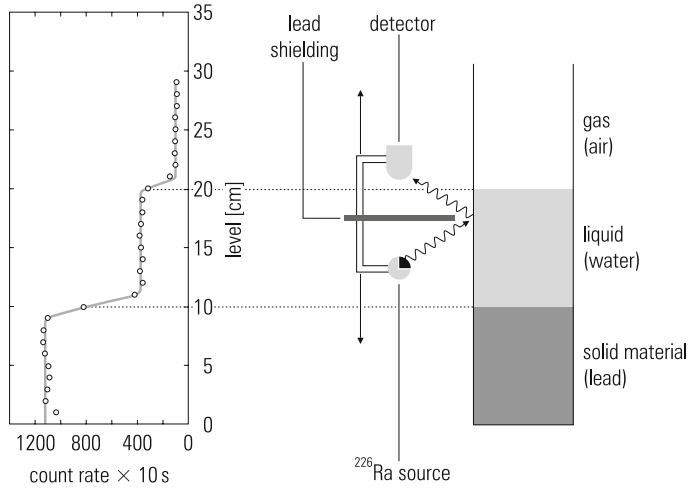


Figure 11.9
Dependence of the gamma backscatter rate on the product of density ρ and atomic number Z of the material

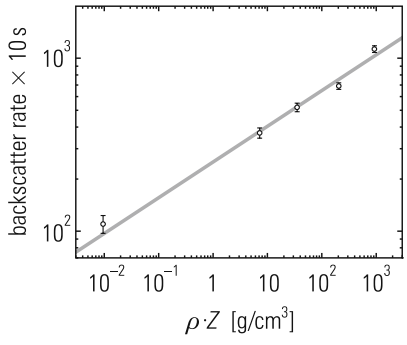


Figure 11.10
Backscatter rate in its material dependence for the gamma backscatter method

Measurement of the radioactivity of cigarette ash

The radioactivity of cigarette ash can be measured with a sensitive scintillation counter shielded against environmental radiation. The scintillation counter is fitted tightly into a thick-walled lead container, where it is exposed to radiation from cigarette ash (see figure). The measured radioactivity of the cigarette ash can be attributed to the following processes:

- Like all soil, the soil in which the tobacco plants are grown is radioactive. Normal soil contains the radioisotopes ^{226}Ra, ^{232}Th, and ^{40}K with total concentration of approximately 500 Bq/kg. Tobacco plants are frequently fertilized with phosphates which are rich in ^{238}U and ^{226}Ra. These radioisotopes from the soil and the phosphate fertilizer enter the tobacco plants via its roots. In the radium decay chain, the radioactive noble gas ^{222}Rn occurs as well as the relatively long-lived radioisotopes ^{210}Pb and ^{210}Po. These radioactive isotopes are partially (via the gaseous intermediate product ^{222}Rn) transferred into the air and may deposit themselves on the tobacco leaves. The content of radioisotopes in tobacco – depending on where it is grown and how it is fertilized – is subject to large fluctuations.
- In the process of smoking, a large number of aerosols is produced to which the decay products of the natural ^{222}Rn isotope can easily attach (the radioactivity concentration of normal air amounts to approximately 30 to 50 Bq/m^3 of ^{222}Rn). Aerosols with attached radon daughters are also found in the cigarette ash, as previously exhaled air is later inhaled through the cigarette. Again mainly the radioisotopes ^{210}Po and ^{210}Pb are found in the ash. This can be confirmed by an accurate gamma-ray spectroscopy of the cigarette ash. These isotopes are also found in the lungs and the bronchial tubes of smokers. The lead isotope ^{210}Pb, with a half-life of 22 years, continuously produces the dangerous alpha-ray emitter ^{210}Po via β^- decay. Therefore, the risk of developing lung cancer is relatively high even for people who have given up smoking. Some experts believe that the majority of cases of lung and bronchial cancer can be traced back to radioactivity and only to a lesser extent to tar and nicotine in the tobacco leaves.

A detailed analysis using gamma-ray spectroscopy with high-purity germanium counters shows that apart from the radioisotopes ^{238}U, ^{226}Ra, ^{232}Th, ^{210}Pb, and ^{210}Po, tobacco ash also contains ^{40}K. The specific radioactivity in tobacco and in tobacco ash varies widely depending on the choice of tobacco. As a typical result for the specific activity of cigarette ash, a value of 2000 Bq/kg can be given.

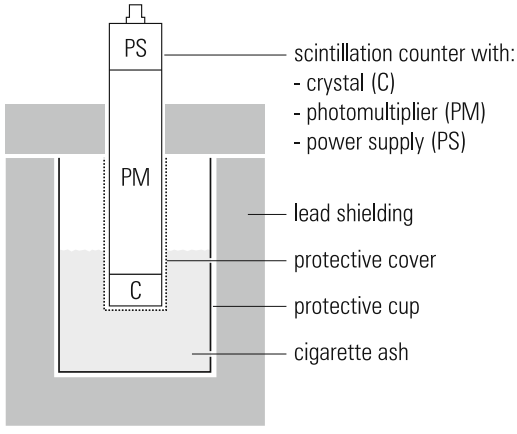


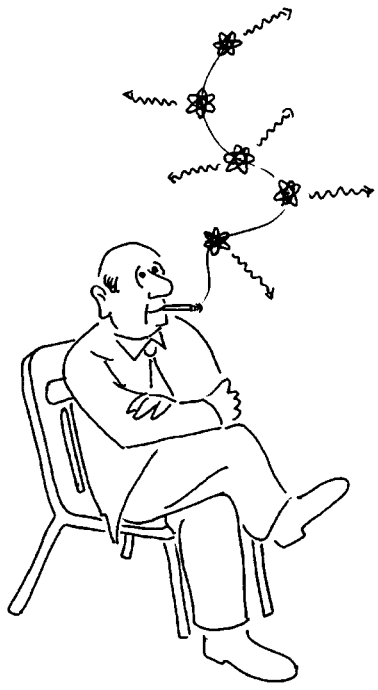
Figure 11.11
Measurement of the absolute activity of cigarette ash with a shielded scintillation counter

mated for people living in Western Europe to be on the order of $\leq$ 4 mSv.

smoking

Finally, in this chapter the aspect of exposures due to smoking shall be discussed. Radioactive isotopes like lead (^{210}Pb) enter the tobacco plant via its root from the soil, also radon (^{222}Rn) will enter the tobacco leaves from the air. This leads to relatively high exposures of the bronchi and the lungs. The isotopes ^{210}Pb and ^{222}Rn decay after a number of radioactive transmutations into the radioisotope polonium (^{210}Po) ending eventually in stable lead (^{206}Pb). The isotopes mentioned and their decay products have a certain affinity to attach to aerosols produced by the smoker. These contaminated aerosols are inhaled and some of them will stick on the surface of the lung of a smoker which is usually covered with traces of tar. As a consequence only part of the contaminated aerosols is exhaled. Values in the literature on the radiation exposure of bronchi and lungs of smokers differ quite substantially. They span a range of 0.05 up to several Sv for the bronchi in 25 years of smoking (1 packet of cigarettes per day). If this dose is translated into an equivalent whole-body dose, this will lead to an additional exposure

radioactive aerosols



"I do like to smoke!"

for a smoker on the order of 1 mSv/yr.[9] The polonium content of tobacco varies considerably so that the values given represent only a very rough estimation. There is, however, agreement among physicians that the additional radioactive exposure of the lungs for smokers eventually may lead to cancer of the bronchi and the lungs. This effect has been clearly established for smokers who work in uranium mines. For these miners a substantially elevated risk for lung cancer compared to non-smokers has been demonstrated. Also cancer of the throat is suspected to be caused by smoking. Obviously the combined effect of tar, nicotine, and exposure to radiation has quite negative consequences. Some scientists comment that smokers manage to combine the negative effects of chemical substances in the cigarette with the cancer-inducing properties of the ionizing radiation of isotopes in the tobacco leaves.

polonium content of tobacco

cancer of the bronchi and the lungs

The total average radiation exposure due to the technical environment is compiled in Table 11.2.

medicine, X-ray diagnostics[10]	$\approx$	1.9 mSv
nuclear medicine	$\approx$	0.05 mSv
science and research	$\leq$	0.01 mSv
occupational exposure	$\approx$	0.03 mSv
reactor accident in Chernobyl (only 1986)[11]	$\approx$	0.5 mSv
sum (without Chernobyl)	$\approx$	2.0 mSv

Table 11.2
Annual per capita radiation exposure (whole-body radiation, smoking not considered) due to radiation from technical installations

Figure 11.12 shows the different contributions of radiation exposure due to the technical environment in graphical form. Occupa-

total exposures

[9] In the literature one finds numbers for the equivalent dose between 5 nSv per cigarette and 40 µSv per cigarette. Some authors quote exposures for strong smokers of 40–400 mSv per year. Such high values can obviously be obtained if the tobacco plants are grown on soil with high concentrations of ^{210}Pb and ^{210}Po, for example, in certain areas of Brazil and Rhodesia (now Zimbabwe).

[10] The radiation exposure due to medical examinations varies quite considerably by country. It has to be noted that this exposure has increased over the last few decades. Some experts complain that too many X-ray images are taken. Several thousand tumors in patients are created annually by unnecessary X-ray examinations. Mammography screening with X rays for women of all age groups and frequent whole-body computer tomography as early detection method for cancer are also highly questionable.

[11] The number given is a rough estimate for the population in Western Europe. The Chernobyl plume was distributed over the whole northern hemisphere and could also be detected in the United States and in Japan. However, the exposures there were very low.

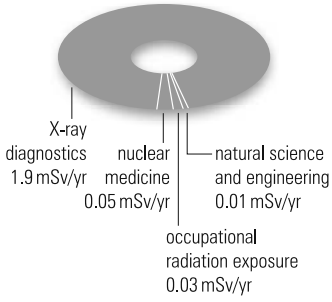


Figure 11.12
Different contributions to radiation exposure due to technical installations

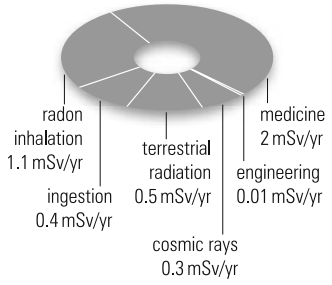


Figure 11.13
Different contributions to the total average per capita radiation exposure

Table 11.3
Typical dose rates or doses for some exposures (whole-body doses)

type of exposure	dose/dose rate
X-ray exposure of teeth	10 µSv
air flight Frankfurt – New York	30 µSv
X-ray examination of the chest	100 µSv
dose limit for normal population by discharges from nuclear power plants	300 µSv/yr
normal smoker	500 µSv/yr
mammography	500 µSv
gamma-ray image of the thyroid gland	800 µSv
limit for a surveyed area	1 mSv/yr
heavy smoker	1 mSv/yr
natural radiation	2.3 mSv/yr
lower limit for a controlled area (cat. A)	6 mSv/yr
positron-emission tomography	8 mSv
computer tomography of the chest	10 mSv
limit for radiation-exposed workers in Europe	20 mSv/yr
limit for radiation-exposed workers in the United States	50 mSv/yr
limit for emergencies	50 mSv
maximum dose over the whole life span	400 mSv
lethal dose	4000 mSv

typical radiation exposures

tional radiation exposure (for physicians, from nuclear technology, or at accelerators, ...) represents only a relatively small fraction compared to the exposures from medical diagnostics and therapy.

The world average of the whole-body exposure can be estimated to be about 4.3 mSv/yr (2.3 mSv/yr from the natural environment, 2.0 mSv/yr from technical installations (mainly medicine), see Fig. 11.13).

Table 11.3 gives an overview of typical radiation exposures.

natural radiation sources

One has to consider that radiation exposures from natural sources can be quite substantial. In terms of the biological effects, there is no difference between ionizing radiation from natural sources and that from technical installations.

Flying personnel are also subject to radiation monitoring, if the exposures exceed a value of 1 mSv/yr. This limit is reached after

only 200 flight hours at standard altitudes in the atmosphere. It goes without saying that the exposure should never exceed the limits given by the radiation-protection regulations, e.g. 20 mSv/yr in Europe.

In addition, it is important to consider exposures from elevated radon concentrations (mining) or in fields where uranium or thorium derivates are used (some welding electrodes and some incandescent mantles contain thorium). In any case a total dose of 400 mSv over the whole lifespan must not be exceeded.

Figure 11.14 shows the changes in the contributions to radiation exposure since 1940. The strong increase in radiation exposure due to medical examinations is quite remarkable. The radiation limit of 20 mSv/yr in European countries for radiation-exposed workers is actually quite close to the upper limit of the fluctuations of natural environmental radioactivity.

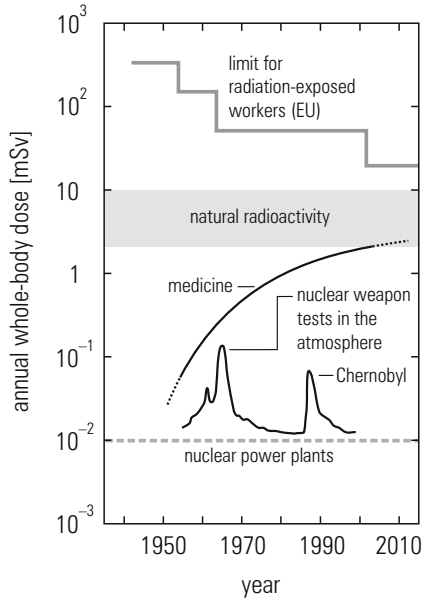


Figure 11.14
Comparison of radiation from the natural environment, exposures from nuclear medicine, legal limits, and exposures from nuclear weapon tests in the atmosphere and from the Chernobyl accident

11.5 Supplementary Information

Example 1

radon contamination of ground water and sea water

Sea water contains 0.01 Bq/l of radon while ground water exhibits radon concentrations of 100 Bq/l. Why?

As the name indicates, ground water originates from the Earth's crust. The Earth's crust and the rocks contain small concentrations

of the radioisotopes uranium, radium, and thorium. In the decay chains of these isotopes, the radioactive noble gas radon occurs. This is washed out by the ground water leading to an elevated radon concentration. In sea water the radon concentration is diluted to a large extent. Also, on average, sea water is separated from the bottom of the sea by a larger distance.

Sea water also contains a substantial amount of salt. This salt occurs in the from of sodium chloride and potassium chloride. Therefore, the sea water contains also the radioactive ^{40}K isotope leading to an activity of about 12 Bq/l. In contrast, this isotope occurs in ground water only with a concentration of about 0.1 Bq/l.

radon in rainwater

Rainwater can also wash out uranium, radium, and thorium from weathered rocks. These natural isotopes enter into the rainwater and also into the ground water, and via rivers they also reach the ocean. It is important to note, in particular, that the radon content in rainwater can be quite considerable.

Example 2

radiation exposure in flights

Radiation exposure during flights has already been discussed quite extensively in this chapter. In particular, the flight personnel themselves pointed out in the past that there is a possible hazard which might even be comparable to exposures in nuclear power plants.

Inside jets flying at a typical altitude of about 10–12 km, a dose rate of about 5 µSv/h is normally measured. For a crossing of the northern Atlantic from Frankfurt to New York (6 hours flight time), one obtains an integrated dose of 30 µSv. A flight from Frankfurt to Tokyo via India corresponds to approximately 60 µSv. Because of the dependence of the radiation exposure on the geomagnetic latitude a flight Frankfurt–Tokyo via the polar route (Alaska) would lead to an exposure of about 100 µSv.[12] A flight Frankfurt–Tokyo via the polar route by high-altitude aircraft (e.g. like with the former French Concorde (flight altitude 18–20 km)) resulted in even higher exposures. This was, however, partially compensated by the shorter flight time. Unusual solar activity during the flight led to an increased radiation. If the radiation level was too high, Concorde descended to below 14 km.

radiation exposure for flying personnel

Personnel flying at altitudes of 10–12 km are exposed to an annual dose of 2.5 mSv (for 500 flight hours per year). Pilots on high-flying research planes receive such a dose in only 125 flight hours. That is to say, flying personnel are working in a radiation-exposed

[12] At the poles charged particles of cosmic rays can penetrate much deeper into the atmosphere because their flight direction is parallel to the magnetic field lines (see also Footnote 1 on page 170). Apart from an elevated radiation exposure at the poles, the low-energy solar particles create fantastic polar lights (aurora borealis and aurora australis).

area and the dose rates received should be monitored by suitable equipment.

Example 3

Directly after the discovery of radioactivity it was suggested that ionizing radiation possesses healing powers. For example, in France a radioactive hair lotion was put on the market and the producer recommended its use with the following advertizement:

radioactive hair lotion?

> The most wonderful discovery of the century
> radium lotion 'Rezall'.
> For the preservation of the hair,
> no loss of hair,
> no baldheadedness,
> no more gray hair!

This advertizement is quite paradoxical, in particular, when one considers that the application of radioactive hair lotion actually leads to the loss of hair.

radioactive toothpaste?

In Germany a radioactive biologically effective toothpaste with the name DORAMAD was advertized. The ionizing radiation originating from this toothpaste – according to the advertizement – was supposed to massage the gums and refresh the whole mouth.

Thorotrast ®

Even up to the fifties of the last century a thorium-containing contrast agent with the name Thorotrast ® for the examination of the stomach and the intestine was used. The ThO_2 contained in the Thorotrast is predominantly stored in the liver and may lead to cancer of the liver and to liver cirrhosis.

radium-containing foot rests

Along similar lines, in the 1950s shops selling shoes provided a special X-ray device to test whether the shoes actually fit well. Also radium-containing foot rests with the brand name Elastosan were recommended as major improvement in modern chiropody. This radioactive foot rests exhibited a surface-dose rate of 2.5 µSv/h, comparable with exposures for flights in northern latitudes.

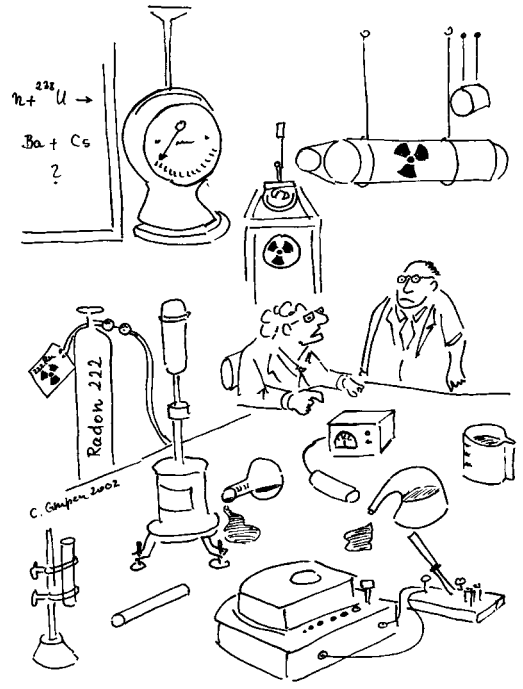
"DORAMAD preserves your teeth!!"
© by Claus Grupen

radioactive electric blankets

Even radium compresses were advertized in the period from 1920 to 1960 as an attractive alternative to electric blankets. According to the producer such a radium compress contained a guaranteed amount of at least 100 µg ^{226}Ra corresponding to an activity of 3.7 MBq. This is clearly above the exemption limit for this isotope. The γ-dose rate of such a compress resulted in a dose rate of 300 µSv/h even at a distance of one meter! They also promoted and advertized the ease of use of this activator blanket and pointed out that absolutely no danger is related to the use of this device. Press reports at the time also certified that for proper use and application of this highly concentrated radium compresses, there was no risk of harm.

radon treatment in baths

In this context, treatments like radon inhalations and drinking radium-containing water should also be mentioned. In the mines of Badgastein, a spa in Austria, the radon concentration was as high as 150 000 Bq/m^3. It has been reported that a research assistant of Otto Hahn, the discoverer of nuclear fission, was worried about the



"Why do you complain? You should be grateful!
In a spa you would be charged a lot of money for it.
Here you get it for free!"

inhalation and incorporation of radon and radioactive dust in his laboratories. When he pointed out this possible hazard to Hahn, Hahn was supposed to have said: Don't worry about that; other people pay a lot of money to go to Badgastein and you will get this radon inhalation here for free!

Summary

Radiation from the natural environment consists of, in roughly equal parts, cosmic rays, radiation from the ground (terrestrial radiation), and the incorporation of radioisotopes from the natural biosphere. The exposure due to technical equipment and installations has its origin almost exclusively in medicine (diagnosis and therapy). There is no difference between ionizing radiation from natural sources and ionizing radiation from technical installations.

11.6 Problems

Problem 1

The main radioisotopes in natural geological formations and in the Earth's crust are ^{40}K, ^{226}Ra, and ^{232}Th. The specific activity of normal ground is around 500 Bq/kg. Estimate the dose rate that originates from 1000 kg of soil at a distance of 1 m!

Problem 2

How does a four-week holiday at mountain altitudes (3000 m) compare to the exposure by an X-ray chest examination?

Problem 3

The personnel accompanying CASTOR transports is exposed to maximum dose rates of 30 µSv/h. How does the dose received for the accompaniment of a CASTOR transport over a time span of 10 hours compare with the annual radiation exposure in the Black Forest?

12 Nuclear Power Plants

"The laboratory technician has succeeded in implementing by means of the atomic pile the Einsteinian principle of inertia of energy."

Gaston Bachelard

annihilation processes

In nuclear power plants mass is converted into energy according to the famous equation $E = mc^2$. However, mass can only be completely converted into energy in annihilation processes, e.g. in electron–positron annihilation into two photons,

$$e^+e^- \rightarrow \gamma + \gamma \ , \tag{12.1}$$

antimatter

or in proton–antiproton annihilation processes. Since large quantities of antimatter are not available, nuclear power plants usually transform only part of the mass of atomic nuclei into energy, mostly in fission processes.

binding energy per nucleon

Fission power plants take advantage of the dependence of the binding energy per nucleon on the mass of nuclei. The binding energy of uranium is about 7.5 MeV/nucleon, that of the fission products is about 8.5 MeV/nucleon. Since the fission products are more tightly bound, they have a smaller mass per nucleon. The fission of a uranium nucleus, therefore, liberates a mass equivalent of 1 MeV/nucleon. This energy is set free in form of kinetic energies

fission products

of the fission products (84.5%), kinetic energies of prompt fission neutrons (2.5%), energy of prompt and delayed γ rays (5%), kinetic energy of electrons (2.5%), and, finally, the energy of electron antineutrinos (5.5%).

The efficiency of mass-to-energy conversion therefore amounts to

$$\eta = \frac{\Delta E/\text{nucleon}}{m_{\text{nucleon}}\, c^2} \approx 1‰ \ , \tag{12.2}$$

where m_{nucleon} is the rest mass of the nucleon (938.3 MeV for protons and 939.6 MeV for neutrons). In fission reactions highly radioactive and also long-lived fission products are generated. Fission nuclear power plants use mostly the relatively rare uranium isotope ^{235}U which has a natural abundance of only 0.7%. Natural uranium (99.3% ^{238}U, 0.7% ^{235}U) therefore has to be enriched to be economically fissionable. The recycling of spent nuclear-fuel rods and their transport may imply certain safety problems.

recycling

C. Grupen, *Introduction to Radiation Protection*,
Graduate Texts in Physics, DOI 10.1007/978-3-642-02586-0_12,

Nuclear energy can also be gained by fusion. Indeed, in contrast to fission reactors one can gain 6.6 MeV per nucleon in the fusion of hydrogen to helium, corresponding to a conversion efficiency of 0.7%. In the Sun, hydrogen is fused according to $4p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e$, while nuclear-fusion plants intend to use deuterium–tritium fusion ($d + t \rightarrow {}^4\mathrm{He} + n$)[1], which has a conversion efficiency of only 0.3%. The radiation-protection problems with fusion reactors are believed to be much less severe since the fusion product, the result of hydrogen burning, is stable helium. It must, however, be considered that radioactive isotopes will be produced by neutron activation, where the neutrons are emitted as a consequence of deuterium–tritium fusion. This activation concerns not only the reactor material but also the steel and concrete shielding.

fusion of hydrogen

deuterium–tritium fusion

neutron activation

12.1 Nuclear-Fission Reactors

The most frequently used isotope in nuclear-fission power plants is $^{235}\mathrm{U}$. It breaks up under bombardment of slow neutrons according to, for example,

$$n + {}^{235}\mathrm{U} \rightarrow {}^{236}\mathrm{U}^* \rightarrow {}^{141}\mathrm{I}^* + {}^{95}\mathrm{Y}^* \ . \qquad (12.3)$$

The radioactive fission products created in these reactions partially decay by emission of prompt and/or delayed neutrons and/or successive β^- decays. The decay of the highly excited fission products, in our example iodine and yttrium, will provide further neutrons which will initiate more fission reactions. By using materials with a high neutron absorption coefficient (control rods) the neutron yield can be regulated. This makes possible a safe operation of the nuclear power plant at constant power.

neutron absorption coefficient

control rods

The distribution of the fission products for fission with thermal and fast neutrons on $^{235}\mathrm{U}$ is plotted in Fig. 12.1. It is evident that the fission yield is highly asymmetric. This asymmetry can be understood in the framework of the nuclear shell model. Nuclei with proton and neutron numbers corresponding to closed shells are very tightly bound. These 'magic' numbers are 2, 8, 20, 28, 50, 82, and 126. Nuclei with magic proton *and* magic neutron numbers, so-called 'doubly magic' ones, are particularly tightly bound. Examples are $^4\mathrm{He}$, $^{16}\mathrm{O}$, or $^{40}\mathrm{Ca}$. The peaks in the fission-yield distribution originate from nuclei around the magic neutron numbers 50 (mass numbers of ≈ 90) and 82 (mass numbers of ≈ 140).

[1] deuterium: ${}^2_1\mathrm{H} = d$, tritium: ${}^3_1\mathrm{H} = t$

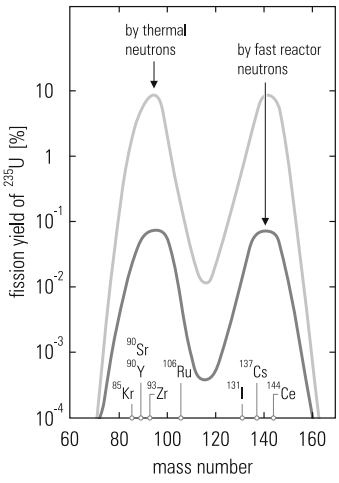


Figure 12.1
Fission yield from ^{235}U by fast and thermal neutrons

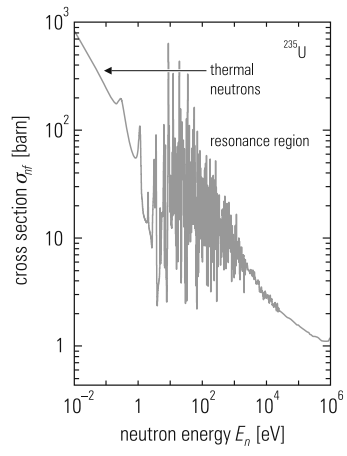


Figure 12.2
Cross section for neutron-induced fission of ^{235}U as a function of the neutron energy

The cross section for fission is particularly large for slow neutrons. It can be parametrized by the $1/v$ law (v – velocity of neutrons). Since neutrons created in the fission process are normally quite energetic (typically several MeV), they have to be moderated to slow them down to thermal energies. The fission cross section of thermal neutrons ($E_n = kT \approx 25\,\text{meV}$) for ^{235}U is $\sigma_\text{f} \approx 700\,\text{barn}$ ($1\,\text{barn} = 10^{-24}\,\text{cm}^2$), much larger than that of fast neutrons ($\sigma_\text{f}(1\,\text{MeV}) \approx 1\,\text{barn}$). The dependence of the fission cross section for ^{235}U is shown in Fig. 12.2 as a function of the neutron energy.

fission cross section

The moderation of fast neutrons is best done by light materials, because a relatively large amount of energy can be transferred in the interaction of neutrons with lighter atomic nuclei. Water (H_2O) is ideally suited for moderation and can be used as a cooling agent at the same time. This provides a very important safety aspect since, if the cooling water should evaporate due to some power excursion, the fast neutrons from the fission products will no longer be moderated thereby reducing the efficiency for the chain reaction or even interrupting it. It presents a safety risk, if different materials are used for cooling and for the moderation. A fission reactor operated with water as cooling agent and graphite as moderator must be considered inherently unsafe. If the cooling agent is lost or evaporates, disrupting the cooling, while neutrons continue to be thermalized by the graphite moderator thus sustaining the chain reaction, this type of reactor can get out of control. Such a situation can easily lead to a core meltdown (see Chernobyl accident, Chap. 14).

moderation of neutrons

safety aspect

Water-cooled and water-moderated reactors therefore represent a reactor design of high security as was also demonstrated by the

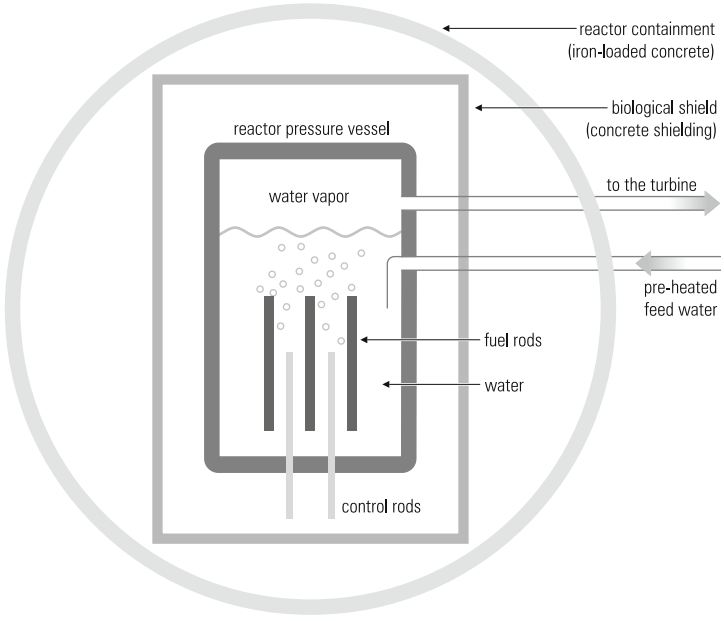


Figure 12.3
Schematic diagram of a boiling-water fission reactor which is water-cooled and water-moderated

natural reactor Oklo

natural reactor Oklo in Gabon in Africa, see also Example 2 in this chapter.

boiling-water reactor
pressurized-water reactor

One has to distinguish between boiling-water reactors (Fig. 12.3) and pressurized-water reactors (Fig. 12.4). In both cases the heat generated is used to evaporate water, and the hot water vapor then powers a generator via a turbine. In boiling-water reactors the water vapor from the primary circuit is used to feed the turbine. In this case the possibility that some contaminated water from the reactor might leak into the mechanical equipment for power generation cannot be completely excluded.

primary circuit

secondary water circuit

To circumvent such a problem, the primary energy can be transferred via a heat exchanger into a secondary water circuit as in the pressurized-water reactor. The water from the secondary circuit will then feed the turbine without risk of contamination. Pressurized-water reactors have large safety advantages, although the construction of a secondary water circuit is much more complex and also more expensive. An additional safety aspect of a pressurized-water reactor is that the control rods are mounted on top of the fuel elements, which is impossible in boiling-water reactors for reasons of construction. In case of emergency, the control rods would have to be moved up into the reactor core against gravity in boiling-water reactors, while, in contrast, in pressurized-water reactors, they fall down into the reactor core following the gravitational pull.

fuel elements

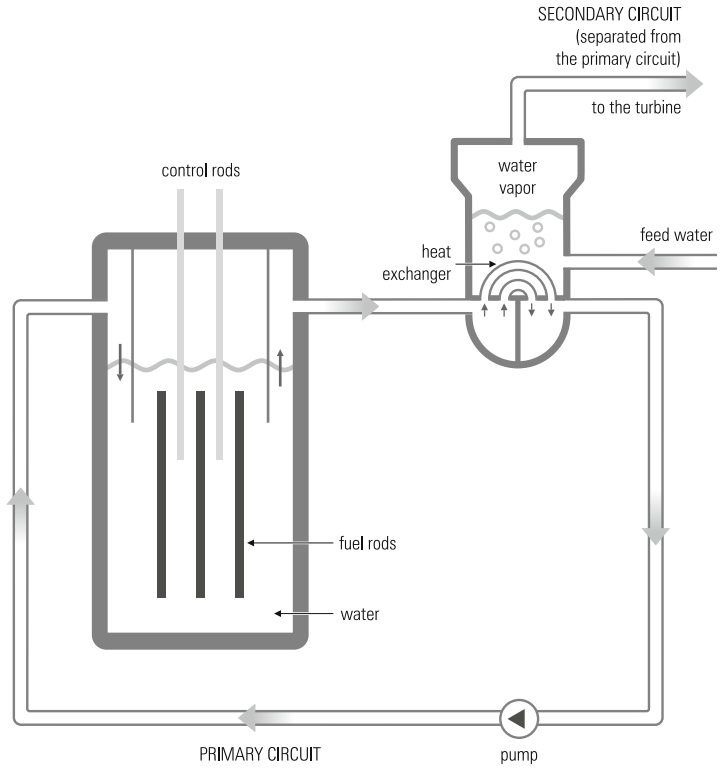
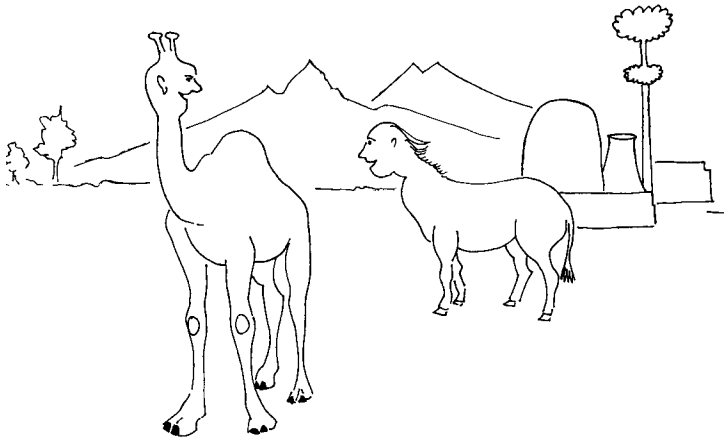


Figure 12.4
Schematic diagram of a pressurized-water reactor. The water is not allowed to boil in the core but rather produces steam behind a heat exchanger to feed a generator



"Since the introduction of nuclear energy the variety of species has obviously increased."

The complete schematic setup of a pressurized-water reactor is shown in Fig. 12.5. Figure 12.6 shows a view of the inner part of a fission reactor in which the fuel rods are clearly visible.

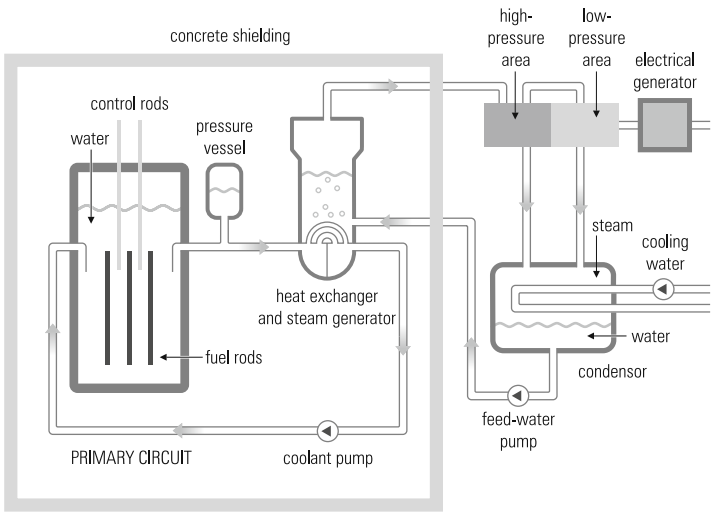


Figure 12.5
Complete schematic setup of a pressurized-water reactor

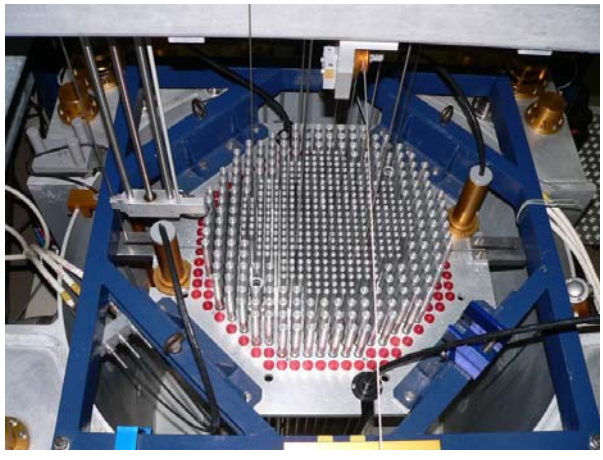


Figure 12.6
Image of fuel elements in the core of a fission reactor. Photo credit: Wikimedia Commons, Ecole Polytechnique Fédérale de Lausanne

It is conceivable that the high-temperature reactor, also called pebble-bed reactor, has a bright future because of its excellent safety aspects. High-temperature reactors are characterized by their efficient use of uranium and by a high operating temperature ($\approx$ 1000 °C) compared to boiling-water reactors ($\approx$ 300 °C). High-temperature reactors use graphite as moderator and helium as coolant.

high-temperature reactor (pebble-bed reactor)

graphite moderation

Highly enriched ^{235}U serves as fuel. The fuel pebbles also contain ^{232}Th, from which the fissile ^{233}U is bred.

graphite pebbles

The uranium fuel is contained as ceramic oxide in graphite pebbles along with the thorium isotope. The fissile material is distributed uniformly as small spheres in a graphite matrix. The graphite pebbles are of tennis-ball size and feel hot to the touch because of their α activity. The reactor core contains several hundred thousand of these graphite pebbles. During reactor operation the fission neutrons breed another easily fissile uranium isotope by neutron attachment to ^{232}Th according to the following reaction:

$$^{232}\mathrm{Th} + n \;\rightarrow\; ^{233}\mathrm{Th} + \gamma \tag{12.4}$$

with the subsequent β decays

$$^{233}\mathrm{Th} \;\rightarrow\; ^{233}\mathrm{Pa} + e^- + \bar{\nu}_e \;\; (T_{1/2} = 22.3\,\mathrm{min}) \;, \tag{12.5}$$

$$^{233}\mathrm{Pa} \;\rightarrow\; ^{233}\mathrm{U} + e^- + \bar{\nu}_e \;\; (T_{1/2} = 27.0\,\mathrm{d}) \;. \tag{12.6}$$

Spent pebbles can simply be removed from the reactor core at the bottom of the reactor container and replaced by fresh ones at the top without problems, guaranteeing a continuous supply of fuel.

helium cooling

Helium gas is an excellent coolant. With its doubly magic numbers, neutrons will not attach to it and therefore it will not be activated. The hot helium evaporates water, and the water vapor drives the turbine. The high operating temperature (1000 °C) guarantees an excellent thermodynamical efficiency. It is even conceivable for the hot helium to drive the turbine directly.

Figure 12.7 shows the design principle of a pebble-bed reactor.

negative reaction coefficient

High-temperature reactors exhibit a negative reaction coefficient, i.e., a temperature increase in the reactor decreases its reactivity. This again provides an automatic stabilization. A number of subtle reasons is responsible for this phenomenon: An increase in temperature leads to a thermal expansion of the graphite pebbles

reducing fuel density

thereby reducing its uranium density. The pebbles are designed in such a way that this effect reduces the criticality and thereby the reaction rate, with the result that the energy-production rate decreases, so that eventually a stable maximum operation temperature is obtained. In terms of physics the temperature increase leads to a Doppler broadening of the resonance-absorption lines of the fuel

neutron attachment to ^{238}U

isotopes. As a result ^{238}U nuclei will also attach some neutrons, which then are missing for ^{235}U fission.[2] In addition, the cross sec-

[2] In the language of reactor builders: the fraction of neutrons escaping resonance capture (the p factor), decreases with increasing temperature. With rising temperature, an increasing number of neutrons cannot escape capture by the isotope ^{238}U. These neutrons then are missing for fission of ^{235}U.

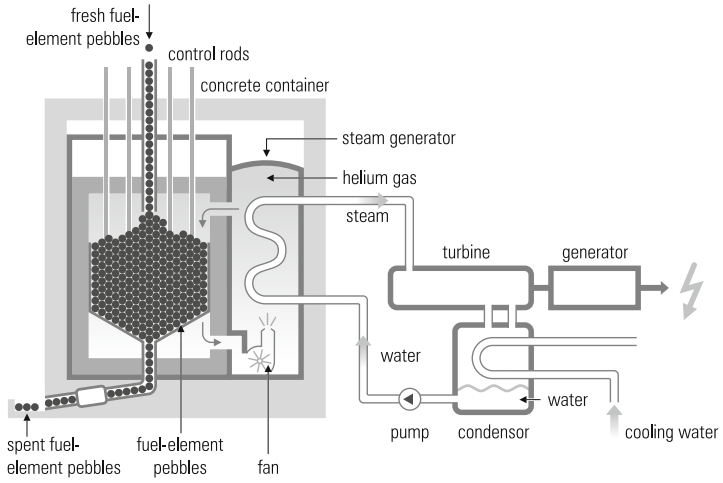


Figure 12.7
Sketch of a pebble-bed reactor

reduced cross section

tion for neutron-induced fission is reduced because of the $1/v$ law. A temperature rise increases the thermal energy of neutrons, and – because $v \sim \sqrt{E}$ – also their velocity, thereby reducing the reaction cross section. These effects therefore guarantee a negative feedback and an automatic self-stabilization. These arguments do not hold for 'normal' reactors, since a core meltdown will happen there before the limiting operation temperature is reached, because uranium melts at 1132.2 °C (1405.3 K).

self-stabilization

The self-stabilization in pebble-bed reactors works because the ceramic graphite pebbles can withstand much higher temperatures (2000 °C). Due to the negative temperature coefficient in pebble-bed reactors, the maximum operating temperature stabilizes at 1600 °C, removing the possibility of a core meltdown, at least in theory. A pebble-bed reactor could in principle function without neutron-absorbing control rods which normally regulate the neutron amplification factor. Instead, the operation temperature could be controlled by the flow rate of the coolant. Nevertheless, control and safety rods will be employed for safety redundancy. They will also be used for reactor shutdown.

no core meltdown

passive cooling

The power density in high-temperature reactors (around 6 MW/m^3) is significantly lower than that of boiling-water reactors (typically 100 MW/m^3). Therefore passive cooling should be sufficient to keep the fuel rods below the melting temperature under all circumstances. For reasons of safety, active cooling will nevertheless be installed to prevent an unforeseen power excursion. Since the activation cross section of helium is extremely low, it is even conceivable to operate this type of reactor only with a primary circuit without a heat exchanger.

heat of reaction

The production of heat in nuclear-fission reactions at high temperature is also considered as advantage.

Countries like Japan, China, and South Africa will use this type of reactor in the near future. China has announced that it will build thirty pebble-bed reactors before 2020.

inherent safety

Because of their inherent safety, pebble-bed reactors do not necessitate a pressure container. Therefore they can be constructed in smaller units economically. A possible disadvantage is that this reactor type requires highly enriched weapons-grade ^{235}U (enrichment up to 97%). Also the recycling of ceramic graphite pebbles containing the fuel needs further study.

One problem of fission reactors is the processing and storage of nuclear waste (see also Sect. 8.12). In nuclear fission enormous amounts of solid and liquid radioactive waste are generated. The liquid waste is usually stored in large tanks. The storage of the radioactive material would be must easier if it could be concentrated. Strontium-90 is a particularly harmful component of nuclear waste with a half-life of about 30 years. It can replace calcium in bones if it gets into the food chain and causes health problems including cancer. A new material that can extract radioactive strontium ions from solutions could help to clean up nuclear waste. A sponge-like material, which looks like a brown powder, has been shown to be able to remove 99.8 per cent of the strontium from a sodium-rich solution of strontium.[3]

12.2 Fusion Reactors

fusion reactor

Fusion reactors provide the energy that makes the stars shine. If this source of energy could be made available on Earth, all energy problems would be solved. In the 1930s hydrogen fusion was discovered to be the energy source of all stars.[4]

energy sources of stars

The main fusion mechanism in stars of the size of the Sun is based on the following reactions:[5]

_pp_ cycle

[3] `www.rsc.org/chemistryworld/News/2008/March/03030802.asp`

[4] About the discovery of the principles of the hydrogen fusion chain that powers the stars the following anecdote is being told: Carl Friedrich von Weizsäcker was taking a walk with a girl on a nice summer night. The girl, who later became his wife, remarks on how nice the stars are shining. “Yes”, says Weizsäcker, “and right now I am the only one who knows why.” Sometimes this anecdote is also attributed to Hans Bethe.

[5] In high-mass stars, the Bethe–Weizsäcker cycle (CNO cycle) also operates.

$$p + p \rightarrow d + e^+ + \nu_e \ , \tag{12.7}$$

$$p + d \rightarrow {}^3\mathrm{He} + \gamma \ , \tag{12.8}$$

$${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p \ . \tag{12.9}$$

In addition to these basic reactions, certain processes with lower probability occur, such as:

$${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma \ . \tag{12.10}$$

^{7}Be can either transform into ^{7}Li by electron capture,

$${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e \ , \tag{12.11}$$

or it can capture one of the plentiful protons according to

$${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma \ . \tag{12.12}$$

boron decay

^{8}B is unstable and decays under positron emission,

$${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + e^+ + \nu_e \ , \tag{12.13}$$

where ^{8}Be decays almost immediately into two α particles. In the same way, ^{7}Li captures a proton and is transformed into helium nuclei,

$${}^7\mathrm{Li} + p \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He} \ . \tag{12.14}$$

conditions for hydrogen fusion

Hydrogen fusion requires three important conditions:

- high temperatures,
- high plasma densities, and
- sufficiently long confinement times of the plasma.[6]

tunnelling probability

The two protons fusing in the initial process are both positively charged and repel each other. High temperatures are required so that these two protons can get as close as possible. Still the protons will not be able to get over the Coulomb barrier, they have to tunnel through the Coulomb barrier of the other collision partner. The tunnelling probability increases with the energy of the protons interacting in this process, i.e., the tunnelling probability increases with temperature ($E \sim T$). High plasma densities and long confinement times are, of course, given in the interior of stars.

deuterium–tritium fusion

For fusion reactors on Earth, deuterium–tritium fusion seems to be most appropriate (see Fig. 12.8)

[6] A plasma is an ionized gas. In the case of fusion reactors, the atoms are fully ionized.

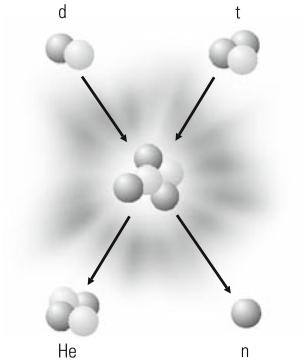


Figure 12.8
Principle of the deuterium–tritium fusion reaction

$$d + t \rightarrow {}^4\mathrm{He} + n \ . \tag{12.15}$$

This interaction allows the tunnelling of deuterium and tritium at relatively large mutual distances compared to the other fusion processes.

In this fusion process, the unstable compound nucleus ^{5}He is initially formed, which decays into ^{4}He and a neutron. The α particle leaves with a kinetic energy of 3.5 MeV and the neutron gains 14.1 MeV. The α particle has a very short range and will deposit its energy in the immediate vicinity, heating up the plasma. If the heating by α particles is sufficient to compensate the energy-leakage rate of the plasma, a self-sustaining fusion can be maintained. The neutron will escape because of its low cross section for interactions in the plasma.

self-sustaining fusion

Deuterium can be extracted from sea water by electrolysis. Tritium can be bred from lithium by neutron bombardment according to

deuterium and tritium extraction

$$n + {}^6\mathrm{Li} \rightarrow {}^4\mathrm{He} + {}^3\mathrm{H} \ . \tag{12.16}$$

If the reaction plasma is surrounded by lithium blankets, the neutrons emerging from the (d, t) fusion can breed further tritons.

There are two fundamentally different proposals to maintain the fusion process on Earth in a controlled fashion. The technique of inertial fusion is predominantly being followed in the United States while fusion with magnetic confinement is mainly being tested and investigated in Europe.

inertial fusion

12.2.1 Inertial Fusion

laser fusion

The technique of inertial fusion, also called laser fusion, uses hollow spheres (made, for example, of plastics) which are filled in equal proportions with deuterium and tritium at high pressure and which are cooled down to cryogenic temperatures (i.e. temperatures at which noble gases become liquid). This causes the deuterium–tritium mixture to freeze as thin solid coating on the inner wall of the hollow sphere. These deuterium and tritium pellets are injected into a target chamber, where they are bombarded by intense laser or heavy-ion beams. The high energy deposition by the laser pulse evaporates the shell of the pellet which expands rapidly outwards. This causes a pressure in an inward direction which accelerates the deuterium–tritium layer to the center of the pellet. That part of the deuterium–tritium gas which had remained at the center of the pellet will be compressed by the deuterium–tritium component streaming under high pressure to the center. In this process temperatures on the order of more than 10^8 K are produced for a short period, which is

heavy-ion beams

laser pulse

sufficient to initiate the fusion process. The expanding fusion wave started in this way will reach the formerly solid, residual deuterium–tritium component and cause it to fuse as well.

It is possible to generate laser beams of extremely high power density. The NOVA laser at the Lawrence Livermore National Laboratory reaches 100 terawatts per square centimeter. Figure 12.9 shows a battery of high-power lasers which are used for laser fusion.

high-power laser

The reaction products of this type of fusion, however, might deteriorate the optical system used to steer the beam. This disadvantage could be overcome if, instead of laser beams, heavy-ion beams were used: these can be focused by magnetic lenses. Magnetic lense systems are not very susceptible to possible damage by the reaction products from the fusion.

focusability of heavy ions

A fusion reactor based on inertial fusion is a strong source of neutrons. Because of the low interaction probability of neutrons – they are electrically neutral – they will deposit part of their energy at large distances from the fusion chamber. It is unavoidable that radioactive isotopes are formed in the process of neutron absorption in the surrounding material. By adequate selection of materials with low neutron activation cross section and short decay times, the production of radioactive waste can be limited.

neutron activation

The burning plasma (temperatures of $\approx 10^8$ K) will, of course, emit its natural characteristic blackbody radiation which at these

blackbody radiation in the X-ray range

Figure 12.9
Giant high-power lasers (terawatt range) are required to enable hydrogen fusion. Shown are some of the lasers which are used in the National Fusion Facility, USA (source: Lawrence Livermore National Laboratory). The size of the lasers can be judged from the technician in the middle row between the lasers

temperatures is in the X-ray range[7]

$$kT = 1.38 \times 10^{-23}\,\mathrm{J/K} \times 10^{8}\,\mathrm{K}\,\frac{1}{1.6 \times 10^{-19}\,\mathrm{J/eV}} = 8.6\,\mathrm{keV}\ . \tag{12.17}$$

In this way, part of the reaction energy will be lost (about 10% to 15%) by this process of thermal X-ray production. The X-ray photons escaping from the fusion plasma will also interact substantially with the material of the reaction chamber. In these X-ray interactions part of the coating of the chamber walls might be ablated, i.e. detached, thereby polluting the target chamber. The continuous neutron bombardment will also cause some brittleness of the reactor materials.

Altogether one would expect that the pollution of the environment by radioactive waste from fusion nuclear plants to be much less than that from fission reactors.

injection of hydrogen D–T pellets

The energy production in a fusion reactor following the principle of inertial fusion is obtained by a high repetition rate of injecting the hydrogen pellets (see Fig. 12.10) into the fusion chamber.

Figure 12.11 sketches a fusion power plant based on the working principle of inertial fusion.

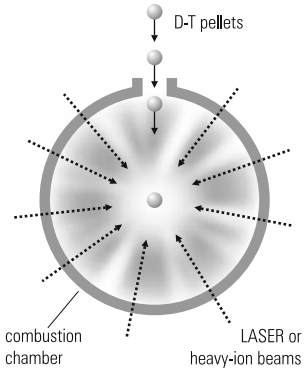


Figure 12.10
Sketch of a fusion reactor by inertial fusion using laser bombardment

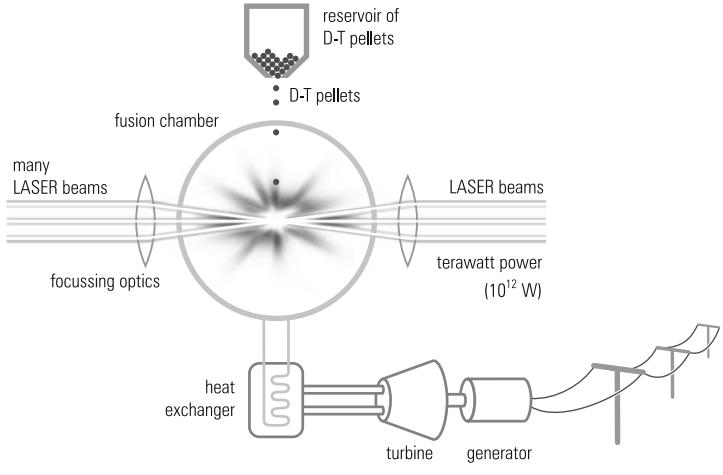


Figure 12.11
Sketch of a fusion power plant based on inertial fusion

[7] A blackbody at temperature T emits exactly the same energy spectrum which would be present in an environment at equilibrium at temperature T. This spectral intensity distribution is described by Planck's law, $P(\nu)\,\mathrm{d}\nu = \frac{2h\nu^3}{c^2}\frac{1}{\mathrm{e}^{\frac{h\nu}{kT}}-1}\,\mathrm{d}\nu$, where ν is the frequency, k Boltzmann's constant, and h Planck's constant.

12.2.2 Fusion by Magnetic Containment

tokamak principle

fusion by magnetic confinement

In a fusion reactor based upon the tokamak principle, a high-temperature plasma is produced, and then stored by magnetic confinement over a longer period of time (several seconds). For this technique, temperatures of about 100 to 200 million kelvin, confinement times of 1 to 2 seconds, and plasma densities (particle densities) of 2–3 $\times$ $10^{20}\,\mathrm{m}^{-3}$ are required.

Energy losses from the plasma are mainly caused by radiation. Since the radiation loss of a plasma is proportional to its surface area, while the energy content of the plasma depends on the volume, one gains in confinement time with increasing size of the plasma. (The ratio of surface to volume (assumed to be spherical) varies as $1/r$, where r is the radius of the plasma, which means that for small radii the losses are largest.) The plasma confinement is obtained by a rather sophisticated arrangement of magnetic fields: the goal is to store the plasma in a closed torus. To confine the charged particles in a torus, a toroidal magnetic field is produced which causes the plasma particles to move on spiral orbits inside the torus. Furthermore, an additional polar magnetic field causes the plasma to pinch, i.e. to be compressed and confined by magnetic forces, and to keep it away from the walls of the torus (see Fig. 12.12).

plasma confinement

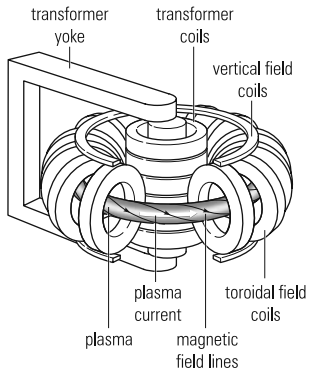


Figure 12.12
Working principle of a tokamak reactor

The heating of the plasma can be performed in various ways, where in most cases all of the following methods will be applied (see Fig. 12.13).

- A powerful transformer with a high current on the primary winding will induce a high current in the plasma, which acts as secondary winding (ohmic plasma heating). The power dissipated into the plasma in this way is proportional to the square of the induced current.
- Deuterium and tritium ions are first accelerated in a linear accelerator up to energies of typically 150 keV/nucleon. Because of the magnetic field, they will not be able to enter the plasma. Therefore the deuterium and tritium ions are neutralized by electron capture allowing them to enter the plasma. The injection of energetic neutral particles increases the plasma temperature (heating by neutral particles).
- In the same way, electromagnetic radiation can heat up the plasma, as long as the frequency of the radiation is tuned in such a way that the radiation will be absorbed in a resonance-like fashion by the charged particles of the plasma.
- Finally, some of the reaction products of fusion, namely, the α particles produced, will be stopped in the plasma leading to further heating.

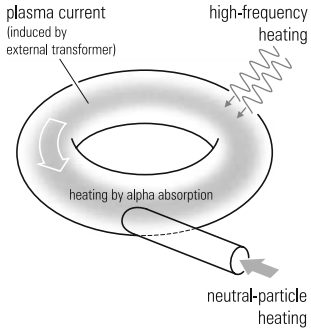


Figure 12.13
Methods of plasma heating in a tokamak fusion reactor. Neutral particles are injected against the plasma stream to increase their absorption

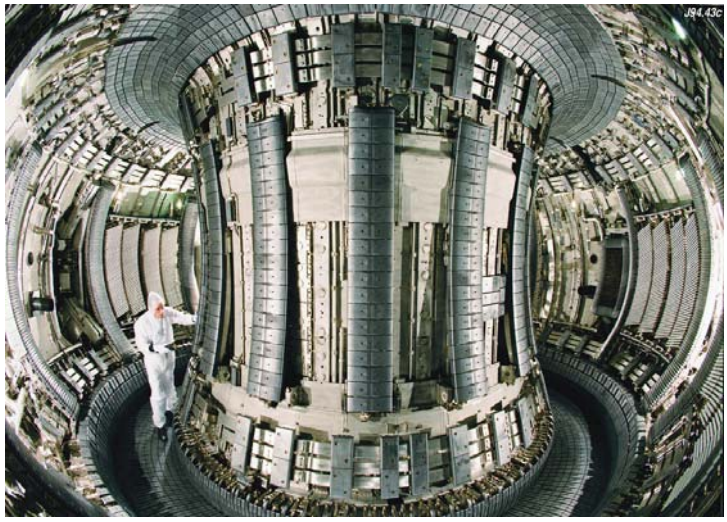


Figure 12.14
Photo of the interior of the Joint European Torus. The dimensions of the fusion reactor can be estimated from the size of the technician in the left-hand part of the photo. Photo credit: JET Culham, England

neutron capture

energy production of a fusion reactor

Joint European Torus

ITER

energy gain

In very much the same way as in inertial fusion, the neutrons produced in the fusion process in the plasma will escape from the burning plasma. These neutrons have substantial energy: they present the basis for the energy production of a fusion reactor.

Figure 12.14 shows a photo of the plasma chamber of a reactor built on the principle of tokamak fusion.

The follow-up project after the JET[8] fusion facility is the International Thermonuclear Experimental Reactor, ITER. ITER is a joint European–American–Japanese–Russian fusion project to demonstrate the feasibility of producing fusion energy economically. The American participation was, however, significantly reduced in 2008 due to financial cuts to this field of science.

10 g of deuterium which can be extracted from 500 l of water, and 15 g tritium which can be produced from 30 g lithium, contain about 3×10^{24} atomic nuclei each. Per fusion process one neutron with energy 14.1 MeV is produced. If the kinetic energy of neutrons can be transformed into the production of electrical power, one will obtain

$$\Delta E = 3 \times 10^{24} \times 14.1\,\mathrm{MeV} = 6.77 \times 10^{12}\,\mathrm{J} = 1.88 \times 10^{6}\,\mathrm{kW\,h}\ . \tag{12.18}$$

This energy is sufficient to cover the energy consumption of a single person over his entire life. This example of energy production shows

[8] The Joint European Torus JET is to date the world's largest nuclear-fusion research facility, built in Culham, England. It is operated as a collaboration between all European fusion organizations with the participation of scientists from around the globe.

that the efficiency of transformation of mass into energy is given by

efficiency of energy production

$$mc^2\,\eta = 6.77 \times 10^{12}\,\mathrm{J}\ , \tag{12.19}$$

$$\eta = \frac{6.77 \times 10^{12}\,\mathrm{J}}{25 \times 10^{-3}\,\mathrm{kg} \times \left(3 \times 10^{8}\,\frac{\mathrm{m}}{\mathrm{s}}\right)^2} \approx 3‰\ . \tag{12.20}$$

Even though this efficiency is somewhat smaller than the efficiency of the proton–proton fusion in the Sun, it is much better than the efficiency that one gets from nuclear power plants based on fission.

neutron-activated reactor material

safety

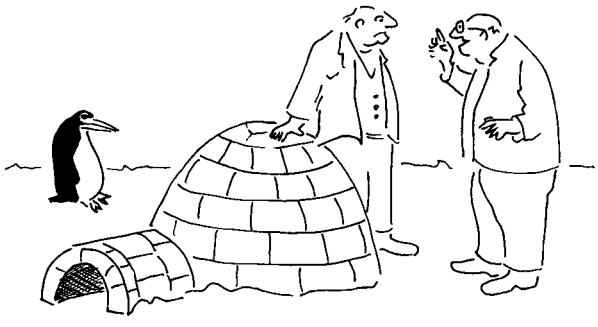
Apart from the neutron-activated reactor material, fusion reactors produce no nuclear waste. In addition to the avoidance of nuclear waste, the improved safety of fusion reactors is a very important aspect. In contrast to fission reactors, a fusion reactor can never suffer a severe radiation accident as happened in the Chernobyl disaster. If the conditions for the fusion of hydrogen nuclei are no longer given, the fusion reactions will terminate and the reactor will shut down all by itself. Since there are no chain reactions in the fusion reactor, it is impossible for the fusion reactor to get out of control. Also events from outside, e.g. a plane crashing into the fusion reactor, cannot cause a sudden uncontrolled fusion.

hydrogen bombs

fission bomb

One might object that hydrogen bombs have been built which work along the fusion principle. However, a fusion bomb, i.e. a hydrogen bomb, needs to be ignited by a normal fission bomb. The overall fusion process is started in the following fashion: Initially, subcritical amounts of uranium or plutonium are brought together by a mechanical implosion, which then start to explode as a standard nuclear-fission bomb. In such an explosion the conditions are created under which nuclear fusion can occur. Only a normal atomic bomb, as it is frequently called, enables the ignition of a hydrogen bomb. Since in a fusion power plant no fission reactions are initiated, a fusion power plant can never undergo a large radiation accident.

inherent safety



"In this research reactor we investigate the possibilities of cold fusion!"

Also a nuclear-fission bomb thrown in a terrorist attack onto the fusion reactor cannot cause the fusion reactor to get out of control since the fission energy must be liberated in a relatively small volume, otherwise the fusion plasma would simply decay. A normal atomic bomb would dilute and pollute the plasma, thereby destroying the conditions for the burning of the plasma. Also smallest amounts of air entering the plasma would stop the burning plasma immediately. Air entering the fusion chamber during normal reactor operation must be avoided under all circumstances. This extreme sensitivity of a fusion reactor represents an important safety aspect, because it will prevent the reactor running out of control in critical emergency situations. In such situations, the reactor will simply stop working without polluting the environment.

safety aspect

These safety aspects are a strong argument for a fusion reactor. It appears possible to master the solar fire and use it on Earth, in this way avoiding the possible risks which are related to the production of nuclear energy by fission.

12.3 Supplementary Information

Example 1

first nuclear reactor
Enrico Fermi

On December 2nd 1942 the first nuclear reactor went critical. Enrico Fermi and his colleagues succeeded to maintain a self-sustaining chain reaction in a graphite-moderated reactor with uranium oxide as fuel. The reactor was set up under the grandstand of the squash court on the site of the sport stadium of the University of Chicago (Fig. 12.15).

This first reactor was constructed as a uranium–graphite matrix. The uranium blocks and the high-purity graphite modules were arranged in the form of a cubic lattice. The reactor was meant as an experiment to demonstrate the feasibility of a self-sustaining chain reaction. There was no cooling.

self-sustaining chain reaction

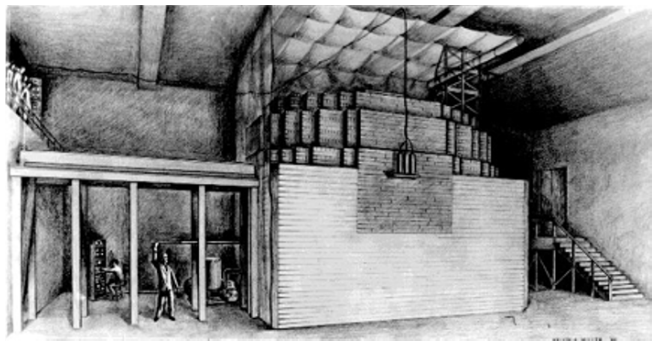


Figure 12.15
Sketch of the historic reactor in Chicago, in which the first controlled, self-sustaining chain reaction was maintained. Image credit: Argonne National Laboratory

Before the reactor was built in Chicago and before it was set into action, thirty subcritical reactors had been tested to measure the neutron yield and to determine the critical mass for a reactor with self-sustaining chain reactions. The reactor was equipped with a three-fold security system by control rods for neutron absorption and further devices which were designed to regulate the neutron flux. There was an automatic system consisting of cadmium control rods and a special safety rod for emergency situations. This hand-operated emergency safety rod was connected to a rope which was held by a physicist. The rope could simply be dropped or cut by an axe if it should turn out to be necessary, e.g. if the automatic shutdown system was not working properly. The third security system consisted of a team of technicians, who were standing by, and would flood the reactor in an emergency situation with a cadmium-salt solution, if the automatic shutdown system and also the hand-operated control-rod system should fail.

three-fold security system

The chain reaction was initiated by withdrawing the cadmium control rods slowly out of the reactor. While this was being done, the neutron yield and neutron flux as a function of the position of the control rods was measured. When the neutron rate increased exponentially, it became obvious that a self-sustaining chain reaction had developed in the reactor. In this way it was demonstrated that a controlled, self-sustaining chain reaction in a uranium reactor would definitely work.

cadmium control rods

controlled chain reaction

Example 2

Oklo, Gabon

natural reactor

1.7 billion years ago, a natural reactor started to operate in Oklo, Gabon in West Africa, and produced energy, with some interruptions, over a period of several million years. In 1970, French scientists found a very unusual ratio of isotopic abundances of $^{235}\mathrm{U}/^{238}\mathrm{U}$ in a mine in Oklo. On Earth, in meteorites, and in lunar rock – just as in the whole solar system – the uranium isotope $^{238}\mathrm{U}$ occurs with an abundance of 99.3% and that of $^{235}\mathrm{U}$ with an abundance of 0.7%. Other uranium isotopes ($^{233}\mathrm{U}$, $^{234}\mathrm{U}$) are quite rare in comparison. The present isotopic ratio $r = \frac{N(^{235}\mathrm{U})}{N(^{238}\mathrm{U})}$ is consistent with the assumption that these two isotopes were of equal abundance during the formation of our solar system. Because of the different half-lives of the isotopes ($T_{1/2}(^{238}\mathrm{U}) = 4.5 \times 10^9$ yrs, $T_{1/2}(^{235}\mathrm{U}) = 7.1 \times 10^8$ yrs), these isotopes developed the currently observed abundance over the course of time.

It came as a surprise that the isotopic abundance of $^{235}\mathrm{U}$ was only 0.35% in the Oklo mine. Comparable values of $^{235}\mathrm{U}$ are also found in spent fuel elements of modern nuclear power plants. Since the observed isotopic abundance of other elements also corresponded to those which are found in nuclear power plants, it was natural to assume that a natural chain reaction and nuclear fission

isotopic abundance

isotopic anomaly

had been running in the Oklo mine. If the present global ^{235}U abundance is extrapolated back in time to the time when the Oklo reactor was in operation, one arrives at a ^{235}U concentration of about 3%.

The rocks in the Oklo mine are very porous and they have many cracks. They are therefore very permeable to rainwater (see Fig. 12.16). Rainwater entering the uranium-containing mineral is an ideal moderator for neutrons. Due to spontaneous fission, or also by cosmic rays, there are always some neutrons available which can initiate nuclear-fission processes. Neutrons created in fission processes are relatively fast, but they will be moderated by the rainwater and initiate a chain reaction and sustain it for a while. The energy created in this way will lead to evaporation of the water, thereby interrupting the chain reaction, because the fast fission neutrons are now no longer moderated. Only if further water enters the rock or if the evaporated water condenses, will the chain reaction restart. Apart from this natural phase transition of the water the natural reactor was certainly also modulated by the alternating rainy and dry seasons in West Africa at the time. It is assumed that the Oklo reactor reached thermal powers of about 100 kW. From the fission products one can estimate that several tons of uranium were processed and also a substantial quantity of plutonium was bred. Of course, the Oklo reactor stopped working when the abundance of ^{235}U fell below a certain critical limit.

rainwater
moderator for neutrons
chain reaction
thermal powers

The fission products of the natural reactor and the transuranic elements bred (e.g. ^{244}Pu, $T_{1/2} = 8.26 \times 10^7$ yrs) migrated only a few meters from where they had been created. They stayed essentially where they were produced. They were also not distributed or washed away by the ground water. In this experiment, which cannot be repeated in a laboratory, nature demonstrated that over a period of 1.7 billion years, certain geological formations are suitable as natural deposit for radioactive waste.

natural deposit

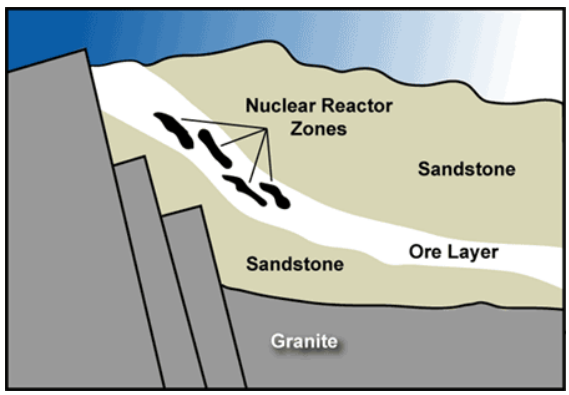


Figure 12.16
Sketch of the uranium-containing deposits held in position in the surrounding geological formation over a long period in the Oklo reactor. Image credit: U.S. Department of Energy, Office of Civilian Radioactive Waste Management, Yucca Mountain Project

Example 3

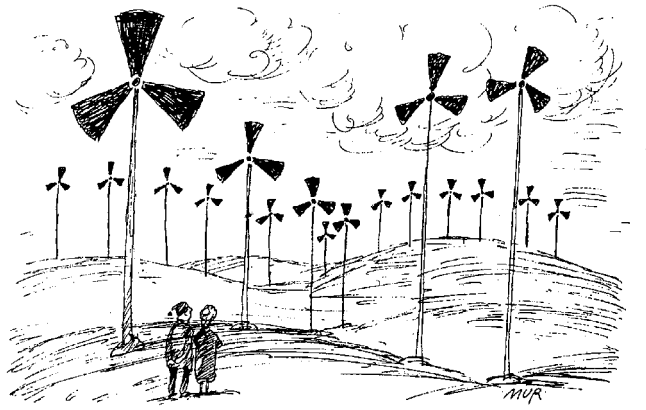
Even after shutdown of a nuclear reactor, still a significant quantity of energy is produced in the form of beta and gamma radiation. This radiation is the result of radioactive decays of highly radioactive fission products produced in fission reactions. It is therefore important to maintain the cooling even after the reactor has been shut down. Immediately after shutting down a reactor, about 7% to 10% of the nominal power is still created by radioactive decays. This activity, responsible for the energy generation after shutdown, will decrease quite rapidly because many fission products are quite short-lived. The cooling system of the reactor, however, should stay in operation for a period of several hours after the reactor has been shut down. If cooling after shutdown is not provided, the temperature of the reactor might increase in an uncontrolled fashion and might even cause the uranium to melt.

cooling after shut down

Exactly that happened near Harrisburg in the Three-Mile-Island reactor in the year 1979. After a fast automatic reactor shutdown the cooling water pumps were also switched off due to an erroneous interpretation of the state of the reactor. Since the heat generated by the radioactive decays of the fission products could no longer be dissipated, the fuel elements got very hot and some even melted. As a consequence of this accident, fission products of high radioactivity entered the primary circuit. Furthermore, gaseous fission products (e.g. $\approx$ 40 PBq of ^{133}Xe) were directly discharged into the atmosphere. Luckily the molten reactor core was retained in the reactor tank by the primary containment system, so the radioactive exposure for the environment was rather small.

Harrisburg
Three-Mile-Island reactor
fast reactor shutdown

containment system



Windy Alternative

Summary

Nuclear fission discovered by Hahn and Straßmann in 1938/39 and correctly interpreted by Meitner and Frisch has led to military and civil use of nuclear power. The transformation of mass into energy can be realized by fission of heavy elements but also by the fusion of hydrogen to helium, the energy production mechanism which makes the stars shine. There are a number of different ways to put nuclear fission and fusion into practice. Carefully designed fission reactors based on water-cooled, water-moderated reactor types or pebble-bed reactors guarantee a high degree of safety. The design, implementation, and specific construction of a fusion reactor, however, is still under research and development. In the long term, the energy demand of mankind will very likely have to include the mechanism of gaining energy with the help of nuclear fusion, as it is demonstrated by the stars in a natural way.

12.4 Problems

Problem 1 After the shutdown of a boiling-water reactor, the cooling was also switched off by mistake. Let us assume that 10% of the original reactor power (1 GW) will be provided by radioactive decays of the fission products. About 70% of this fraction will be released typically over a period of 200 seconds. By how much will the temperature of the reactor increase (50 tons of uranium)? The specific heat of uranium at 25°C is 116 J/(kg K).

Problem 2 It is assumed that the Oklo reactor produced energy intermittently over a period of 10^6 years, with peak powers of up to 100 kW. Work out the amount of ^{235}U processed, if one assumes that the reactor had an average power of 50 kW over a period of half a million years.

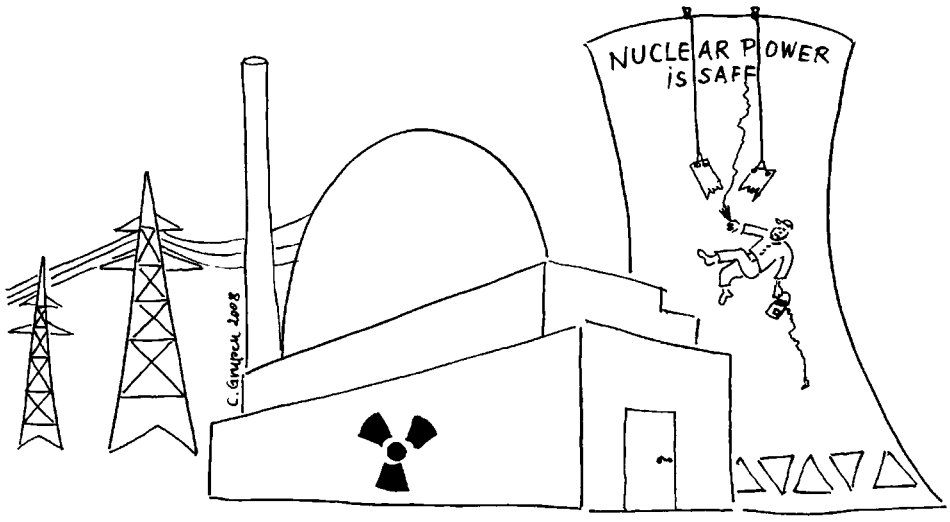
Problem 3 The present isotopic abundance of ^{235}U in the Oklo reactor is 0.35%. Work out the age this uranium deposit would have if this particular value of the isotopic abundance had been caused only by normal radioactive decay. For the solution of this problem it is natural to assume that the uranium isotopes ^{235}U and ^{238}U were originally of equal abundance.

Problem 4 The dose rate after a nuclear accident or a nuclear-weapon explosion decays with time according to

dose rate

$$\dot{D}(t) = \dot{D}(t_0) \left(\frac{t}{t_0} \right)^{-\alpha} ,$$

where $\alpha = 1.2$ and $\dot{D}(t_0)$ is the dose rate at the time t_0. Assume that $\dot{D}(t_0 = 6\,\mathrm{h}) = 10\,\mathrm{mSv/h}$, and work out
a) the dose rate after one further day;
b) the integral dose which one obtains if one stays in this area over a period from $t_1 = 30\,\mathrm{h}$ to $t_2 = 40\,\mathrm{h}$.



13 Biological Effects of Ionizing Radiation

"The technology used to detect if vehicles are carrying radioactive material is so sensitive it can tell if a person recently received radiation as part of a medical procedure."

Timothy Murphy

Any radiation exposure might have negative effects on health. This can be considered as the basic principle of radiation protection. It is therefore no surprise that radiation damage due to ionizing radiation was first observed right after the discovery of radioactivity by Becquerel. The biological effect of ionizing radiation is a consequence of the energy transfer by ionization and excitation to body cells. The radiosensitivity of tissue is directly proportional to the reproductivity of cells it is made of (mitosis) and inversely proportional to the differentiation of the cells. If the mitosis in tissue proceeds at a high pace, only very little time remains for repairing damage before the next division of the cell occurs. The highest sensitivity of humans exists during the embryonic state. This is caused by the fact that the primordial organs at this time consist of relatively few cells. If these are damaged, there are no other intact cells which could replace them.

physical–biological effects of radiation

The physical–biological effects of radiation absorption are shown in Fig. 13.1 in detail. Figure 13.2 shows a very rough classification of different types of radiation damage. Usually they are divided into three different categories:

early effects

- Early effects: This radiation damage occurs immediately after the irradiation. From a whole-body dose of 0.25 Sv upwards a modification of the hemogram is visible. From 1 Sv on clear symptoms of radiation sickness are to be expected. However, the recovery of the patients is nearly guaranteed. For a whole-body dose of 4 Sv the chance of survival is 50%. This dose is called the lethal dose. For a dose of 7 Sv the mortality is nearly 100% (see Fig. 13.3).
  For high radiation doses the symptoms of radiation sickness occur within a few hours of irradiation. The symptoms are headaches, nausea, and vomiting. Depending on the dose these symptoms will disappear after some time. After a quiet state of several days almost without any symptoms the second phase of the radiation sickness starts. The symptoms are then fever, hemorrhage, vomiting of blood, bloody feces, and loss of hair. For higher radiation doses the quiet phase is shortened or may not even occur. If the

radiation sickness

lethal dose

course of disease

C. Grupen, *Introduction to Radiation Protection*,
Graduate Texts in Physics, DOI 10.1007/978-3-642-02586-0_13,

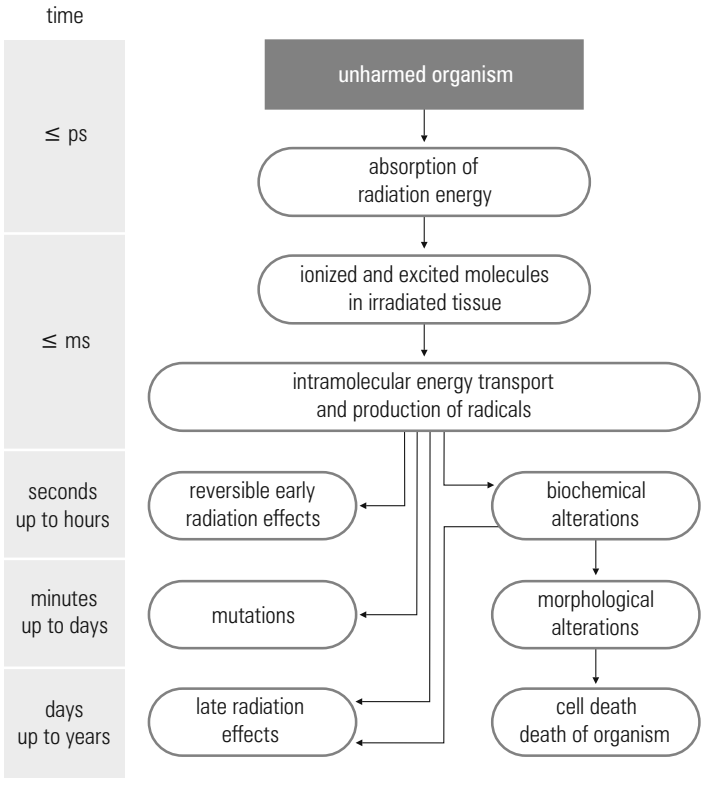


Figure 13.1
Development of the physical–biological effects of absorbed radiation energy

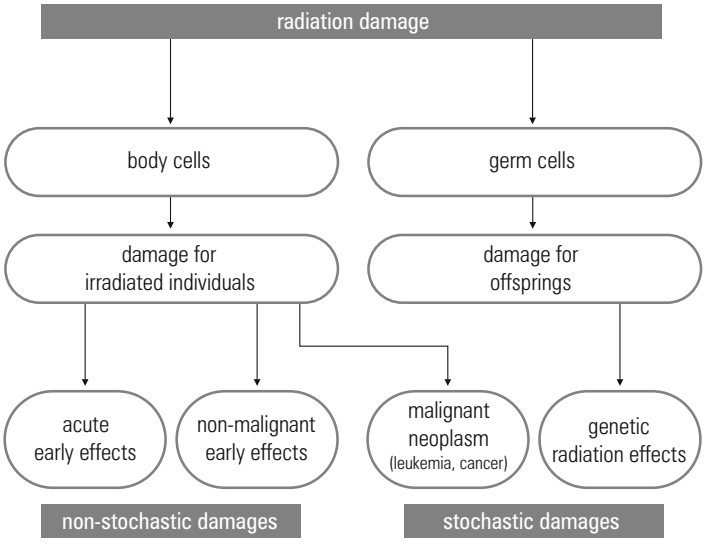


Figure 13.2
Overview over the different kinds of radiation damages

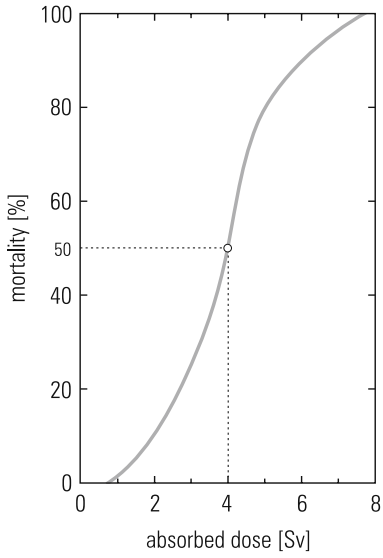


Figure 13.3
Mortality after 30 days as a function of the whole-body dose for humans

exposed person survives for eight weeks, there is good reason to expect a complete recovery from radiation sickness. However, in some cases death can also occur after several months.

There are a number of repair mechanisms in biological tissue. Therefore, a threshold dose for early effects after irradiation exists, below which no permanent damage is observed. This threshold dose depends on the time distribution of the dose. Radiation exposure from natural radiation is certainly well below this threshold. According to current wisdom there is, however, no threshold dose for stochastic late radiation damage and genetic effects.

late effects
cancer

- Delayed radiation damage: A typical late effect is cancer after a period of latency, which can amount to several decades. In contrast to prompt damage, whose effect is proportional to the received dose, delayed radiation-damage effects represent a

stochastic risk

stochastic risk, which means the probability of a damage to occur depends on the dose, but nothing can be said about whether the

cancer risk

sickness will be serious or not. The total cancer risk per absorbed dose of 10 mSv is estimated to be to about 5×10^{-4}. This means that out of 10 000 people being irradiated with 10 mSv, on average five of these will develop cancer.

It is generally assumed that the relation between the probability to develop cancer and the absorbed dose is linear (see Fig.

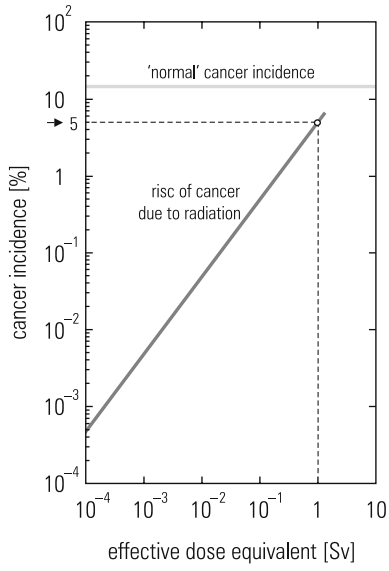


Figure 13.4
Dependence of the radiation risk on the absorbed whole-body dose in comparison to the 'normal' incidence of cancer

13.4).[1] Also a quadratic dependence of the cancer probability on the equivalent dose is discussed. If this were true, extrapolations of damage from high to low doses would lead to much smaller cancer risks for low doses compared to a linear response. Some scientists even assume that humans have no sense organ to warn against ionizing radiation because they do not need one since low doses do not present any risk.[2]

low radiation doses

It is interesting to compare the cancer incidence as a result of exposure to radiation with other risks. The probability to suffer a fatal accident (traffic accident, in-house accident, ...) is about 5×10^{-4} per year, which is comparable to the total cancer risk after a whole-body exposure of 10 mSv.

- Genetic damage: radiation absorption in germ cells can result in mutations. For the irradiated person mutations are not recognizable. They will only manifest themselves in the following generations. During the genetically significant age of humans (up to the age of 35) about 140 genetic mutations occur due to environmental factors. A radiation exposure of 10 mSv will add another 2 mutations; this corresponds only to one or two per cent of the natural rate of mutations. The average risk factor for radiation

genetic damage
mutations

rate of mutations

[1] This is the essence of the LNT hypothesis (Linear No-Threshold). In addition to the assumption of a linear dependence it is argued that there is no threshold for radiation damage. The assumption of a 'no-threshold' effect is certainly rather conservative.

[2] Zbigniew Jaworowski, Physics Today, Sept. 1999, page 24–29

effects, which can be inherited in the first two generations, is estimated to be 10^{-4} per 10 mSv.

risk factors

The risk factors for malignant late radiation damage are very low for doses in the range of several millisievert. In individual cases it is therefore impossible to establish correlations between an observed sickness and a possible irradiation, since the natural rates of cancer and mutations are usually much higher. It is even controversial at the moment whether low doses (several millisievert per year) are generally harmful for humans or possibly even helpful ('hormesis'). The argument is that life and mankind developed under a permanent irradiation by natural radioactivity. For the purposes of radiation protection, however, one must assume that any additional irradiation should be avoided if possible.

hormesis

It should be mentioned that there are certain chemical substances which can modify the biological effect of radiation quite substantially. For example, oxygen, bromouracil, and fluorouracil increase the radiation sensitivity, i.e., they sensitize the human tissue. Also the water content in the cell has quite a large influence on the radiation sensitivity because of the increased production of H_2O radicals. All carcinogenic substances also increase the sensitivity of tissue.

sensitizers

water content

fractionated irradiation

regeneration mechanisms

The effect of radiation is reduced for fractionated irradiation. Obviously, regeneration mechanisms come into play which repair radiation damage between the individual fractions. Also a higher resistance is observed after a pre-irradiation. The method of fractionated irradiation or pre-irradiation can mitigate early radiation damage, however, they do not reduce the genetic risk and cancer risk.

radioprotective substances

In the same way as sensitizing substances exist there are also radioprotective substances. For example, mice will survive a radiation dose of 7 sievert if they receive an injection of cystamine before the irradiation, while this dose is lethal for mice without injection of cystamine.

It is also possible to remove incorporated radioactive substances from humans by administering suitable drugs. These methods of

"I like this radioactively enriched food.
It strengthens my immune system!"

methods of decorporation

decorporation rely essentially on inhibiting resorption or intensifying the elimination of the radioactive substances from the body. The best results for intensifying the elimination of radioactive substances have been obtained with DTPA (diethylenetriamine pentaacetate) and EDTA (ethylenediamine tetraacetate) (compare Fig. 13.5).

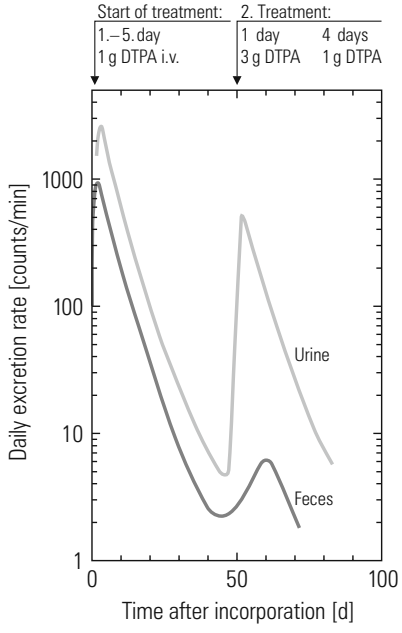


Figure 13.5
Excretion of plutonium in urine and feces for humans after accident-caused incorporation of plutonium

physical half-life

biological half-life

The activity of incorporated radioactive substances usually decreases much faster than it would compared to the physical half-life ($T_{1/2}^{\text{phys}}$) of the incorporated radioactive material.

The effective half-life must also include the biological half-life $T_{1/2}^{\text{bio}}$ (for more details on the isotope-specific effective half-lives see Appendix N). This is the time in which a biological system eliminates half of the incorporated substance in a natural way. Including this biological half-life the effective half-life is worked out from the decay constants:

$$\lambda_{\text{eff}} = \lambda_{\text{phys}} + \lambda_{\text{bio}} \ , \tag{13.1}$$

$$T_{1/2}^{\text{eff}} = \frac{T_{1/2}^{\text{phys}}\, T_{1/2}^{\text{bio}}}{T_{1/2}^{\text{phys}} + T_{1/2}^{\text{bio}}} \ . \tag{13.2}$$

Figure 13.6 shows the decrease of ^{137}Cs ($T_{1/2}^{\text{phys}} = 30\,\text{yrs}$) stored in the body of humans and some mammals. As can be seen, the effective half-life of ^{137}Cs for humans is about 110 days.

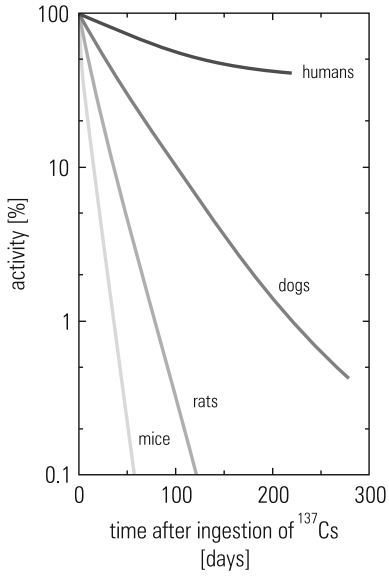


Figure 13.6
Decrease of the accumulated ^{137}Cs in the body for humans and for various mammals

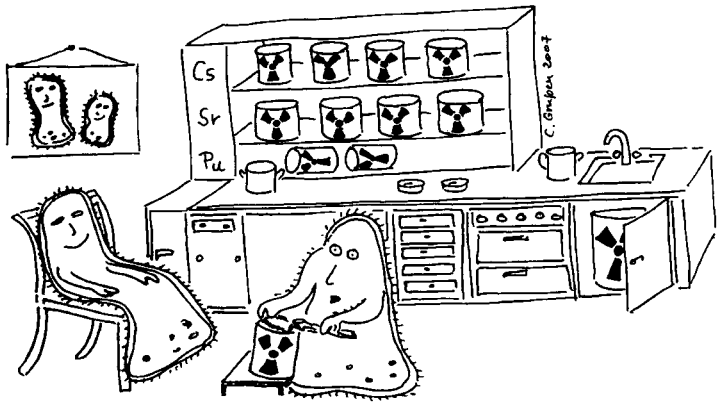
radiation sensitivity

It remains to be mentioned that animals are resistant against ionizing radiation in a different way. For example, the lethal dose for all mammals is about the same (humans: 4 Sv, dogs: 4 Sv, apes: 5 Sv, rabbits: 8 Sv, marmots: 10 Sv). In contrast to that, spiders with a lethal dose of 1000 Sv and viruses with 2000 Sv are much more resistant against ionizing radiation. A conceivable nuclear holocaust would probably only be survived by spiders, viruses, bacteria, and certain types of grass.

deinococcus radiodurans
micrococcus radiophilus

The bacteria deinococcus radiodurans and micrococcus radiophilus can even survive a dose of 30 000 Sv based on their extraordinary ability to repair radiation damage. Bacteria of the type deinococcus radiodurans have been found even in the hot reactor core of nuclear power plants. These bacteria somehow manage to repair DNA damage with the help of a special enzyme system, even if the helix structure of the DNA exhibits about one million breaks. Deinococcus radiodurans is also able to decompose highly radioactive waste into its components which can then more easily be disposed of. Because of the high level of resistance against radiation and extreme temperatures these organisms can survive in meteorites under space conditions over a long time. Consequently they can also propagate over large distances. Therefore they represent good candidates for the origin of life on Earth, since our planet presents suitable conditions for their development. It is conceivable that the evolution on Earth was initiated by the impact of meteorites containing such organisms (‘panspermia’).

‘panspermia’



"Deino, what do you think about some delicious cesium dessert?!"

Apart from damage due to ionizing radiation favorable effects after radiation exposures have also been observed. This effect is called hormesis. It is suggested that low doses of non-natural radiation might increase the lifetime of cells. The idea is that cells are able to repair minor damage as caused by natural radioactivity and that cells become more resistant if they are regularly stimulated to repair themselves by being exposed to additional non-natural low-level radiation.

hormesis

13.1 Supplementary Information

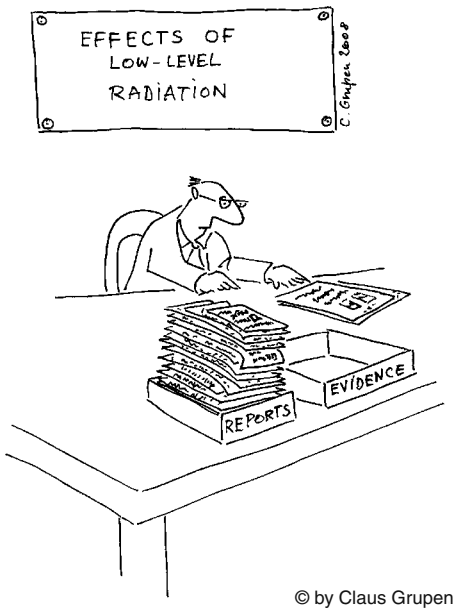
Example 1

risk factor
radiation-induced cancerogenesis

Based on cancer incidents in the aftermath of radiation accidents or after the dropping of nuclear bombs on Hiroshima and Nagasaki, a risk factor for the occurrence of radiation-induced cancerogenesis can be inferred. The estimations on risk factors due to ionizing radiation normally assume that there is a linear relation between the absorbed dose and the probability of radiation-induced cancer and that there is no threshold dose (LNT hypothesis, Linear No-Threshold). For this purpose a risk factor is defined: If N persons are exposed to a whole-body dose equivalent H and if n persons develop a stochastic radiation effect, then the risk factor is defined by

$$f = \frac{n}{H\,N} \ .$$

Initially, the risk factors had been developed based on cancer types with relatively short latency periods like leukemia. With the help of biochemical models these results have been extrapolated to other types of cancer. The results of approximations to very low doses



are, however, somewhat problematic. Additional hypotheses are required to arrive at risk factors which are believed to be reliable for very low doses (something like 20 to 50 mSv), which are of interest for radiation-protection purposes. In the early 1980s the risk factors determined in this way led to values for radiation-induced cancer of 1.3% per sievert. Based on new results and better models and the conservative assumption of a linear relation between dose and effect, even down to very low doses, one now assumes that a somewhat higher risk factor of 5% per sievert is justified. The risk factor for different types of radiation-induced cancer, determined according to the present state of the art, are compiled in Table 13.1.

relation between dose and effect

For radiation workers being exposed to a total dose of 400 mSv over the full lifetime the total risk amounts to 2%, which means that for 1000 persons working under these conditions about 20 will develop a radiation-induced cancer. Such an occupational risk appears to be acceptable.[3]

occupational risk

[3] It is well-known that Marie Curie, who handled measurable quantities of polonium and radium in her laboratory, finally died of leukemia. In contrast, Otto Hahn lived until old age. The fact that he did not share the same fate as Marie Curie was considered as a miracle. An American colleague visiting Otto Hahn commented on this phenomenon very drastically: "After having received such high doses from your experiments it is really a shame that you are still alive!"

concerned organ or tissue	risk factor for 10 mSv whole-body irradiation
red bone marrow (leukemia)	50×10^{-6}
periosteum, surface of bones	5×10^{-6}
colon	85×10^{-6}
liver	15×10^{-6}
lung	85×10^{-6}
esophagus	30×10^{-6}
skin	2×10^{-6}
stomach	110×10^{-6}
thyroid gland	8×10^{-6}
bladder	30×10^{-6}
chest	20×10^{-6}
ovaries	10×10^{-6}
other organs or tissue	50×10^{-6}
total radiation-induced cancer risk	500×10^{-6}
genetic risk	100×10^{-6}

Table 13.1
Risk factors for radiation-induced cancer[4]

Compared to this, the equivalent dose for the bronchi of a strong smoker (two packets of cigarettes daily) might be as high as 5 Sv over a period of 25 years. This would lead to a lung-cancer risk or risk of a cancer of the bronchi on the order of magnitude of 5%. If, in addition, the carcinogenic effect of nicotine and tar is considered, one arrives at a total risk of cancer for the lungs and bronchi for strong smokers of about 30%. This high value is obtained because the cancer risks due to ionizing radiation and chemical effects will multiply.

lung-cancer risk by smoking
bronchi-cancer risk by smoking

In addition to individual risk factors, other quantities are also defined which characterize the radiation risk for population groups.[5] If R is the mortality rate in a group of radiation-exposed people, and R_{ref} the corresponding mortality rate in a non-irradiated control group, one defines

$$\delta = \frac{R}{R_{\mathrm{ref}}}$$

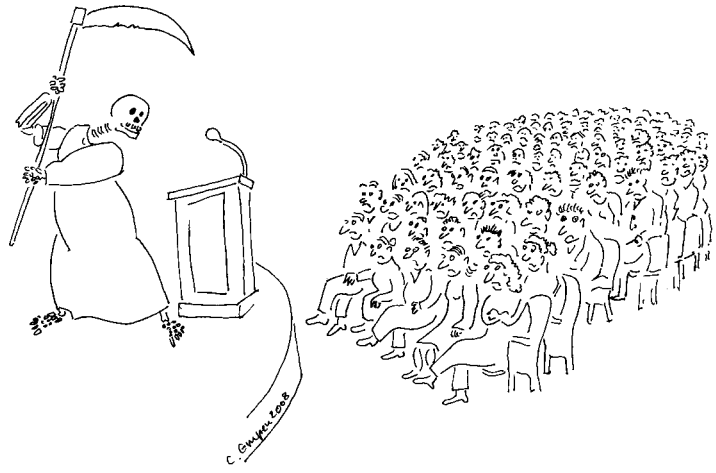
as relative risk ($\delta = 1$ means that there is no additional risk). The excess relative risk ERR is defined as

excess relative risk

$$\mathrm{ERR} = \frac{R}{R_{\mathrm{ref}}} - 1 \ .$$

[4] The relatively few cases of cancer incidence after the Chernobyl accident appear to indicate that the risk factors have been estimated somewhat pessimistically.

[5] P. Jacob, W. Rühm, H.G. Paretzke; Physik Journal, Vol. 5, p. 43, April 2006



"Someone of you has to take the 1 mSv risk!"
© by Claus Grupen

Frequently this excess relative risk is normalized to a dose of 1 Sv leading to

$$\beta = \frac{\mathrm{ERR}}{H} \ .$$

As an example, the relative risk δ for $\beta = 3$ and a dose of 1 Sv is obtained as

$$\frac{R}{R_{\mathrm{ref}}} - 1 = 3 \ \rightarrow \ \delta = \frac{R}{R_{\mathrm{ref}}} = 4 \ ,$$

risk in the group of exposed people

which means that the risk in the group of exposed people is higher by a factor of four compared to the non-exposed reference group.

additional absolute risk

Occasionally also the additional absolute risk α is given:

$$\alpha = \frac{R - R_{\mathrm{ref}}}{H} \ .$$

If, for example, five additional cases of mortality over a period of 10^3 person-years for a dose of 1 Sv are observed, one can work out the number of expected mortality cases in some other group of people. For a group of 100 people five cases are expected in 10 years, because

$$R - R_{\mathrm{ref}} = \alpha(1\,\mathrm{Sv}) = \frac{5}{10^3\ \text{person-years}} \times 100\ \text{persons}$$
$$= \frac{5}{10\ \text{years}} \ .$$

Example 2

food irradiation
food conservation
sterilization

In many countries food is irradiated by gamma rays to kill microorganisms and to increase the durability of food or even to sterilize it. In the same way the germination of food can be prevented by ionizing radiation. The ripening of food during long transports can also be retarded by irradiation.

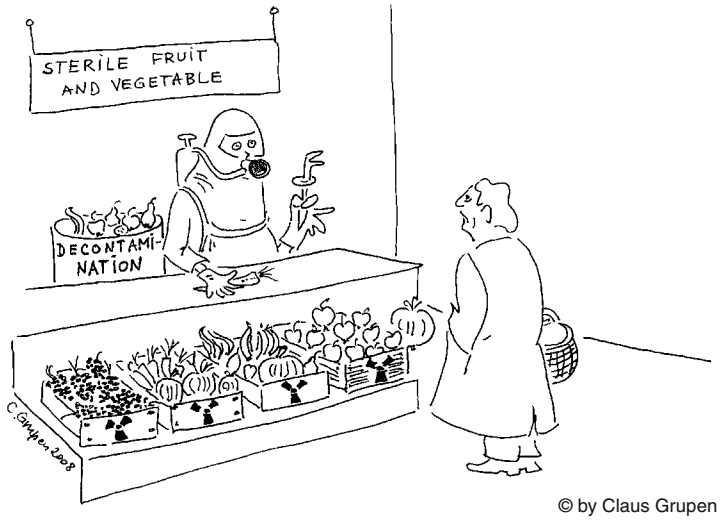
For this purpose radiation sources emitting γ rays are used because α and β rays do not provide sufficient penetration. Most frequently the isotopes ^{137}Cs ($E_\gamma = 662\,\text{keV}$) and ^{60}Co ($E_{\gamma_1} = 1.17\,\text{MeV}$, $E_{\gamma_2} = 1.33\,\text{MeV}$) are used.

Since microorganisms usually exhibit very high radiation resistance, the food must be exposed to extremely high doses. To prevent the germination of onions and potatoes doses between 10 and 1000 Sv are chosen. The reduction of microbes even requires between 1000 to 10 000 Sv, and for sterilization one has to use doses up to 50 000 Sv.

These techniques for food conservation are questionable for a number of reasons:

- even at high doses a complete kill rate of germs cannot be guaranteed;
- the increase of stability of food mostly goes along with loss of aroma;
- vitamins and proteins are damaged or even destroyed by γ rays;
- γ rays also produce highly reactive radicals, which are suspected to favor the occurrence of cancer;
- germinating and spoilt food can be 'improved' by irradiation and made marketable again;

risks of food irradiation



- warnings against spoilt food (e.g. due to bad smell) are suppressed because microorganisms creating this bad smell might have been killed by the irradiation;
- in a similar way as bacteria can develop resistance against antibiotics also microorganisms might develop resistance against ionizing radiation.

Contrary to common belief the food does not get radioactive by irradiation. To produce induced radioactivity the γ energy has to be on the order of magnitude of the binding energy per nucleon; that means it has to exceed a minimum value of 5 MeV. Most γ emitters fall below this margin.

sterilization by radiation

Sterilization by ionizing radiation plays also a role in the maintenance of reusable instruments and implements in health care and clinical medicine. For this purpose the radiation resistance of bacteria, fungi, viruses, and prions must be known, so that these microorganisms can be definitely inactivated by γ radiation.

Example 3

fighting the tsetse fly

A breakthrough in fighting the tsetse fly on the island of Zanzibar was achieved by the so-called sterile-insect technique.[6] The tsetse fly had infected animals with the devastating epidemic trypanosomiasis and had spread the terrible sleeping sickness (epidemic encephalitis) among humans in Africa. Due to the sterile-insect technique this fly was practically eradicated on Zanzibar. In this method tsetse flies are bred in a research laboratory in large quantities, and the male flies are sterilized with low-level γ rays.[7] The infertile

sterile-insect technique

[6] carried out be the International Atomic Energy Organisation IAEO based in Vienna

[7] Since it is next to impossible to separate male from female insects, all bred flies are irradiated.

"Yesterday they put me on a radioactive diet; today I am testing cigarettes!"

males are released from planes over Zanzibar. They mate with feral females, which remain without offsprings. The release of 8 million sterile male tsetse flies decreased the rate of trypanosomiasis among cattle from 20% to below 0.1%. The success of this sterile-insect technique was eased by the fact that out of a total of 22 different species of this fly only one type existed on Zanzibar. In addition, the isolated location of an island is particularly suited for such an endeavor.

The sterile-insect technique has also successfully been used to eradicate the screw-worm fly (cochliomyia hominivorax) in areas of North America. There have also been many successes in controlling species of fruit flies using this technique. This biological method can also be considered to control the population of some species rather than eradicating it.

control of populations

Example 4

cryptococcus neoformans

fungus living on radioactivity

The fungus cryptococcus neoformans appears to exhibit the astonishing ability to transform the energy of ionizing radiation into usable energy. The fungus was described for the first time in greater detail in 1976. Its special accomplishment became generally known when it was found after the Chernobyl accident in the sealed nuclear reactor. Fungi, in general, are rather radiation resistant. They can survive radiation doses of up to 30 000 Sv. Cryptococcus neoformans can even transform the energy of ionizing radiation into an energy variety which can be used by it. It is suspected that the fungus achieves this by melanin, a class of compounds found in plants or animals, where it serves predominantly as a pigment. The metabolism of cryptococcus neoformans increases significantly under irradiation. Obviously, cryptococcus neoformans cannot only endure high levels of radiation, but it also gains benefit from it. In a similar way as normal plants can transform electromagnetic radiation from the visible range into chemical energy by photosynthesis, it is conceivable that this fungus can convert energy from the γ energy range into usable biomass energy.

As a side remark, cryptococcus neoformans can also cause meningitis, especially as a secondary infection for AIDS patients.

Example 5

protective drugs against high-level radiation

Radiation damage is one of the most frightening aspects of nuclear emergencies. But also serious side effects of radiation in the treatment of cancer patients cause much concern. Therefore news about protective drugs against high-level radiation are highly welcomed.[8]

A new drug, derived from salmonella, can protect mice and monkeys from radiation effects if it is administered before exposure to

[8] L.G. Burdelya et al. Science, **320**, 226, 2008, and `http://medheadlines.com/2008/04/11/new-drug-prevents-radiation-damage/`

radiation, even if the lethal dose is exceeded. The big advantage for cancer treatment is that the drug hardly affects normal cells, while leaving tumor cells vulnerable. The new compound uses a trick that normally is applied by the cancer cells themselves.

apoptosis
cellular suicide

The trick is cellular suicide (apoptosis). When healthy cells are exposed to radiation, even at doses that produce damage that can be repaired, they instead appear to commit suicide.

In contrast, cancer cells find a way to block apoptosis, thereby allowing cancerous tumors to grow. The researchers succeeded to imitate this tumor trick by blocking apoptosis in healthy tissue by introducing the newly developed drug, which is a protein made from bacteria in the gastrointestinal tract.

When mice were given this drug an hour after receiving rather high doses of radiation, their survival rate still improved, however, the effect was not as dramatic as when it was given beforehand.

radioprotective drug

The big advantage of this new radioprotective compound is that it protects normal cells from radiation damage while leaving the tumor cells sensitive.

Example 6

Metabolism of plutonium[9]

Manhattan Project

In the course of the construction of the first nuclear bombs in the United States (the Manhattan Project) the workers building the bombs were exposed to dust particles containing plutonium. Naturally, the question arose about the biological effects of inhaled plutonium. One of the bombs was made of enriched ^{235}U and the other of ^{239}Pu.

There were warnings of potential health risks and it was suggested to undertake immediate studies to understand the metabolism of plutonium. A small fraction of the plutonium that was separated for the bombs was allocated for animal studies. The plutonium was injected into different animals, and the excretion and retention rates were studied. Since these rates differed substantially for different species, it was difficult to correlate animal excretion and retention data to humans. As a result it was proposed to administer small amounts of plutonium to humans to obtain reliable excretion and retention data.

animal studies with plutonium

effect of plutonium in humans

In this framework plutonium was injected into hospital patients at Rochester and Chicago. The patients were thought to be either terminally ill, or to have a life expectancy of less than ten years either due to age or chronic diseases. Different quantities between a few and up to about 100 µg were administered, corresponding to activities of up to 220 kBq. After injection samples of blood, urine, and feces were analyzed at Los Alamos. The physicists and physi-

[9] William Moss, Roger Eckhardt, The Human Plutonium Injection Experiments, Los Alamos Science Report No. 23, 1995.

cians felt reasonably certain that there would be no additional harm to those patients who suffered already from cancer.

The urinary excretion curves showed a rapid initial rate, although much slower than those for radium, and a levelling off after about 20 days was observed. A prolonged retention rate was found making the problem of chronic plutonium poisoning a matter of serious concern.

retention and excretion of plutonium

Out of the tracked 16 patients ten died within ten years. Four patients survived more than 20 years. Three of the four survivors were examined in 1973, 28 years after the injections had taken place, providing long-term patterns of plutonium retention and excretion. The results of these studies were used as source for estimating tolerance limits in the framework of radiation-protection regulations.

Naturally, these experiments with radioactive substances on humans raised questions about medical ethics, especially also because the absence of informed consent of the selected patients.

Summary

Biological effects of ionizing radiation are subdivided into early and late damages. Early effects are only observed for doses larger than 250 mSv. In this case the seriousness of the damage is proportional to the dose. The lethal dose (50 per cent mortality) is around 4 sievert for humans. Late effects are characterized by a rather long latency (typically 20 years). Here, the severity of the damage does not depend on the dose, rather the probability of occurrence is proportional to it. Ionizing radiation can also cause mutations in germ cells.

13.2 Problems

Problem 1

^{137}Cs is stored in humans with a biological half-life of 111 days ($T_{1/2}^{\text{phys}} = 30$ yrs). Assume that a singular quantity of ^{137}Cs, namely, 4×10^6 Bq, was incorporated in the course of an accident. Work out the ^{137}Cs content of the worker who was involved in the accident after three years.

Problem 2

Assume that the human pancreas (mass 50 g) contains 120 kBq (3.25 µCi) of ^{14}C. Estimate which fraction of β rays escapes from the pancreas! Work out the radiation exposure of the pancreas and the surrounding tissue.
(The average energy of electrons from ^{14}C decay is 45 keV. One can assume that the ^{14}C isotope is uniformly distributed in the pancreas.)

Problem 3

In the early days shining dials (e.g. in clocks) contained ^{226}Ra. The radium solution was applied with paint brushes to the hands and dials of the clocks. The dial painters, a profession traditionally practised by women only, wetted the paint brushes frequently with their lips causing a partial incorporation of the radium isotope.

Estimate the 50-years commitment dose equivalent of a dial painter after a singular incorporation of 1 µg of radium 226, if the biological half-life for this radium isotope in the gastrointestinal tract is assumed to be 300 days.

Figure 13.7
Radium dial painters working in a factory in the United States around 1920 (`http://en.wikipedia.org/wiki/Radium_Girls`)

14 Radiation Accidents

"Although personally I am quite content with existing explosives, I feel we must not stand in the path of improvement."

W. Churchill 1874–1965 (about the development of nuclear bombs 1945)

Many radiation accidents in the fields of medicine and technology are caused by losses and careless disposal of radioactive material. The reason for unnecessary exposures is frequently due to improper storage of disused radioactive sources. Unused sources have been found in scrapyards where they were 'discovered' by children, who were fond of finding pieces of e.g. good-looking silver-gray cobalt metal, which, in fact, was highly radioactive and dangerous. Table 14.1 shows a number of examples of losses of radioactive sources and events of accidental irradiations.

Table 14.1 Radiation accidents with radioactive sources

year	place	source and application	activity	fatal casualties	comment
1962	Mexico	^{60}Co radiographic gauge for metal structure analysis	5 Ci	4	discovered by children
1963	China	^{60}Co for seed irradiation	10 Ci	2	discovered by children
1978	Algeria	^{192}Ir for industrial radiography	25 Ci	1	accidental exposition of workers
1987	Brazil	^{137}Cs nuclear medicine	10 Ci	4	discovered by children

Radiation accidents in large manufacturing plants and nuclear-medical sections of hospitals are frequently caused by non-existing elementary safety rules. In the case of existing safety rules they are often ignored. It is also essential that the maintenance personnel are suitably trained and aware of the radiation risks. Radiation-protection regulations must be meticulously respected, otherwise accidental irradiations or even accidents may occur.

missing safety rules

respect safety rules!

An example of gross human failure is the radiation accident in a hospital in Indiana, Pennsylvania/USA, in the year 1992: In the

C. Grupen, *Introduction to Radiation Protection*,
Graduate Texts in Physics, DOI 10.1007/978-3-642-02586-0_14,

brachytherapy

framework of brachytherapy an elderly lady was irradiated with an iridium source, and it was forgotten to remove the source after the treatment.[1] When the patient excreted the catheter containing the source four days later, the catheter, including the source, was thrown into the garbage by a nurse. The patient died the following day without realizing that the death could have been related to the excess radiation. During the time of storage and garbage collection many people were accidentally exposed to radiation over a period of 90 days. The loss of the iridium source was only discovered when radiation monitors in the waste-management facility triggered an alarm.

loss of sources

Only in recent times, after the period of the Cold War has it become public how many radiation accidents occurred in military operations in the past. These include plane crashes with nuclear weapons on board, sunk nuclear-operated submarines, or the loss of missiles or satellites which carried radioactive materials.

radiation accidents in military operations

Nuclear reactors gain energy by fission. During the operation of such reactors 'incidents' of different severities occasionally occur. The most severe accident in a nuclear reactor to date happened in Chernobyl in 1986. This catastrophe was the result of a flawed electro-technical experiment at an inherently unsafe reactor which was badly carried out. In this fatal experiment a large fraction of the radioactive inventory was released into the environment. The water-cooled graphite-moderated reactor contained a total of 150 tons of natural uranium, with a total activity of 3.2×10^{19} Bq, including the fission products in the reactor core. The gaseous components (radioactive ^{85}Kr (3.3×10^{16} Bq) and ^{133}Xe (1.7×10^{18} Bq)) escaped completely from the reactor. The fractions of the other fission products which were released (iodine 131, cesium 137, strontium 90, lanthanum 140, ...) can be estimated to be about 50%. Table 14.2 shows the relative nuclear abundance of the Chernobyl plume.

reactor catastrophe in Chernobyl

inherently unsafe reactor

nuclear abundance of the Chernobyl plume

In the meantime the short-lived fission products have decayed, so that the remaining sources of radiation are the long-lived isotopes ^{137}Cs and ^{90}Sr. These nuclides will, however, remain for a long time in the biosphere.

^{137}Cs content of humans

Figure 14.1 shows the average ^{137}Cs content of humans over the period from 1960 to 1995. The cesium exposure due to the reactor accident in Chernobyl nearly equalled the level of the above-ground nuclear weapons tests in the atmosphere in the 1960s. These surface tests released about 3 tons of plutonium which was distributed

[1] In the field of brachytherapy the radiation source is applied in the immediate vicinity of the tumor directly inside the body of the patient. The source can be placed in a suitable orifice of the body (e.g. in the colon) or in cavities created artificially by surgery.

isotope	fraction [%]	half-life
iodine 131	36.5	8 days
tellurium 132	22.7	3.2 days
iodine 132	11.0	2.3 hours
praseodymium 144	10.3	17 minutes
ruthenium 103	4.7	39 days
cesium 137	3.7	30 years
barium 140	3.7	12.8 days
strontium 90	3.7	28.5 years
cesium 134	1.8	2 years
lanthanum 140	1.6	40 hours
iodine 133	0.4	21 hours

Table 14.2
Relative nuclear abundance of the Chernobyl plume

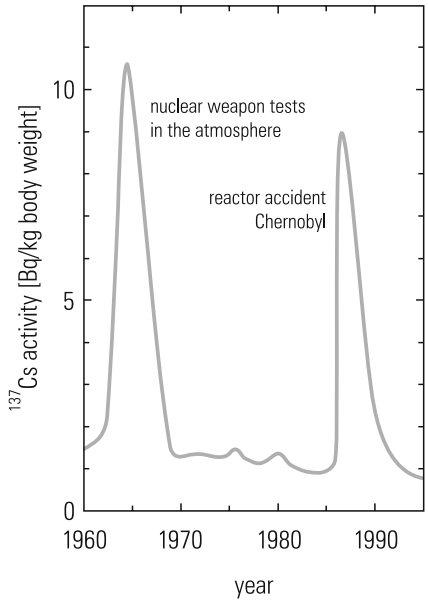


Figure 14.1
Average ^{137}Cs content of humans over the years from 1960 to 1995

worldwide. In addition, the released neutrons produced large quantities of tritium and ^{14}C in the atmosphere.

The passage of the Chernobyl plume over Europe led to various fallout patterns for different radioisotopes. Exposures to ^{131}I were caused mainly by drinking milk from cows that had eaten fallout-tainted vegetation. Other exposures arose from breathing contaminated air or eating contaminated food, such as mushrooms. The contamination of the ground showed large variations, depending on the weather conditions (rainfall and wind). For example, Germany exhibited a pronounced North–South divide. In the southern part maximum values of the contamination of the ground of 50 kBq/m^2 ^{137}Cs were found, while in the northern part values as low as $\approx$ 2 kBq/m^2

Chernobyl accident

contamination of the ground

^{137}Cs were observed. The high degree of pollution in Bavaria was mainly due to adverse winds, atmospheric fallout, and washout.

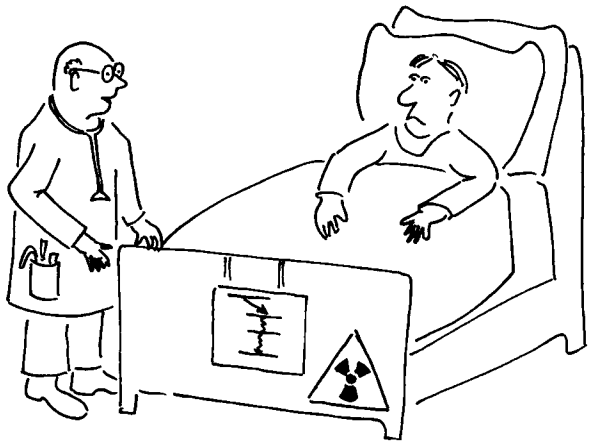
A pessimistic estimate of the average additional exposure of the population in Western Europe due to the Chernobyl accident is less than 0.5 mSv in the year 1986. For most of the countries the exposures were significantly less than that. In the subsequent years the excess radiation was at a level of less than 10 μSv annually in Europe. Using a cancer risk factor of 2.5×10^{-5} per 0.5 mSv (see Chap. 13) one would expect an additional number of cancer incidents of less than $500 \times 10^6 \times 2.5 \times 10^{-5} = 12\,500$ in Europe for a population of 500 million people. These cases of cancer would be distributed over a period of 20–30 years. In individual cases it would be impossible to establish correlations between cancers induced by radiation and 'normal' cancers. The normal cancer rate is so high, that the Chernobyl-induced cases of cancer would not be recognized in the 'noise' of the normal ones. There are anyway arguments that the extrapolation of cancer incidence from high doses in the sievert range down to low doses are problematic. An additional radiation dose of 0.5 mSv per year is well within the variation of the natural radiation. Under these circumstances the estimated number of additional cases of cancer above must be considered to be very pessimistic.[2]

cancer incidence rate due to the Chernobyl disaster

The situation in Russia and the Ukraine is entirely different. At the moment the rate of cancer of the thyroid gland among children has significantly increased. The leukemia rates, however, showed no correlation with the Chernobyl disaster. In fact, they stayed constant. People living in Belorussia (2 millions) and the Ukraine (1 million) received estimated doses around 20 mSv. If the latest risk factors are taken at face value (see Table 13.1), this would correspond to an additional cancer rate of 3000 cases. Another 1000 cases are expected among the rescue workers and people staying in the immediate vicinity of the reactor. Because of the long latency period for

late effects caused by the Chernobyl accident

[2] Because of the uncertainty of health effects at low doses the ICRP writes in their recommendations in 2007 "that it is not appropriate, for the purposes of health planning, to calculate the hypothetical number of cases of cancer or heritable disease that might be associated with very small radiation doses received by large numbers of people over very long periods of time." According to new results, the LNT hypothesis (Linear No-Threshold) for the dose–effect curve is merely a fit to values obtained at high exposures which is not expected to hold for very low doses. The effect of low doses is influenced by the elaborate defense system of the human body which allows the repair of minor radiation damage. It is even believed that the human immune system is activated by low-level radiation, thereby alleviating the radiation effect (hormesis).



"The good news is: With your whole-body scintigraphy no tumor or disease was detected. The bad news: You are now radioactive!"

cancer incidence the culmination of the diseases should occur in the next couple of years.[3]

These frighteningly high expectation values are based on the latest risk factors (5%/Sv). The actually observed cases of cancer in the former Soviet Union, in particular, the non-observation of an increase of the leukemia rates, appears to indicate that the used risk factors somewhat overestimate the real risk.

risk factors too high?

The radiation accident in the recycling plant Tokaimura in Japan on September 30th 1999 represents an example for a criticality accident which could have been avoided. Three workers of the plant had filled a highly enriched solution of uranium with buckets into a large tank. The radiation-protection regulations would not have allowed to transport large quantities of the uranium solution in buckets. In boiling-water or pressurized-water reactors one normally uses uranium which is enriched to a level of 3% to 5% with ^{235}U. In the framework of the plutonium production project with fast breeders the level of enrichment in this case was 18.8%. The workers filled 16 kilogram of a highly enriched uranyl-nitrate solution into a container. This quantity corresponds to seven times the criticality limit (2.4 kg) for this compound. Because of the high density of uranyl nitrate its volume corresponds to only 6–7 liters. To handle such a large quantity in a single container was forbidden under all circumstances. Under these conditions a chain reaction will start instantaneously. The workers reported that they observed a blue flash

Tokaimura accident

[3] A relatively new comprehensive analysis about the Chernobyl consequences can be found in `www.ibrae.ac.ru` (2002).

criticality

when the chain reaction was initiated explosively. The blue light could have originated from the Cherenkov radiation of relativistic electrons in the surrounding cooling water. The critical state of the uranium solution persisted for 18 hours. The fission conditions were essentially maintained over such a long period, because the container was surrounded by water whose initial purpose was to cool the solution. A fatal side effect of the cooling water was, however, that water acts as a perfect moderator and neutron reflector, so that the chain reaction was not discontinued.

One of the workers received a dose of 17 sievert. In spite of intensive medical care (e.g. blood transfusion) he died after 83 days. The other two workers received doses of at least 8 or 3 sievert, respectively. Other workers on the site of the recycling plant were mainly exposed to penetrating neutron radiation resulting in individual doses of more than 20 mSv. In total several grams of ^{235}U were fissioned. This chain reaction, persisting nearly over a full day, generated fission products corresponding to activities of 10^{16} to 10^{17} Bq. Out of these about 1% were released into the environment.

safety regulations

In this example it became evident that the safety regulations were grossly violated. A seven times overcritical amount of fissile material should have never been filled into a single container. Even worse, this container was immersed in cooling water, which acted as moderator and neutron reflector. After the event it was observed that the safety regulations in this recycling plant were habitually disregarded. Also the handling of the accident indicated that emergency plans and evacuation plans either did not exist or were ignored.

emergency plans

From the incidents mentioned above some general lessons on the causes and management of radiation accidents can be learnt. Frequently it takes too long for an accident to be identified. It might be suspected that there is even a substantial number of unreported cases. Time wasted can have serious implications: a delay in handling the accident normally leads to a deterioration of the situation. Prevention of accidents is essential. The appropriate safety regulations must be known to the relevant people and they must be respected. The staff must be properly trained, and critical operations have to be well prepared. Common sense helps in most situations. Special attention must be paid to the human factor: it happens again and again that safety regulations are ignored.

how to avoid radiation accidents

The responsibility of the personnel has to be clearly defined. The authorities must be able to recognize the scale of an accident. Therefore advance emergency plans at every level are essential. It is also important that such emergency plans are actually exercised and trained well before critical situations or accidents arise.

14.1 Supplementary Information

Example 1

discovery of radiation sources

In many cases the loss of radioactive sources or accidental irradiations has been recognized only after a long delay. In the first example of Table 14.1 nearly all members of a family were killed. A boy, living in Mexico, had found an abandoned, pencil-sized radiography gauge containing a highly radioactive, sealed, but broken 5-Ci ^{60}Co source in a scrapyard in March 1962. The boy played with the source and took it home. The boy's mother then found the source and placed it on the kitchen shelf. The 10-year old boy died in April and her mother followed in July. No one suspected that the deaths were related to ionizing radiation from the source. Only when a 3-year old child of the family died, the common cause of the deaths was recognized. Still there was another casualty in October. Only the father of the family survived, because he spent relatively little time together with the other family members in their house.[4]

Example 2

loss of nuclear weapons

salvage of nuclear submarines

Radiation accidents in the military sector have mostly been kept secret, especially during the Cold War. Typical examples originate from the disastrous management of military installations and the loss of nuclear weapons by the superpowers, the United States and the former Soviet Union. Quite a large number of nuclear weapons were lost at sea following air accidents. Also failed nuclear-missile launches released substantial radioactive material. In particular, nuclear-powered submarines that have sunk discharged large quantities of nuclear material into the oceans. In addition, the atmosphere has been polluted by radioisotope batteries on board of satellites (containing the highly toxic plutonium), which broke up when re-entering the atmosphere. The secrecy in the field of military operations became obvious when a Soviet nuclear submarine was wrecked in the Atlantic in 1961. The Soviet authorities were anxious that the submarine might be recovered by other powers and decided not to abandon it, but instead ordered to repair it on the spot. The authorities accepted that several members of the crew received rather high doses during the repair operations. At least eight of them died as a result of high exposure.[4]

Example 3

Ra–Be source

In the 1940s radium–beryllium sources were fabricated manually in laboratories. A strong one-gram Ra–Be source can be very dangerous if it is not tight. Radium decays into the noble gas radon

[4] A relatively complete compilation of radiation accidents in civil and military fields can be found in the article "Radiation Accidents" by J.C. Nénot in M.C. O'Riordan's book "Radiation Protection Dosimetry", Nuclear Technology Publishing, London 1996. Some of the aforementioned examples are taken from this article.

which can easily be released from the source. If the source was not tightly sealed in the manufacturing process, it was almost impossible to handle it after some hours because of continuous radon exhalation. A substantial radiation exposure must be accepted to seal such a leaking source afterwards. During the fabrication and sealing of such a source co-workers of E. Fermi received a γ dose of about 2 Sv. This exposure halved their number of white blood cells (leucocytes), which recovered only slowly back to normal. However, late radiation effects were not observed.

Example 4

Hiroshima
Nagasaki

The dropping of atomic bombs on Hiroshima and Nagasaki (1945) certainly represents a major radiation catastrophe with the most severe consequences. It is estimated that 140 000 Japanese citizens were killed in Hiroshima and 80 000 in Nagasaki by the end of 1945. Of those, 110 000 died on the day of the bombings. Since then, thousands more have died from delayed radiation effects and injuries attributed to exposure to radiation released by the bombs. The official number of casualties given by the Japanese authorities by the year 2009 is 258 000. Many people also suffered from permanent injuries. Due to genetic effects subsequent generations are also affected.

Example 5

radiation accidents
sources of accidents

medicine
accidental overexposition

reactors

military installations

A rather extensive list of radiation accidents and other events causing radiation casualties has been compiled by W. Robert Johnston. This list is continuously updated (`www.johnstonsarchive.net/nuclear/radevents/radaccidents.html`). Details of every accident are collected in a "Data Base of Radiological Incidents and Related Events", which is accessible from the given web address. The different events listed are sorted according to the involved facility or type of accident, e.g. nuclear reactor, accelerators, dispersal of radioactive material, accidental internal exposure to radioisotopes, irradiator accident, medical radiotherapy, medical X-ray accident, lost sources, radiography, criminal acts, exposures resulting from theft of sources, nuclear-weapon tests, or combat use of nuclear weapons. Apart from the nuclear bombing on Hiroshima and Nagasaki in 1945 (about 258 000 deaths), and the reactor catastrophe in Chernobyl (official number of deaths 31, independently estimated number of deaths 4000), 192 cases of death are reported. These occurred mainly in medicine (radiotherapy (67), accidental overexposure (18)), reactor accidents (research or commercial reactor (33), reactors for military use (15)), and due to lost sources (39). This compilation covers the time from the discovery of radioactivity (1896) up to now, and lists altogether 385 radiation accidents until to May 30, 2008.

Summary

Radiation accidents are frequently caused by ignoring elementary safety rules. The loss of radioactive sources or careless disposal of radioactive waste can also lead to unnecessary exposures. Many radiation accidents in military installations or operations have frequently been kept secret. The largest accident to date occurred with the then Soviet nuclear reactor in Chernobyl in 1986. This catastrophe was caused by a fatal experiment on the reactor, and the absence of a reliable safeguard system. The nuclear meltdown of the reactor provoked a radioactive cloud that floated over the whole northern hemisphere.

14.2 Problems

Problem 1

The risk factor for leukemia is 5×10^{-4} per 100 mSv whole-body exposure. Estimate the number of expected leukemia cases as a consequence of the reactor catastrophe in Chernobyl worldwide!

Problem 2

During the installation of a 10-Ci ^{60}Co source in an irradiation facility the source was accidentally dropped. It was recovered by the operators with bare hands and placed into the foreseen position. Estimate the dose which the operators received on their hands, and give also an estimate for the whole-body exposure.

Problem 3

uranium in drinking water

The accidental release of a solution containing depleted uranium into the environment from the French nuclear power and recycling plant Tricastin in July 2008 caused considerable concern. An amount of 30 m^3 of water containing 360 kg of depleted uranium was discharged into tributaries of the river Rhône. Work out the uranium concentration of the discharged water and compare it to the WHO limit for drinking water (15 µg/l). Compare its specific activity with the ICRP-recommended value for the maximum allowed limit for discharges from nuclear power plants ($\leq 3000\,\mathrm{Bq/m^3}$, see Appendix C).

15 Non-Ionizing Radiation

"High frequency radiation is sometimes thought to be the cause of cancer, while low frequency radiation is generally assumed to be harmless."

Susan Dean and Barbara Illowsky

electromagnetic radiation

Radiation-protection regulations concern ionizing radiation like α, β, γ radiation and neutrons. Separate regulations concern the handling of X rays and X-ray-generating devices. γ radiation and X rays are electromagnetic waves: they differ from visible light or microwave radiation only by their energy or, equivalently, by their frequency or wavelength. It is only natural to ask to what extent electromagnetic radiation of other frequencies might be dangerous for humans.

Energy and frequency are related in a simple way following the relation discovered by Max Planck:

$$E = h\nu \ , \tag{15.1}$$

where ν is the frequency in hertz (cycles per second), and $h = 6.62 \times 10^{-34}\,\mathrm{W\,s^2}$ is Planck's constant. The frequency itself is related to the wavelength λ by

$$\nu\,\lambda = c \ , \tag{15.2}$$

where c is the velocity of light in vacuum.

Depending on the frequency or energy, electromagnetic radiation has quite different effects. The following Table 15.1 gives some characteristics of frequency ranges along with their commonly used names.

ionizing radiation

non-ionizing radiation

The transitions between the different characteristic ranges are not particularly well defined. To ionize atoms in human tissue an energy of approximately 30 eV is required. Therefore, radiation with frequencies below 10^{16} Hz corresponding to 30 eV are termed non-ionizing. Apart from defining electromagnetic waves by their frequency, wavelength, or energy, they can also be characterized by the associated electromagnetic field. An electromagnetic wave can be described by a transverse electrical and magnetic field, which are both perpendicular to the direction of emission. Electric and magnetic field vectors are also perpendicular to each other.

electric field strength

magnetic field strength

magnetic flux density

The electric field strength E is measured in V/m, the magnetic field strength H in A/m, and the magnetic flux density B in tesla

C. Grupen, *Introduction to Radiation Protection*,
Graduate Texts in Physics, DOI 10.1007/978-3-642-02586-0_15,

classification	frequency ν[s^{-1}]	wavelength λ[m]	energy [eV]
mains, AC current	≈ 50	$\approx 6 \times 10^{6}$	$\approx 2 \times 10^{-13}$
long-wave radiation	$\approx 6 \times 10^{4}$	≈ 5000	$\approx 2.5 \times 10^{-10}$
short-wave radiation	$\approx 3 \times 10^{6}$	≈ 100	$\approx 1 \times 10^{-8}$
ultrahigh-frequency radiation	$\approx 10^{8}$	≈ 3	$\approx 4 \times 10^{-7}$
mobile-phone communication	$\approx 3 \times 10^{9}$	≈ 0.10	$\approx 1 \times 10^{-5}$
microwaves	$\approx 6 \times 10^{9}$	≈ 0.05	$\approx 2 \times 10^{-5}$
radar	$\approx 3 \times 10^{10}$	≈ 0.01	$\approx 1 \times 10^{-4}$
infrared	$\approx 10^{12}$	$\approx 3 \times 10^{-4}$	$\approx 4 \times 10^{-3}$
visible light	$\approx 6 \times 10^{14}$	$\approx 5 \times 10^{-7}$	≈ 3
UV	$\geq 1.5 \times 10^{15}$	$\leq 2 \times 10^{-7}$	≥ 6
X rays	$\geq 2 \times 10^{17}$	$\leq 1 \times 10^{-9}$	$\geq 10^{3}$
γ rays	$\geq 2 \times 10^{20}$	$\leq 1 \times 10^{-12}$	$\geq 10^{6}$

Table 15.1
Characterization of electromagnetic radiation for different frequency ranges

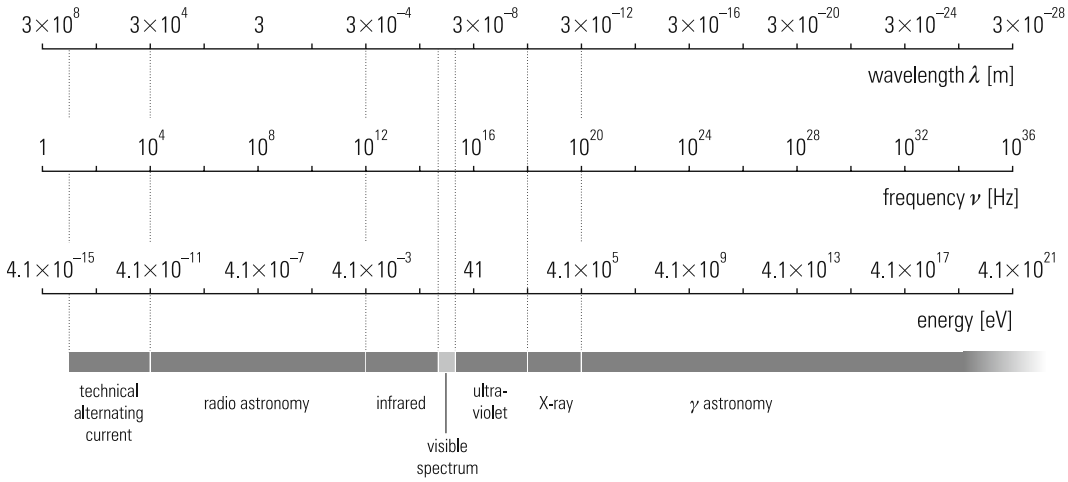


Figure 15.1
Spectrum of the electromagnetic radiation along with fields of typical applications

(1 tesla = $\frac{1\,\mathrm{V\,s}}{\mathrm{m}^2}$). The magnetic flux density B is related to the magnetic field strength by

$$B = \mu\mu_0 H \ , \tag{15.3}$$

where μ and μ_0 are the relative permeability and the permeability of free space ($\mu_0 = 4\pi \times 10^{-7}\,\mathrm{N/A^2}$),

$$[B] = [\mu_0]\,[H] = \frac{\mathrm{N}}{\mathrm{A}^2}\,\frac{\mathrm{A}}{\mathrm{m}} = \frac{\mathrm{N\,m}}{\mathrm{A\,m}^2} = \frac{\mathrm{V\,A\,s}}{\mathrm{A\,m}^2} = \frac{\mathrm{V\,s}}{\mathrm{m}^2} \ . \tag{15.4}$$

current density

Electrical fields in conducting material lead to currents, where the current density (in ampere/cm^2) is responsible for possible biological effects.

nervous system
electrocardiogram
electroencephalogram

There are, however, already natural currents in the human body for conduction in the nervous system. The activity of the heart can be measured with an electrocardiogram (ECG), that of the brain with an electroencephalogram (EEG). The associated natural current densities vary between $0.1\,\mu A/cm^2$ and $1\,\mu A/cm^2$. These currents are related to low-frequency fields. Limits for additional low-frequency fields have to be set taking these natural current densities into account.

current density

The current density is related to the electrical voltage and field strength according to Ohm's law:

$$U = \varrho\,\frac{\ell}{q}\,I \qquad \text{and} \qquad E = \frac{U}{\ell} = \varrho\,\frac{I}{q} = \varrho\,j \tag{15.5}$$

(ϱ – specific resistance in $\Omega\,m$, ℓ – length of the conductor, q – cross section of the conductor, $\frac{I}{q} = j$ – current density).

For the production of current densities of $0.1\,\mu A/cm^2$ in the human body external electrical fields of about $\approx 5\,kV/m$ and magnetic fields of $80\,A/m$ at frequencies of $50\,Hz$ are required. This corresponds to a magnetic induction of

$$B = \mu\mu_0 H = 4\pi \times 10^{-7} \times 80\,\frac{V\,s}{m^2} = 100\,\mu\text{tesla}\ , \tag{15.6}$$

Earth's magnetic field

which is on the same order of magnitude as the magnetic induction of the Earth's magnetic field. Therefore, it is only natural that limits for permanent exposure to low-frequency electromagnetic AC fields of $5\,kV/m$ and $100\,\mu T$ are proposed.

effects in nerve and muscle cells

Low-frequency electromagnetic fields create effects in nerve and muscle cells. In contrast, high-frequency radiation ($\gg 50\,kHz$) is characterized by its heat production after absorption. Therefore, it makes sense for this frequency range to consider the radiation power per mass unit. For a whole-body exposure, a limit of $\approx 0.1\,W/kg$ is recommended. For partial-body doses higher limits are tolerated[1] (head and body $2\,W/kg$, legs and arms $4\,W/kg$).

heat production of high-frequency radiation

mobile-phone communication
pulsed microwave radiation

In mobile-phone communications peak powers of up to 2 watts are reached. It has to be mentioned, however, that the biological effect of pulsed microwave radiation requires further research. The proposed limits in radiation-protection regulations for non-ionizing radiation depend on the assumption that the biological effect of microwave radiation for high frequencies can be characterized by its heating effect on tissue. Particular care must be taken for the brain and the eyes where one has to consider that the human body has poor heat-conducting properties. The limits are defined for the heat power

radiation-protection limits

[1] ICNIRP – International Commission on Non-Ionizing Radiation Protection

per unit area. As an example, some limits which are recommended in the European Union are compiled in the following table:

radiation source	frequency range	maximum allowed power per square meter
ultrashort wave	88–108 MHz	$2\,\mathrm{W/m^2}$
VHF	174–216 MHz	$2\,\mathrm{W/m^2}$
UHF	470–890 MHz	$2\text{–}4\,\mathrm{W/m^2}$
D network	890–960 MHz	$4.5\,\mathrm{W/m^2}$
E network	1710–1880 MHz	$9\,\mathrm{W/m^2}$
UMTS	≈ 2 GHz	$10\,\mathrm{W/m^2}$
microwave ovens	2.45 GHz	$10\,\mathrm{W/m^2}$

For comparison: the radiation power of the Sun in the visible range at the edge of the atmosphere is about $1400\,\mathrm{W/m^2}$. This radiation power is attenuated in the atmosphere to different extents in different weather conditions. Under a cloudy sky, about $100\,\mathrm{W/m^2}$ can be measured at sea level.

solar ultraviolet radiation

In the ultraviolet range, the heating of the skin becomes particularly important. For the spectral range between 315 and 400 nm, a limit for the eyes of $10\,\mathrm{W/m^2}$ is recommended corresponding to an area energy density of $10\,\mathrm{kJ/m^2}$ for an exposure time of 1000 s. For a solar radiation power in clear weather conditions corresponding to $300\,\mathrm{W/m^2}$, an assumed exposure time of 1000 seconds and an exposed area of the skin of $0.5\,\mathrm{m^2}$, one obtains an absorbed energy of

$$E = \frac{300\,\mathrm{W}}{\mathrm{m^2}} \times 0.5\,\mathrm{m^2} \times 1000\,\mathrm{s} = 150\,\mathrm{kJ}\ , \qquad (15.7)$$

reddening of the skin

which already leads to a reddening of the skin for people with sensitive skin. This is due to the fact that the radiation is absorbed at low skin depths and transformed into heat.

15.1 Supplementary Information

Example 1

radiation cancer
ultraviolet radiation

Also non-ionizing radiation can cause skin cancer. An example for this is ultraviolet radiation, which is present in the spectrum of sunlight. The ultraviolet spectrum is subdivided into three ranges:

- UVA wavelength 400–315 nm energy 3.1–3.9 eV
- UVB wavelength 315–280 nm energy 3.9–4.4 eV
- UVC wavelength 280–100 nm energy 4.4–12.4 eV

tanning of the skin
pigmentation

The main effect of absorption of low-frequency or low-energy UV radiation is heating of the tissue. UVA radiation results in tanning the skin: the maximum effect is obtained at a wavelength of 340 nm. The threshold value for pigmentation is around $10\,\mathrm{W\,s/cm^2}$. If the dose of UVA, or more commonly UVB, is too high, sunburn results. Sunburn is not only created by the thermal effect of radiation. UV radiation also induces photochemical reactions in the skin which for high intensities can lead to the release of cellular poison.

UVC radiation is already energetic enough for quantum effects to occur. Depending on the absorbed energy, rotational or vibrational levels of electrons can be excited. For the highest energies, ionization processes can even occur. The required ionization energy depends on the type of atom. The biologically relevant atoms like carbon, oxygen, and nitrogen are only ionized for wavelengths below 100 nm, however. As well as ionization, the breaking of molecular bonds can occur. Atoms and molecules affected in this way tend to interact more intensively with the tissue leading to possible biological hazards.

grassing

In the early days this effect was taken advantage of for grassing. The ultraviolet radiation from the Sun produces hydrogen peroxide from the water using the oxygen of the air. The peroxide destroys the colorant embedded in the laundry thereby whitening the clothes. The exposure of plastic materials to UV radiation frequently also causes brittleness.

sunburn
inflammations of the cornea, keratitis
cataract
skin cancer

Apart from tanning and sunburn (erythema) also inflammations of the cornea (keratitis) and cataract of the eye may occur. Also damages with substantial latency which depend on the integrated radiation dose have been observed. The late effects mainly concern skin cancer (malignant melanoma) which shows up only after a certain delay. Already an excess of UVB radiation might lead to a formation

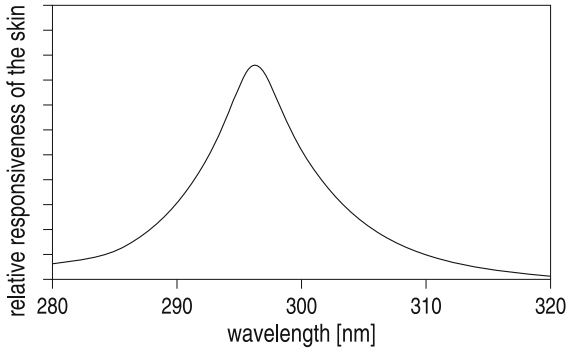


Figure 15.2
Relative responsiveness of the skin for UV radiation in the wavelength range from 280 nm to 320 nm (≈ UVB) (Canadian Centre for Occupational Health and Safety)

of precursors of cancer, the so-called solar keratoderma. Also basal cell carcinoma may emerge. This type of cancer is the most common and least lethal form of all cancers. An early treatment is important and usually effective. In contrast, high-frequency UV radiation favors the formation of malignant melanoma. In this case an early detection of the skin cancer is essential since malignant melanoma have the tendency to form metastases. Skin cancers are the fastest growing type of tumors in most countries with intense sunshine.

basal cell carcinoma

The negative effect of UV, particularly UVC, on biology can also be useful. With intense UVC radiation microorganisms, and especially bacteria, can be killed. Therefore, this type of radiation is suited for disinfection, in particular, for transparent media like water and air.

disinfection

Threshold values for the eyes, related to inflammations of the cornea and cataracts, are around $5\,\mathrm{W\,s/cm^2}$ for a wavelength of 315 nm. Limits for ultraviolet whole-body irradiations as well as those for inflammations of the eye depend strongly on the wavelength of the radiation. For the tanning effect of UVA radiation a safe limit is about $10^4\,\mathrm{W\,s/m^2}$ for an 8-hour day. For the dangerous UVC radiation (around 280 nm) the limit per day is considerably lower at $30\,\mathrm{W\,s/m^2}$. These energy area doses correspond to radiation powers in the respective wavelength range of $0.35\,\mathrm{W/m^2}$ (for 315 nm) and $1\,\mathrm{mW/m^2}$ (for 280 nm).

Example 2

Laser

Of particular importance are the radiation-protection regulations for Lasers (= Light Amplification by Stimulated Emission of Radiation). The biological effect of laser radiation is related to its extremely high power density. Because of the production mechanism, a laser beam is highly collimated. Laser beams are frequently used for alignment and laser-optical experiments. With laser beams very small holes can be burnt, tissue and material can be cut, and lasers can even induce fusion in a hydrogen plasma. The proposed limits for lasers show a rather complicated time and wavelength dependence. In particular, the eyes are potentially at risk when working with laser radiation. A commercial laser pointer emits mostly in the wavelength range between 630–680 nm (red). It has an output power of less than 1 mW and a beam cross section of about $2\times 2\,\mathrm{mm^2}$. Even this leads already to radiation power densities of $< 25\,\mathrm{mW/cm^2}$, corresponding to a maximum exposure of $250\,\mathrm{J/m^2}$ for an exposure time of one second.

extremely high power density

laser pointer

In addition to red lasers, green lasers are now available, which have higher power and better visibility. In the handling of laser beams, one must be aware of reflecting surfaces, as even reflections can be harmful.

femtosecond laser

Particular care has to be taken for lasers in the pulsed mode. At present there are femtosecond lasers which produce high-power laser pulses of 10^{-15} s duration.

hazard categories

Because of the large number of applications and laser variants, lasers are subdivided into different classes according to their potential hazard:

class 1: High security class. With such a type of laser it is impossible to exceed the allowed limits.

class 2: Laser of low radiation power in the optical range. For continuous-wave lasers the power limit is 1 mW. 'Red' laser pointers belong to this class 2.

class 3: Optical laser with powers > 1 mW. A direct view into the laser beam is dangerous. Diffuse reflexes of unfocused lasers of this class, however, are not dangerous.

high-power laser

class 4: High-power lasers for which diffuse reflexes are also hazardous.

CW laser

Limits for continuous-wave lasers (CW lasers) in the micrometer range (> 1400 nm) are 100 mW/cm^2, and for nanosecond-pulse lasers the intensity limit is $< 10^{10}$ mW/cm^2. In the visible range the limits are 1 mW/cm^2 (CW) or 5×10^5 mW/cm^2 for nanosecond pulses.

safety goggles

Scientists and technicians handling lasers have to wear safety goggles which are adapted for the relevant wavelength range. These goggles absorb laser beams reliably. However, the disadvantage is that in adjusting laser-beam equipment it is impossible to see the laser beam when wearing these safety goggles.

Example 3

mobile phone

antennas for mobile-phone communication

The discussion about possible dangers from the use of mobile phones has become quite widespread. Antennas for mobile-phone communications work at rather high frequencies, which depend on the network (900 MHz, 1800 MHz, or even 2 GHz for Universal Mobile Telecommunications System (UMTS)). The power from these antennas is not emitted continuously but in pulses with a frequency of 217 Hz. The photon energies are in the range of 5 μeV well below values which could lead to the breakup of molecular bonds or to ionizations. Therefore, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) has recommended a limit

heating effect

for the emitted power based only on the effect of heating the tissue. The heat generated in the head during the use of mobile phones is of particular importance. The limit is at 2 W/kg. Exposures are characterized by the so-called SAR value (specific absorption rate), which judges on the biological effectiveness of non-ionizing radiation. For an exposure time of 30 minutes the 2 W/kg limit corresponds to an energy deposition of 3600 J/kg. Such a high non-hazardous value

SAR value

demonstrates the increased sensitivity of human tissue against ionizing radiation, for which only 4 J/kg gives a mortality of 50%.

By special precautions the exposure to microwave radiation can be reduced. It is better to use an areal antenna instead of a stub or helix antenna[2]. Also a metallic foil between head and antenna is advantageous. Further possibilities exist to decrease the power, like the optimization of the geometrical emission characteristic by appropriate electronic circuitry. Mobile phones with separate microphone and loudspeaker are also preferable. It has to be mentioned that children are much more sensitive to mobile-phone radiation because their nervous system is still developing.

areal antenna
helix antenna

Currently it is a matter of debate whether the limitation of mobile-phone radiation solely on its effect of heating of the tissue makes sense or can be justified. Even though it is known that electromagnetic fields have an effect on the nervous system and the cell membranes, there are still no solid scientific results which demonstrate that electrosmog effects might result in biological damage other than heating. However, it is conceivable that for certain frequencies resonance effects might show up. For UMTS frequencies (2 GHz), the resonance length is on the order of the dimensions of the head ($\lambda = 15$ cm). It has, however, to be mentioned that the electromagnetic skin depth at these high frequencies is only a few cm.[3]

heating effect

UMTS frequencies

"I no longer suffer from cold ears, since I use my mobile phone in winter time!"

© by Claus Grupen

[2] A helical antenna is an antenna consisting of a conducting wire wound in the form of a helix. In an areal antenna the linear arrangement of a stub antenna is replaced by a two-dimensional one, i.e., the conducting wire is spread over a surface. Areal antennas are mounted on a ground plane shielding the user of the mobile phone considerably against possible exposures.

[3] High-frequency electromagnetic radiation is attenuated in matter according to

$$I = I_0 \, \mathrm{e}^{-x/\delta} \ , \tag{15.8}$$

where δ is a characteristic skin depth.

δ depends on the material properties as

$$\delta = \sqrt{\frac{2\varrho}{\omega\mu_0}} \ , \tag{15.9}$$

where ϱ is the specific resistance, ω the angular frequency ($2\pi \times$ frequency), and μ_0 the absolute magnetic permeability ($4\pi \times 10^{-7}$ N/A^2). For tissue typical penetration depths of about 3 cm for frequencies of 2 GHz are obtained.

Summary

From the point of view of physics non-ionizing radiation is not fundamentally different from short-wave, X-ray, and gamma radiation. For frequencies below 10^{16} hertz, electromagnetic radiation is non-ionizing, but biological processes in the human body are also influenced by non-ionizing radiation. Low-frequency radiation (alternating current, 50 Hz) affects humans via its electric and magnetic fields. High-frequency radiation (GHz range) leads to heating of the tissue. Ultraviolet light can lead to a burning of the skin and even to skin cancer because this radiation is completely absorbed at very shallow depths of the tissue. Particular care has to be taken with collimated laser beams which are characterized by very high power density.

15.2 Problems

Problem 1 Show that an external AC field ($\approx 50\,\mathrm{Hz}$) of $5\,\mathrm{kV/m}$ is necessary to create a current density of $\approx 0.1\,\mu\mathrm{A/cm^2}$ in the human body.

Problem 2 Estimate the electric and magnetic field strengths underneath a high-tension cable (220 kV, 1000 A current, height 30 m).

Problem 3 Low-voltage halogen lamps produce strong magnetic fields over a large area. Compare the magnetic field of a 12-V cable supplying a halogen lamp of 100 W at a distance of 1 m with the corresponding magnetic field caused by a conventional bulb operated at 220 volt.

16 Solutions to the Problems

16.1 Solutions to the Problems of Chapter 2

Problem 1

$$\begin{aligned}\text{dose} &= \frac{\text{absorbed energy}}{\text{unit mass}} \\ &= \frac{\text{activity} \times \text{energy per decay} \times \text{time}}{\text{mass}} \\ &= \frac{10^9\,\text{Bq} \times 1.5 \times 10^6\,\text{eV} \times 1.602 \times 10^{-19}\,\text{J/eV} \times 86\,400\,\text{s}}{10\,\text{kg}} \\ &= 2.08\,\text{J/kg} = 2.08\,\text{Gy}\ .\end{aligned}$$

Here, we have used the electron volt as unit for the energy, in addition to the standard unit of joule: $1\,\text{eV} = 1.602 \times 10^{-19}\,\text{J}$ (see also Footnote 1, page 21).

Problem 2

The decay in the body of the worker is composed of two components. The total effective decay constant λ_{eff} is

$$\lambda_{\text{eff}} = \lambda_{\text{phys}} + \lambda_{\text{bio}}\ .$$

Because of $\lambda = \frac{1}{\tau} = \frac{\ln 2}{T_{1/2}}$ we get

$$T_{1/2}^{\text{eff}} = \frac{T_{\text{phys}}\,T_{\text{bio}}}{T_{\text{phys}} + T_{\text{bio}}} = 79.4\,\text{d}\ .$$

Using $\dot{D} = \dot{D}_0\,\text{e}^{-\lambda t}$ and $\dot{D}/\dot{D}_0 = 0.1$ we arrive at[1]

$$t = \frac{1}{\lambda}\ln\left(\frac{\dot{D}_0}{\dot{D}}\right) = \frac{T_{1/2}^{\text{eff}}}{\ln 2}\ \ln\left(\frac{\dot{D}_0}{\dot{D}}\right) = 263.8\,\text{d}\ .$$

A mathematically more demanding calculation allows to determine the dose the worker was exposed to over this period:

[1] The notation $\dot{D}_0$ describes the dose rate at $t = 0$. It does not represent the time derivative of the constant dose D_0 (which would be zero!).

C. Grupen, *Introduction to Radiation Protection*,
Graduate Texts in Physics, DOI 10.1007/978-3-642-02586-0_16,

$$
\begin{aligned}
D_{\text{total}} &= \int_0^{263.8\,\text{d}} \dot{D}_0\, \mathrm{e}^{-\lambda t}\, \mathrm{d}t \\
&= \dot{D}_0 \left(-\frac{1}{\lambda}\right) \mathrm{e}^{-\lambda t} \Bigg|_0^{263.8\,\text{d}} \\
&= \frac{\dot{D}_0}{\lambda} \left[1 - \mathrm{e}^{-\lambda \times 263.8\,\text{d}}\right] \ .
\end{aligned}
$$

Using

$$
\lambda = \frac{1}{\tau} = \frac{\ln 2}{T_{1/2}^{\text{eff}}} = 8.7 \times 10^{-3}\,\text{d}^{-1}
$$

we get ($1\,\mu\text{Sv/h} = 24\,\mu\text{Sv/d}$)

$$
D_{\text{total}} = \frac{24\,\mu\text{Sv/d}}{\lambda}[1 - 0.1] = 2.47\,\text{mSv} \ .
$$

The 50-years committed dose equivalent $D_{50} = \int_0^{50\,\text{yrs}} \dot{D}(t)\,\mathrm{d}t$ is determined to be

$$
\begin{aligned}
D_{50} &= \int_0^{50\,\text{yrs}} \dot{D}_0\, \mathrm{e}^{-\lambda t}\, \mathrm{d}t = \frac{\dot{D}_0}{\lambda} \left[1 - \mathrm{e}^{-\lambda \times 50\,\text{yrs}}\right] \\
&\approx \frac{\dot{D}_0}{\lambda} = 2.75\,\text{mSv} \ .
\end{aligned}
$$

Problem 3

At a distance of 2 m the electrons from ^{60}Co decay are already absorbed (compare Figs. 3.4 and 4.4). Therefore only the γ dose is of interest. The specific γ dose constant for ^{60}Co is $\Gamma_\gamma = 3.41 \times 10^{-13}\,\frac{\text{Sv m}^2}{\text{Bq h}}$. Using the relation

$$
\dot{H} = \Gamma_\gamma \frac{A}{r^2}
$$

we get

$$
A = \frac{r^2}{\Gamma_\gamma}\,\dot{H} = \frac{(2\,\text{m})^2\,\text{Bq h} \times 10^{-4}\,\text{Sv}}{3.41 \times 10^{-13}\,\text{Sv m}^2\,\text{h}} = 1.17\,\text{GBq} \ .
$$

Problem 4

The solution of this problem can be obtained in two ways. After one half-life the activity has decayed by a factor of 2; that is, after two days corresponding to $48/6 = 8$ half-lives the activity is decreased by a factor of 2^8. Therefore the patient still 'radiates' after two days with an activity of

$$
A(48\,\text{h}) = A_0 \times 2^{-8} = 10^7\,\text{Bq}/2^8 = 39\,\text{kBq} \ .
$$

In an analogous way the time dependence of the activity can be represented by

$$A = A_0\,\mathrm{e}^{-t/\tau} \ .$$

Because of

$$\tau = \frac{T_{1/2}}{\ln 2} = 8.66\,\mathrm{h}$$

we arrive at the same result,

$$A(48\,\mathrm{h}) = A_0\,\mathrm{e}^{-\frac{48\,\mathrm{h}\times\ln 2}{T_{1/2}}} = 39\,\mathrm{kBq} \ .$$

16.2 Solutions to the Problems of Chapter 3

Problem 1

The electrostatic repulsion of protons reduces the binding energy of nuclei. The electrically neutral neutrons do not experience electrostatic forces and therefore have no electromagnetic effect on nuclear binding. A nucleus with relative proton excess or even equal number of protons and neutrons at high atomic masses has the tendency to transform some of the protons into neutrons, so that the nucleus gains higher stability.

Problem 2

Because of the non-linear relation between atomic number Z and mass number A nuclear fission nearly always leads to fission products with relatively large neutron excess. The shell model of the nucleus (magic numbers) explains why the fission is asymmetric in most cases (see Fig. 12.1). For example, fission of ^{235}U with slow neutrons may result in the production of highly excited ^{141}I and ^{95}Y nuclei. The reduction of the neutron excess can proceed by the emission of prompt or delayed neutrons or by transformation of some neutrons into protons by β^- decays, for example,

$$\begin{aligned}
^{141}\mathrm{I}^* &\longrightarrow {}^{140}\mathrm{I} + n \\
&\hookrightarrow {}^{140}\mathrm{Xe} + e^- + \bar{\nu}_e \\
&\quad\hookrightarrow {}^{139}\mathrm{Xe} + n \\
&\qquad\hookrightarrow {}^{139}\mathrm{Cs} + e^- + \bar{\nu}_e \\
&\qquad\quad\hookrightarrow {}^{139}\mathrm{Ba} + e^- + \bar{\nu}_e \\
&\qquad\qquad\hookrightarrow {}^{139}\mathrm{La} + e^- + \bar{\nu}_e \ .
\end{aligned}$$

^{139}La is the stable end product, where the proton and neutron numbers are balanced.

Problem 3

The range of a 100-keV electron in tissue is about 0.2 mm (see Fig. 4.4). It is still marginally acceptable to use the non-relativistic, classical relation between energy and velocity in this case. Its initial velocity can be worked out from

$$E_{\text{kin}} = \frac{1}{2} m_e \, v^2$$

to be

$$v = \sqrt{\frac{2\,E_{\text{kin}}}{m_e}} = \sqrt{\frac{2 \times 100\,\text{keV}}{511\,\text{keV}}}\, c \approx 1.9 \times 10^8 \,\frac{\text{m}}{\text{s}} \ .$$

c is the velocity of light in vacuum. This allows to estimate the traveling time t from

$$\begin{aligned} s &= \frac{1}{2}\, a\, t^2 \\ \text{and} \quad v &= a\, t \\ \text{to be} \quad t &= \frac{2\,s}{v} = 2.1 \times 10^{-12}\,\text{s} = 2.1\,\text{ps} \ . \end{aligned}$$

Problem 4

a) The initial kinetic energies are determined to be:

$$\begin{aligned} E_{\text{kin}}^{\text{tennis ball}} &= \frac{1}{2} m v^2 \\ &= \frac{1}{2} \times 0.06\,\text{kg} \times \left(200\,\text{km/h} \times \frac{1000\,\text{m/km}}{3600\,\text{s/h}} \right)^2 \\ &= 92.6\,\frac{\text{kg}\,\text{m}^2}{\text{s}^2} = 92.6\,\text{joule} \ , \\ E_{\text{kin}}^{\alpha} &= 5 \times 10^6\,\text{eV} \times 1.602 \times 10^{-19}\,\text{J/eV} \\ &= 8 \times 10^{-13}\,\text{joule} \ , \\ E_{\text{kin}}^{\text{tennis ball}} / E_{\text{kin}}^{\alpha} &= 1.16 \times 10^{14} \ . \end{aligned}$$

b) The energy density ρ_E is the energy per unit volume:

$$\begin{aligned} \rho_E^{\text{tennis ball}} &= \frac{1}{2} m v^2 / \frac{4}{3} \pi r_{\text{T}}^3 = 6.4 \times 10^5\,\text{J/m}^3 \ , \\ \rho_E^{\alpha} &= 5\,\text{MeV} / \frac{4}{3} \pi r_{\alpha}^3 = 4.7 \times 10^{31}\,\text{J/m}^3 \ . \end{aligned}$$

The energy density in the α particle exceeds by far that of the tennis ball.

Problem 5

1 ton of ^{235}U contains

$$N_{\text{A}} \times \frac{10^3\,\text{kg}}{0.235\,\text{kg}} = 2.56 \times 10^{27}\,\text{nuclei}$$

(N_{A} – Avogadro number; 1 mol ^{235}U corresponds to 235 g).

Therefore we get for the mass loss Δm:

$$\Delta m = \frac{2.56 \times 10^{27}\,\text{nuclei} \times 235\,\frac{\text{MeV}}{\text{nucleus}} \times 1.6 \times 10^{-13}\,\frac{\text{J}}{\text{MeV}}}{c^2}$$
$$\approx 1\,\text{kg} \ .$$

The complete fission of one ton of ^{235}U results in a mass defect of about 1 kg. The efficiency of mass-to-energy conversion is therefore on the order of magnitude of 1‰.

16.3 Solutions to the Problems of Chapter 4

Problem 1

The half-value layer (tenth-value layer) is that thickness of an absorber which reduces the γ intensity by a factor of two (ten). Using

$$I = I_0\,\mathrm{e}^{-\mu x}$$

we get

$$x = \frac{1}{\mu}\,\ln\left(\frac{I_0}{I}\right) \ ,$$
$$x_{1/2} = \frac{1}{\mu}\,\ln\left(\frac{I_0}{I_0/2}\right) = 5.8\,\text{cm} \ ,$$
$$x_{1/10} = \frac{1}{\mu}\,\ln\left(\frac{I_0}{I_0/10}\right) = 19.2\,\text{cm} \ .$$

Problem 2

Photons from ^{60}Co γ decay are hardly absorbed in air. Therefore the inverse-square ($1/r^2$) law is a reasonable approximation for photons:

$$\dot{D}_\gamma(1\,\text{m}) = \dot{D}_\gamma(5\,\text{cm})\,\left(\frac{5}{100}\right)^2 = 12.5\,\frac{\mu\text{Sv}}{\text{h}} \ .$$

In contrast, electrons are strongly absorbed in air. Since the energy of electrons from ^{60}Co decay is rather low ($E_{\max} = 310\,\text{keV}$), almost no electrons will survive a distance of 1 m. Therefore we can safely assume

$$\dot{D}_\beta(1\,\text{m}) = 0 \ .$$

The estimate of the effect of electrons via their range is only an approximation. The energy spectrum of electrons in nuclear beta decay is continuous. A large number of low-energy electrons is already absorbed by very thin layers. Therefore the absorption of electrons from continuous spectra can also be approximated by an exponential attenuation law:

$$I_\beta(x) = I_\beta(0)\,\mathrm{e}^{-\kappa\,x}\ ;$$

κ is the linear absorption coefficient. For electron energies typical for the field of radiation protection ($0.1\,\mathrm{MeV} \le E_\beta \le 3.5\,\mathrm{MeV}$) κ can be approximated by the empirical relation

$$\kappa = \frac{15}{E_{\beta_{\max}}^{1.5}}$$

($E_{\beta_{\max}}$ in MeV and κ in $(\mathrm{g/cm^2})^{-1}$).

The exponential law for the absorption of electrons from continuous beta spectra can only be applied for thin absorbers. For absorber layers comparable to the range of electrons the exponential attenuation law fails. In these cases the beta intensities are significantly overestimated by the exponential law. In our example we get for the beta dose considering the electron absorption in 5 cm of air ($E_{\beta\,\max} = 0.31\,\mathrm{MeV}$ for $^{60}\mathrm{Co}$):

$$\begin{aligned}\dot{D}_\beta(5\,\mathrm{cm}) &= \Gamma_\beta\,\frac{A}{r^2}\,\frac{I_\beta(5\,\mathrm{cm})}{I_\beta(0\,\mathrm{cm})}\\ &= 388\,\frac{\mathrm{mSv}}{\mathrm{h}}\,\mathrm{e}^{-\rho_{\mathrm{air}}\,\kappa\times 5\,\mathrm{cm}} = 222\,\frac{\mathrm{mSv}}{\mathrm{h}}\ .\end{aligned}$$

For a distance of 1 m this approximation gets questionable. The application of the absorption law would give in this case

$$\dot{D}_\beta(1\,\mathrm{m}) \le 388\,\frac{\mathrm{mSv}}{\mathrm{h}} \times \left(\frac{5\,\mathrm{cm}}{100\,\mathrm{cm}}\right)^2 \times \frac{I_\beta(1\,\mathrm{m})}{I_\beta(0\,\mathrm{cm})} = 0.013\,\frac{\mu\mathrm{Sv}}{\mathrm{h}}\ .$$

Here we used the $\le$ symbol, because the exponential overestimates the dose rate for large distances.

Problem 3

We have

$$I = I_0\,\mathrm{e}^{-\mu\,x\,\rho} \quad \text{with} \quad \mu = 0.07\,(\mathrm{g/cm^2})^{-1}$$

and

$$x = 1\,\mathrm{m} \mathrel{\widehat{=}} 100\,\mathrm{g/cm^2}\ .$$

From

$$\frac{I_0}{I} = \mathrm{e}^{\mu\,x\,\rho}$$

we get an absorption factor of 1097.

16.4 Solutions to the Problems of Chapter 5

Problem 1

The measured charge ΔQ is related to the change of the voltage ΔU via the capacitor equation:

$$\begin{aligned}\Delta Q &= C\ \Delta U \\ &= 7 \times 10^{-12}\,\mathrm{F} \times 30\,\mathrm{V} = 210 \times 10^{-12}\,\text{coulomb}\ .\end{aligned}$$

The mass of the air is

$$m = \rho_\mathrm{L}\ V = 3.225 \times 10^{-3}\,\mathrm{g}\ .$$

This leads to an ion dose of

$$\begin{aligned}I = \frac{\Delta Q}{m} &= 6.5 \times 10^{-8}\,\frac{\mathrm{C}}{\mathrm{g}} \\ &= 6.5 \times 10^{-5}\,\frac{\mathrm{C}}{\mathrm{kg}}\ .\end{aligned}$$

Because of $1\,\mathrm{R} = 2.58 \times 10^{-4}\,\mathrm{C/kg}$ this corresponds to a dose of 0.25 roentgen. Since $1\,\mathrm{R} = 8.8\,\mathrm{mGy}$, we get

$$D = 2.2\,\mathrm{mGy}\ .$$

Problem 2

The true dead-time-corrected rate at a distance of $d_1 = 10\,\mathrm{cm}$ is

$$R_1^* = \frac{R_1}{1 - \tau\ R_1}\ .$$

Because of the inverse-square law ($\sim 1/r^2$) the true rate R_2^* at $d_2 = 30\,\mathrm{cm}$ is

$$R_2^* = \left(\frac{d_1}{d_2}\right)^2\ R_1^*\ ;$$

and because of $R_2^* = R_2/(1 - \tau\ R_2)$ one arrives at the equation

$$\left(\frac{d_1}{d_2}\right)^2\ \frac{R_1}{1 - \tau\ R_1} = \frac{R_2}{1 - \tau\ R_2}\ .$$

Solving for τ yields

$$\tau = \frac{\left(\frac{d_2}{d_1}\right)^2\ R_2 - R_1}{\left[\left(\frac{d_2}{d_1}\right)^2 - 1\right]\ R_1\ R_2} = 10\,\mu\mathrm{s}\ .$$

Problem 3

For the solid-angle factor we get

$$f_1 = \frac{\pi \left(\frac{d}{2}\right)^2}{4\pi r^2} = 5.625 \times 10^{-5}$$

and for the efficiency

$$f_2 = 0.08 \ ,$$

resulting in an activity of

$$A = \frac{(\text{count rate} - \text{background rate}) \times \text{min}/60\,\text{s}}{f_1\ f_2}$$
$$= 1.1 \times 10^7\,\text{Bq} = 300\,\mu\text{Ci} \ .$$

Problem 4

The initial contamination is N. After single wiping we have the residual contamination $N(1-\varepsilon)$; after the third decontamination step one has $N(1-\varepsilon)^3$. Therefore we get for N:

$$N = \frac{512\,\text{Bq/cm}^2}{(1-\varepsilon)^3} = 1000\,\text{Bq/cm}^2 \ .$$

The third decontamination step removes an area activity of

$$N(1-\varepsilon)^2\,\varepsilon = 128\,\text{Bq/cm}^2 \ .$$

16.5 Solutions to the Problems of Chapter 6

Problem 1

1 m^3 ground air contains a krypton activity of 1.1 Bq. However, 1 m^3 air contains only 1.1 ppm krypton, corresponding to a fraction of 1.1×10^{-6}. Therefore 1 m^3 of krypton has an activity of 10^6 Bq. This means that the exemption limit is already exhausted by an amount of 0.01 m^3 = 10 l.

A different, more formal approach to solve this problem, is presented by the following consideration: ^{85}Kr has a half-life of 10.4 yrs. Consequently, the decay constant is

$$\lambda = \frac{1}{\tau} = \frac{\ln 2}{T_{1/2}} = 2.11 \times 10^{-9}\,\text{s}^{-1} \ .$$

Since the activity of ^{85}Kr in 1 m^3 of ground air is 1.1 Bq, the number of krypton-85 nuclei in 1 m^3 of air can be worked out from

$$A = \lambda\, N$$

to be

$$N = \frac{A}{\lambda} = 5.2 \times 10^8 \ .$$

1.1 ppm krypton, corresponding to 1.1 cm^3 in 1 m^3 air, leads to an amount of krypton of 4.125 mg (the density of krypton is $\rho = 3.75\,g/l$). This corresponds to $\frac{4.125\times10^{-3}}{83.8} = 4.92 \times 10^{-5}$ mol $\widehat{=}$ 2.96×10^{19} nuclei. (1 mol has 6.022×10^{23} atoms, Avogadro number.) This leads to an atomic abundance of ^{85}Kr of

$$\frac{5.2 \times 10^8}{2.9 \times 10^{19}} = 1.75 \times 10^{-11} \ .$$

The exemption limit is at 10^4 Bq ^{85}Kr, corresponding to $5.2 \times 10^8 \times \frac{10^4}{1.1} = 4.73 \times 10^{12}$ nuclei. Considering the isotopic abundance we get

$$\frac{4.73 \times 10^{12}}{1.78 \times 10^{-11}} = 2.70 \times 10^{23} \text{ krypton atoms}$$
$$\widehat{=} 0.448\,\text{mol} \widehat{=} 37.5\,\text{g} \widehat{=} 10 \text{ liters} \ .$$

Problem 2

The activity of a substance is derived from

$$N = N_0\, e^{-\lambda t} = N_0\, e^{-t/\tau}$$
$$\text{to be} \quad A = -\frac{dN}{dt} = \lambda N = \frac{N}{\tau} \ .$$

For a mixture of isotopes the total activity is

$$\begin{aligned} A_{\text{total}} &= A_1(^{238}\text{U}) + A_2(^{235}\text{U}) + A_2(^{235}\text{U}) \\ &= \frac{N_1}{\tau_1} + \frac{N_2}{\tau_2} + \frac{N_3}{\tau_3} \\ &= N \left\{ \frac{0.992\,75 \ln 2}{T_{1/2}(^{238}\text{U})} + \frac{0.007\,195 \ln 2}{T_{1/2}(^{235}\text{U})} + \frac{0.000\,055 \ln 2}{T_{1/2}(^{234}\text{U})} \right\} \\ &= N \ \{1.53 + 0.0712 + 1.59\} \times 10^{-10}\,\text{yr}^{-1} \ . \end{aligned}$$

This leads to

$$N = \frac{A_{\text{total}}}{3.19 \times 10^{-10}}\,\text{Bq yrs} = 3.135 \times 10^{13}\,\text{Bq yrs}$$
$$= 9.886 \times 10^{20}\,\text{Bq s} = 9.886 \times 10^{20} \text{ nuclei} \ .$$

Since the atomic mass is practically completely concentrated in the nucleus, and 1 mol uranium contains 6.022×10^{23} atoms, 9.886×10^{20} nuclei correspond to 1.64×10^{-3} mol.

1 mol uranium in its natural isotopic abundance has

$$(238\times0.992\,75+235\times0.007\,195+234\times5.5\times10^{-5})\,\text{g} = 237.98\,\text{g}.$$

Therefore the uranium fraction of the lump of ore is given by

$$M_{\text{chunk of uranium ore}} = 0.390\,\text{g} \ .$$

Since the density of uranium is rather large, $\rho_U = 18.95\,g/cm^3$, we are only dealing with a uranium volume of $0.0206\,cm^3 = 20.6\,mm^3$!

Problem 3

The maximum dose for workers of category A in controlled areas is 20 mSv/yr. A whole-body irradiation of 12 mSv and a liver exposure of 40 mSv leads to an effective whole-body dose of

$$H_{\text{eff}} = (12 + 0.05 \times 40)\,\text{mSv} = 14\,\text{mSv} \ ,$$

where 0.05 is the tissue weighting factor for the liver. To exhaust the maximum allowable whole-body dose an additional whole-body exposure of

$$H_{\text{max}} - 14\,\text{mSv} = 6\,\text{mSv}$$

would be acceptable.

If this dose were received exclusively on the lung, a maximum lung dose of

$$\frac{6\,\text{mSv}}{0.12} = 50\,\text{mSv}$$

would keep the total effective dose still within the limit of 20 mSv/yr.

16.6 Solutions to the Problems of Chapter 7

Problem 1

A work load of 40 hours a week and 52 weeks a year (no holiday assumed) leads to a total residence time of workers in a radiation area of 2080 hours per year. The legislator has fixed the annual residence time to 2000 hours per year. (Does this mean that the authorities allow only two weeks of holiday in a year?) This leads to an annual dose of 8 mSv for the given dose rate. Therefore this room must be considered as controlled area and the worker counts as belonging to the category-A group (dose range $6\,\text{mSv/yr} < \dot{D} \leq 20\,\text{mSv/yr}$).

Problem 2

The total activity is calculated to be

$$A_{\text{total}} = 100\,\text{Bq/m}^3 \times 4000\,\text{m}^3 = 4 \times 10^5\,\text{Bq} \ .$$

Consequently the original activity concentration in the reactor core was

$$A_0 = \frac{4 \times 10^5\,\text{Bq}}{500\,\text{m}^3} = 800\,\text{Bq/m}^3 \ .$$

Problem 3

The activity is given by

$$A = \lambda\, N = \frac{1}{\tau}\, N = \frac{\ln 2}{T_{1/2}}\, N \ ,$$

corresponding to

$$N = \frac{A\, T_{1/2}}{\ln 2} = 1.9 \times 10^{12}\ \text{cobalt nuclei}$$

and $m = N\, m_{\text{Co}} = 0.2\,\text{ng}$. Such a low amount of cobalt can hardly be detected by analytical chemistry.

16.7 Solutions to the Problems of Chapter 8

Problem 1

For a radioactive source to be considered leak-proof, the result of a wipe test of the source must not exceed an activity of 200 Bq. The measurement, however, yielded a larger value, namely,

$$\frac{20 \text{ counts per second}}{0.8 \times 0.1} = 250\,\text{Bq} \ .$$

Therefore the source cannot be considered leak-proof.

Problem 2

The activity per cm^2 is

$$\frac{\text{activity}}{\text{cm}^2} = \frac{R - R_0}{F\ \eta_1\ \eta_2} = 550\,\frac{\text{Bq}}{\text{cm}^2} \ .$$

Problem 3

The radiated power is

$$S = 10^{17}\,\text{Bq} \times 10\,\text{MeV} = 10^{24}\,\text{eV/s} = 160\,\text{kJ/s} \ ,$$

which leads to a temperature increase of

$$\begin{aligned} \Delta T &= \frac{\text{heat input}}{m\ c} \\ &= \frac{160\,\text{kJ/s} \times 86\,400\,\text{s/d} \times 1\,\text{d}}{120\,000\,\text{kg} \times 0.452\,\text{kJ/(kg K)}} \\ &= 255\,\text{K} \ . \end{aligned}$$

The temperature rise of 255 degrees leads to a final temperature of 275 °C.

Problem 4

The dose rate from a pointlike emitter of activity A at a distance r is given by

$$\dot{H} = \Gamma_\gamma\ \frac{A}{r^2} \ .$$

Using the specific γ dose constant of ^{60}Co (see Table 2.3),

$$\Gamma_\gamma(^{60}\text{Co}) = 3.41 \times 10^{-13}\,\frac{\text{Sv m}^2}{\text{Bq h}} \ ,$$

we can solve for the minimum distance r:

$$r \le \sqrt{\frac{\Gamma_\gamma\ A}{\dot{H}}} = 1.85\,\text{m} \ .$$

If we assume that the source has been dropped to the floor, and if we further assume that the dosimeter is carried at a height of 1 m, the search will cover a radial distance of $\sqrt{1.85^2 - 1}\,\text{m} = 1.55\,\text{m}$. Therefore it is sufficient to search for the radioactive source in places about 3 m apart.

Problem 5

We have

$$\dot{D} \sim \frac{1}{r^2} \ ;$$

with the result

$$\frac{\dot{D}(x)}{\dot{D}(100\,\mathrm{m})} = \frac{(100\,\mathrm{m})^2}{x^2} = \frac{25\,\mu\mathrm{Sv/h}}{1\,\mu\mathrm{Sv/h}} \ .$$

Solved for x we get

$$x = 20\,\mathrm{m} \ .$$

Problem 6

The decay of the radioactive uranium in the filter can be safely neglected. This leads to the activity

$$A = m\,\kappa\,\eta\,t = 40.32\,\mathrm{MBq} \ .$$

If the decay of the long-lived uranium isotope is taken into account ($T_{1/2} = 4.5 \times 10^9$ yrs, decay constant $\lambda = \frac{\ln 2}{T_{1/2}} = 1.76 \times 10^{-14}\,\mathrm{h}^{-1}$), the solution of the problem is more demanding. In this case we have to solve the following differential equation for the time-dependent activity:

$$\frac{\mathrm{d}A}{\mathrm{d}t} = m\,\kappa\,\eta - \lambda\,A$$

with the result[2]

$$A = \frac{m\,\kappa\,\eta}{\lambda}\left(1 - \mathrm{e}^{-\lambda\,t}\right) \ .$$

Because of $\lambda\,t \ll 1$ and $A = \frac{m\,\kappa\,\eta}{\lambda}\,(1 - (1 - \lambda\,t + \cdots)) \approx m\,\kappa\,\eta\,t$ the above numerical result is practically unchanged.

Problem 7

According to the rules laid down in Chap. 8 (radiation safety) the dose rate at the outside surface of goods for II–yellow cargo-container types is in the range

$$5\,\mu\mathrm{Sv/h} \leq \dot{D} \leq 0.5\,\mathrm{mSv/h} \ .$$

The transport index $t = 0.3$ means that $\dot{D}(1\,\mathrm{m}) = 0.3\,\mathrm{mrem/h}$ corresponding to $\dot{D}(1\,\mathrm{m}) = 3\,\mu\mathrm{Sv/h}$.

16.8 Solutions to the Problems of Chapter 9

Problem 1

The average energy loss of α particles of $1.37\,\mathrm{MeV/(mg/cm^2)}$ can be converted into a range of

[2] compare supplementary information No. 1, Chap. 8

$$\lambda = \frac{5\,\mathrm{MeV}}{1.37\,\mathrm{MeV/(mg/cm^2)}} = 3.65\,\mathrm{mg/cm^2} \ .$$

Only this distance is relevant for neutron production. The neutron production probability per incident α particle is then

$$\begin{aligned}\phi &= \frac{N_\mathrm{A}[\mathrm{mol}^{-1}] \times \mathrm{g}^{-1}}{A}\,\sigma\,\lambda \\ &= \frac{6.022 \times 10^{23}}{9} \times 3 \times 10^{-25} \times 3.65 \times 10^{-3} = 7.3 \times 10^{-5} \ .\end{aligned}$$

According to this calculation 73 neutrons are generated for one million of incident α particles.

Problem 2

The solid-angle–area product of the coincidence arrangement can be approximated by

$$\Omega A = \frac{F_1\ F_2}{d^2} = \frac{100 \times 100\,\mathrm{cm}^4}{(50\,\mathrm{cm})^2} = 4\,\mathrm{cm}^2\,\mathrm{sr} \ .$$

The flux of cosmic-ray muons is (see Eq. (9.12))

$$\phi = 8 \times 10^{-3}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1} \ ,$$

giving $\phi\ \Omega A = 0.032\,\mathrm{s}^{-1}$, which corresponds to 2765/d. For a signal width of 100 µs the total dead time is

$$\tau = 2765 \times 10^{-4}\,\mathrm{s} \approx 0.28\,\mathrm{s}$$

corresponding to a negligibly small fraction of 3.2×10^{-6} of the total measurement time.

Problem 3

Tissue consists essentially of water. From 1 mol of water (18 g H_2O) one obtains $N = N_\mathrm{A} \times 2\,\mathrm{g}/(18\,\mathrm{g/mol}) = 6.69 \times 10^{22}$ 'quasi-free' protons per gram (N_A – Avogadro number). The average mean free path of 5-MeV neutrons in tissue is $\lambda = \frac{1}{N\sigma\rho} \approx 15\,\mathrm{cm}$. This means that such a neutron interacts on average only once in the human body. Depending on the scattering angle in the (n, p) reaction an energy between 0 and 5 MeV is transferred, which corresponds on average to half the neutron energy. This energy will be deposited in a volume of $15\,\mathrm{cm} \times 1\,\mathrm{cm}^2$. This leads to an energy dose of

$$D(\mathrm{J/kg}) = \frac{N\ \sigma\ \Delta E\ d\ \rho}{m} \ .$$

The 'target thickness' is $d = 15\,\mathrm{cm}$ and its density is $\rho = 1\,\mathrm{g/cm}^3$. The irradiated tissue per cm^2 has a mass of 15 g. Therefore the dose per incident neutron is given by

$$D(\mathrm{Gy}) = \frac{1}{15 \times 10^{-3}\,\mathrm{kg}} \times 6.69 \times 10^{22}\,\frac{1}{\mathrm{g}} \times 10^{-24}\,\mathrm{cm}^2 \times 2.5\,\mathrm{MeV} \times 1.602 \times 10^{-13}\,\frac{\mathrm{J}}{\mathrm{MeV}} \times 15\,\frac{\mathrm{g}}{\mathrm{cm}^2} = 2.68 \times 10^{-11}\,\mathrm{Gy}\ .$$

For a neutron flux of $10^6/\mathrm{cm}^2$ and a radiation weighting factor of 10 for 5-MeV neutrons one obtains

$$H(\mathrm{Sv}) = D(\mathrm{Gy}) \times 10^6 \times 10\,\frac{\mathrm{Sv}}{\mathrm{Gy}} = 268\,\mu\mathrm{Sv}\ .$$

16.9 Solutions to the Problems of Chapter 10

Problem 1

The accelerating voltage has to be chosen in such a way that the shortest wavelength is $\lambda_{\min} \leq 0.5\,\text{Å}$. Because of

$$e\,U = h\nu = \frac{h\,c}{\lambda_{\min}}$$

(ν – frequency, h – Planck constant) we get

$$U \geq \frac{h\,c}{\lambda_{\min}\,e} = 24\,816\,\mathrm{V} \approx 25\,\mathrm{kV}\ .$$

Problem 2

The absorption of X rays is described by

$$I = I_0\,\mathrm{e}^{-\mu\,x} \Rightarrow \mathrm{e}^{\mu\,x} = \frac{I_0}{I}\ .$$

Solved for x we get

$$x = \frac{1}{\mu}\,\ln\left(\frac{I_0}{I}\right) = 30.7\,\frac{\mathrm{g}}{\mathrm{cm}^2}$$

or, equivalently,

$$x^* = \frac{x}{\rho_{\mathrm{Al}}} = 11.4\,\mathrm{cm}\ .$$

Problem 3

1.) $\dot{D}(\mathrm{concrete} + \mathrm{lead}) = \dot{D}(\mathrm{concrete})\,\mathrm{e}^{-\mu_{\mathrm{Pb}}\,x}$.

This leads to

$$\mathrm{e}^{\mu_{\mathrm{Pb}}\,x} = \frac{\dot{D}(\mathrm{concrete})}{\dot{D}(\mathrm{concrete} + \mathrm{lead})}\ .$$

This can be solved for x to give

$$x = 0.59\,\mathrm{cm}\ .$$

2.) First of all we have to work out the dose rate without any shielding:

$$\dot{D}(\text{without shielding}) = \dot{D}_0 = \dot{D}(20\,\text{cm concrete}) \times \mathrm{e}^{\mu_{\text{concrete}}\, y} \ ;$$

if $y = 20\,\text{cm}$ is the thickness of the concrete shielding, we get

$$\dot{D}_0 = 282\,\text{mSv/h} \ .$$

For a shielding exclusively of lead one would obtain:

$$\dot{D}(x\,\text{cm Pb}) = \dot{D}_0\, \mathrm{e}^{-\mu_{\text{Pb}}\, x} = 1\,\mu\text{Sv/h} \ ,$$

$$\mathrm{e}^{\mu_{\text{Pb}}\, x} = \frac{282}{10^{-3}} = 2.82 \times 10^5$$

with the result (see above)

$$x = 1.14\,\text{cm} \ .$$

16.10 Solutions to the Problems of Chapter 11

Problem 1

At a distance of one meter practically only the γ activity counts, because both the α particles and the β particles have been almost completely absorbed. Most of the α particles will even not have been able to escape from the ground. Based on a γ activity of 500 Bq/kg and an assumed average specific γ dose constant for the mixed radiation field[3] of $10^{-13}\ \frac{\text{Sv m}^2}{\text{Bq h}}$, we arrive at a dose rate of

$$\begin{aligned} \dot{H} &= 10^{-13}\ \frac{\text{Sv m}^2}{\text{Bq h}} \times 500\,\text{Bq/kg} \times 1\,\text{m}^{-2} \\ &= 5 \times 10^{-11}\ \frac{\text{Sv}}{\text{h kg}} \ . \end{aligned}$$

Under the assumption that persons are irradiated from one ton of the soil, this leads to a dose rate of 5×10^{-8} Sv/h and an annual dose of about 0.5 mSv.

Problem 2

With modern medical X-ray machines patients are exposed to a whole-body dose of 0.1 mSv or even less. A stay at an altitude of 3000 m at average geographical latitudes leads to a dose rate due to cosmic rays of about 0.1 µSv/h corresponding to 67 µSv in four weeks. If also the effect of terrestrial radiation is considered (about

[3] Standard soil usually contains the radioisotopes ^{40}K, ^{226}Ra, and ^{232}Th, dominated mostly by ^{40}K. Averaged over these three isotopes the given specific γ dose constant is a reasonable approximation.

40 µSv in four weeks), one arrives at a total dose which is comparable to the exposure from an X-ray of the chest. However, it has to be mentioned that older X-ray machines may lead to higher exposures. Also, it has to be considered that the dose from an X-ray is received in a very short time interval (ms) with the consequence of a much higher dose rate compared to the effect of natural radiation.[4]

Problem 3

$$D(\text{CASTOR}) = 30\,\mu\text{Sv/h} \times 10\,\text{h} = 0.3\,\text{mSv} \ ,$$
$$\overline{D}(\text{Black Forest}) \approx 5\,\text{mSv/yr} \ .$$

This means that people accompanying a single CASTOR transport will get a dose that corresponds roughly to 6% of the annual dose one gets when living in the Black Forest and only 1.5% of the permitted maximum annual dose of workers of category A in controlled areas.

16.11 Solutions to the Problems of Chapter 12

Problem 1

$$\Delta T = \frac{Q}{c \cdot m} = \frac{0.1 \times 10^9\,\text{W} \times 0.7 \times 200\,\text{s}}{0.116 \times 10^3\,\text{J/(kg K)} \times 50 \times 10^3\,\text{kg}} = 2414\,\text{K} \ .$$

This means that the water evaporates completely and also the reactor core will melt (melting point of uranium 1132.2 °C).

Problem 2

Energy gain $\Delta E = 50\,\text{kW} \times 5 \times 10^5\,\text{yrs} = 7.884 \times 10^{17}\,\text{J} = 4.92 \times 10^{36}\,\text{eV}$. Per fission process about 200 MeV are liberated. Thus the number of fission processes is

$$N = 2.46 \times 10^{28} \ .$$

Given the mass of an ^{235}U nucleus of $m = 235 \times 1.66 \times 10^{-27}\,\text{kg} = 3.90 \times 10^{-25}\,\text{kg}$, the total amount of uranium ^{235}U processed is

$$M = m\,N = 9597\,\text{kg} \approx 9.6\,\text{tons} \ .$$

Problem 3

$$N(^{238}\text{U}) = N_0(^{238}\text{U})\ \exp(-\lambda_1\,t) \ ,$$
$$N(^{235}\text{U}) = N_0(^{235}\text{U})\ \exp(-\lambda_2\,t) \ ;$$
$$N_0(^{235}\text{U}) = N_0(^{238}\text{U}) \, , \ N(^{238}\text{U}) = 0.9965 \, , \ N(^{235}\text{U}) = 0.0035 \, ;$$

[4] For more information about exposures from X-ray examinations see `www.radiologyinfo.org/en/info.cfm?pg=chestrad`. Detailed comparisons with radiation exposures from natural sources are given in the 'safety page', which is linked to the given web page.

$$r = \frac{N(^{238}\mathrm{U})}{N(^{235}\mathrm{U})} = \exp((\lambda_2 - \lambda_1)\, t) \ ;$$

$$t = \frac{1}{\lambda_2 - \lambda_1} \ln r \ ;$$

$$\lambda_2(^{235}\mathrm{U}) = 3.08 \times 10^{-17}\,\mathrm{s}^{-1} \ , \quad \lambda_1(^{238}\mathrm{U}) = 4.87 \times 10^{-18}\,\mathrm{s}^{-1} \ ;$$

$$t = 2.18 \times 10^{17}\,\mathrm{s} \approx 6.9 \times 10^{9}\,\mathrm{yrs} \ .$$

This means that this deposit would be older than the solar system. In other words, a fraction of the observed ^{235}U must have been transformed by fission processes.

Problem 4

The dose rate after one day can be scaled using the given power law: a) $\dot{D}(t = 30\,\mathrm{h}) = \dot{D}(t_0) \cdot (\frac{30}{6})^{-1.2} = 1.45\,\mathrm{mSv/h}$.
The dose obtained in a 10-hour period 30 hours after the accident is obtained by integration: b) $D(t = 30\,\mathrm{h}\text{–}40\,\mathrm{h}) = \int_{t_1}^{t_2} \dot{D}(t)\,\mathrm{d}t$
$= \dot{D}(t_0)\, \frac{1}{t_0^{-\alpha}}\, (t_1^{-0.2} - t_2^{-0.2}) \times 5 = 12.16\,\mathrm{mSv}$.

16.12 Solutions to the Problems of Chapter 13

Problem 1

The effective half-life for ^{137}Cs in humans is

$$T_{1/2}^{\mathrm{eff}} = \frac{T_{1/2}^{\mathrm{phys}}\, T_{1/2}^{\mathrm{bio}}}{T_{1/2}^{\mathrm{phys}} + T_{1/2}^{\mathrm{bio}}} = 109.9\,\mathrm{days} \ .$$

The residual amount of ^{137}Cs after three years can be determined in two different ways:

a) the time interval of three years corresponds to $\frac{3\times365}{109.9} = 9.9636$ half-lives:

$$\mathrm{activity}(3\,\mathrm{yrs}) = 4 \times 10^{6} \times 2^{-9.9636} = 4006\,\mathrm{Bq} \ ;$$

b) on the other hand, the time dependence of the activity yields the same result:

$$\mathrm{activity}(3\,\mathrm{yrs}) = 4 \times 10^{6} \times \mathrm{e}^{-3\,\mathrm{yrs}\times\ln 2/T_{1/2}^{\mathrm{eff}}} = 4006\,\mathrm{Bq} \ .$$

Problem 2*

Let us assume the pancreas to be spherical. For a density of $\rho = 1\,\mathrm{g/cm^3}$ the radius of the pancreas is worked out from

$$50\,\mathrm{cm}^3 = \frac{4}{3}\,\pi\, r^3 = V_r$$

* The solution of this problem is mathematically demanding.

to be $r = 2.29\,\text{cm}$. The range of 45-keV electrons can be read from Fig. 4.4 by extrapolation to be $R = 5 \times 10^{-3}\,\text{cm}$. Only those electrons in the spherical shell between r and $r - R$ can escape, where $R \ll r$.

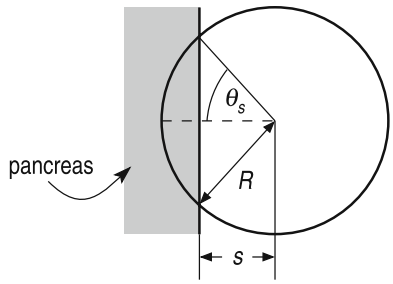
The activity $3.25\,\mu\text{Ci}$ can be converted to $120\,\text{kBq}$. For an average beta energy of $45\,\text{keV}$ an amount of $\langle E \rangle = 5.4 \times 10^9\,\text{eV}$ is deposited per second in the human body. This corresponds to

$$\langle \dot{E} \rangle = 8.7 \times 10^{-10}\,\text{J/s} \ .$$

For the inner part of the pancreas (positions with radii smaller than $r - R$) this leads to a dose rate of

$$\dot{D}_0 = \frac{8.7 \times 10^{-10}\,\text{J/s}}{50 \times 10^{-3}\,\text{kg}} = 1.74 \times 10^{-8}\,\frac{\text{Sv}}{\text{s}} = 62.64\,\mu\text{Sv/h} \ .$$

We now assume that all electrons have the fixed range R. Let s be the distance of a point outside the pancreas from its surface. Then only those rays from a spherical surface with radius R lying inside the pancreas contribute to the dose rate at this point. For $R \ll r$ one can replace the spherical surface of the pancreas by a plane.



The dose rate scales with the ratio of the solid angle Ω_s to the full one (4π); it is integrated in spherical coordinates, where the polar angle varies from 0 to θ_s, which is identified through $\cos\theta_s = s/R$:

$$\begin{aligned}\Omega_s &= 2\pi \int_0^{\theta_s} \sin\theta \, \mathrm{d}\theta = 2\pi \, [-\cos\theta]_0^{\theta_s} = 2\pi(1 - \cos\theta_s) \\ &= 2\pi \left(1 - \frac{s}{R}\right) \ .\end{aligned}$$

Therefore, the dose-rate fraction $f_s = \Omega_s/4\pi$ varies linearly with the distance to the surface, $f_s = (1 - s/R)/2$. This result is also valid for the inner part, $-R \le s < 0$. On average, for the outside the dose rate is scaled by $f_{\text{out}} = (f_0 + f_R)/2 = 1/4$ to be $\dot{D}_2 = \dot{D}_0/4$. On the inside the averaged factor f_{in} is obtained by using the volumes in question, $f_{\text{in}} = (V_r - 4\pi r^2 R f_{\text{out}})/V_r = 1 - 3 f_{\text{out}} R/r \approx 0.9984$, leading to the dose rate $\dot{D}_1 = f_{\text{in}} \dot{D}_0 = 0.9984\ \dot{D}_0$.

Problem 3*

^{226}Ra has a physical half-life of 1600 years. Therefore the effective half-life is

$$T_{1/2}^{\text{eff}} = \frac{T_{1/2}^{\text{phys}}\, T_{1/2}^{\text{bio}}}{T_{1/2}^{\text{phys}} + T_{1/2}^{\text{bio}}} = 299.8\,\text{days}\ ,$$

i.e., it is dominated by the biological half-life.

The old activity unit 1 curie was defined as activity of 1 g ^{226}Ra. The incorporated amount of 1 µg ^{226}Ra corresponds to an activity of

$$A_0 = 3.7 \times 10^{10}\,\frac{\text{Bq}}{\text{g}} \times 1 \times 10^{-6}\,\text{g} = 3.7 \times 10^{4}\,\text{Bq}\ .$$

In the radium decay chain to the stable lead isotope ^{208}Pb a total amount of 33 MeV of α rays, 3 MeV of β rays, and 1.5 MeV of γ rays is liberated. Considering the high biological effectiveness of α rays (radiation weighting factor w_R = 20) the weighted equivalent energy deposition is worked out to be about 665 MeV per 1 Bq ^{226}Ra.

The instantaneous dose rate is

$$\dot{H} = \frac{A\ W}{m}\ ,$$

where A – activity, W – liberated energy per Bq, and m – body mass,

$$\dot{H} = A_0\,\frac{W}{m}\,\exp\left\{-\frac{\ln 2}{T_{1/2}^{\text{eff}}}\,t\right\}\ .$$

The 50-years commitment dose equivalent is obtained by integration to be

$$\begin{aligned} H_{50} &= \int_0^{50\,\text{yrs}} \dot{H}(t)\,\text{d}t \\ &= -\frac{A_0\ W}{m}\,\frac{T_{1/2}^{\text{eff}}}{\ln 2}\,\exp\left\{-\left((\ln 2)\,/T_{1/2}^{\text{eff}}\right)\,t\right\}\Big|_0^{50\,\text{yrs}} \\ &= \frac{A_0\ W\ T_{1/2}^{\text{eff}}}{m\ \ln 2}\left(1 - \exp\left\{-\frac{\ln 2}{T_{1/2}^{\text{eff}}} \times 50\,\text{yrs}\right\}\right)\ . \end{aligned}$$

Using $A_0 = 3.7 \times 10^4\,\text{Bq}$ and $W = 665\,\text{MeV} = 665 \times 1.6 \times 10^{-13}\,\text{J} = 1.064 \times 10^{-10}\,\text{J}$ as well as $T_{1/2}^{\text{eff}} = 299.8\,\text{d} \times 86\,400\,\text{s/d} = 2.59 \times 10^7\,\text{s}$ and $m = 50\,\text{kg}$ we get

$$H_{50} = 2.94 \times \left(1 - 5 \times 10^{-19}\right)\,\text{Sv} = 2.94\,\text{Sv}\ .$$

* The solution of this problem is mathematically demanding.

It is obvious that predominantly lips and tongues were affected by this activity with the consequence that the female dial painters contracted cancer of the lips and tongue and frequently died of heavy radiation damage. Some of the women even intentionally painted their lips and teeth with the radium solution when going to a rendezvous, because the radium caused such a romantic glow in the dark. It is reported that the bodies of the deceased women shone in the dark of the morgue, which is probably an exaggeration.

16.13 Solutions to the Problems of Chapter 14

Problem 1

Such an estimate is subject to substantial uncertainties.[5] This is also related to the fact that individual exposures have not been recorded, even not for the personnel involved in the cleanup ('liquidators'). It is almost unbelievable that suitable radiation detectors were not available. The received radiation doses were only estimated after the fact based on symptoms of radiation sickness and chromosome aberrations in blood samples of the exposed workers. It has also to be considered that the radiation sensitivity of children is significantly higher than that of adults. This comes about because of the increased mitosis in the period of growth, which tends to multiply radiation damage in the body of the children.

Further it has to be considered that the Chernobyl cloud spread over the whole northern hemisphere. For the following estimate we break down the northern hemisphere into five regions. For the increased radiation sensitivity of children we assume a factor of five (which is probably a little pessimistic).

Based on this rather crude estimate we would expect about 10 000 cases of leukemia in children and about the same number of incidents in adults worldwide. In contrast, at the present time, 23 years after the catastrophe in Chernobyl, no significant increase in leukemia rates is observed. However, the thyroid-gland cancer rate in children in the area around Chernobyl has clearly increased.

In view of the non-observation of an increase of leukemia rates (at the time of 2009) the relatively high 'predicted' cancer rates shown in the table could indicate that either the assumed doses or the risk factor were too high. According to the literature the radiation risk factors have changed over the years from previously lower values (ICRP-26 (1977): risk factor for leukemia 0.20% per sievert) to the presently assumed ones (ICRP-60 (1990): risk factor for

[5] I appreciate the information given by Dipl. Phys. Helmut Kowalewsky, Berlin, about the actual number of cases of leukemia and cancer of the thyroid gland in Russia and the Ukraine.

region	number of inhabitants	average estimated dose	expected incidents of leukemia
Chernobyl; 'liquidators'	700 000	0.1 Sv	350
Belorussia and Ukraine;			
children	600 000	20 mSv	300
adults	2.4 Mio.	20 mSv	240
remaining Russia;			
children	60 Mio.	5 mSv	7500
adults	240 Mio.	5 mSv	6000
Western Europe;			
children	100 Mio.	0.5 mSv	1250
adults	400 Mio.	0.5 mSv	1000
USA, Japan, China, . . .;			
children	680 Mio.	0.1 mSv	1700
adults	2 700 Mio.	0.1 mSv	1350

Table 16.1
Estimate of possible leukemia rates based on the given doses and the new risk factors (ICRP-60 (1990)) as shown in Table 13.1[6]

leukemia 0.50% per sievert). In the light of the observed current leukemia rates the new radiation risk factors as presented in Table 13.1 appear to be too pessimistic.

Problem 2

The specific dose constants for β and γ rays of ^{60}Co are

$$\Gamma_\beta = 2.62 \times 10^{-11} \times \frac{\mathrm{Sv\,m^2}}{\mathrm{Bq\,h}} \ ,$$

$$\Gamma_\gamma = 3.41 \times 10^{-13} \times \frac{\mathrm{Sv\,m^2}}{\mathrm{Bq\,h}} \ .$$

For the irradiation of the hands the β dose dominates. Let us assume an average distance of 10 cm and a handling time of the source of 60 seconds. This would lead to a partial-body dose of

$$H_\beta = \Gamma_\beta \frac{A}{r^2} \Delta t = 2.62 \times 10^{-11} \times \frac{3.7 \times 10^{11}}{0.1^2} \times \frac{1}{60} \,\mathrm{Sv} = 16.1 \,\mathrm{Sv} \ .$$

On the other hand, the whole-body dose essentially depends on γ rays from the ^{60}Co source. For an average distance of 0.5 m and an exposure time of 5 minutes the whole-body dose is estimated to be

$$H_\gamma = \Gamma_\gamma \frac{A}{r^2} \Delta t = 42 \,\mathrm{mSv} \ .$$

[6] Based on information from the report of L. A. Iljin: Atomnaja Energija, Volume 92, Issue 2, 2002.

Actually, such an accident happened to technicians in Saintes, France, in 1981. Under no circumstances they should have handled the strong source with their bare hands. Due to the severe radiation damage the hands of two technicians had to be amputated. For a third technician the amputation of three fingers was necessary.

Problem 3

360 kg uranium in 30 m^3 of water corresponds to a concentration of 12 g/l. This is a factor of $\frac{12\,\mathrm{g}}{15\,\mu\mathrm{g}} = 800\,000$ larger than the WHO-recommended limit for drinking water.

Natural uranium mainly consists of the isotopes ^{234}U (0.0055%, $T_{1/2} = 2.455 \times 10^5$ yrs), ^{235}U (0.7204%, $T_{1/2} = 7.038 \times 10^8$ yrs), and ^{238}U (99.2742%, $T_{1/2} = 4.468 \times 10^9$ yrs). Given the isotopic abundances and the half-lives the total activity of 12 g natural uranium contained in one liter of water is 305 kBq. In depleted uranium the amount of ^{234}U and ^{235}U is reduced resulting in an estimated activity of $\approx$ 200 kBq. This corresponds to 200 MBq/m^3. Compared to the ICRP limit for discharges from nuclear power plants this is higher by a factor of $\frac{2\times10^8}{3000} \approx 67\,000$. Naturally, the uranium concentration was rapidly decreased when it was discharged into the rivers.

Typical values for the activity of uranium isotopes in tap water in Europe are around 10 to 20 Bq/m^3. Apart from the radioactivity, uranium solutions are also highly toxic from the chemical point of view.

16.14 Solutions to the Problems of Chapter 15

Problem 1

In Maxwell's theory the current density j, the magnetic field H, and the electrical field in a poorly conducting medium are related by

$$\mathrm{rot}\,\boldsymbol{H} = \boldsymbol{j} + \boldsymbol{j}_\mathrm{V}\ , \quad \boldsymbol{j}_\mathrm{V} = \varepsilon\,\varepsilon_0\,\frac{\partial \boldsymbol{E}}{\partial t}$$

(ε, ε_0 – relative and absolute dielectric constant). The currents in a poorly conducting medium can be neglected. Only the displacement current density $\boldsymbol{j}_\mathrm{V}$ contributes. In one period (50 Hz, corresponding to 20 ms) the electric field varies according to a sine function ($\boldsymbol{E} = \boldsymbol{E}_0 \sin\omega t$). From $E = 0$ up to the first maximum it takes 5 ms.

Using $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m and $\varepsilon(\mathrm{water}) = 81$ as tissue-equivalent medium, one finds for the current density

$$\begin{aligned} j_\mathrm{V} &= 81 \times 8.85 \times 10^{-12}\,\frac{\mathrm{F}}{\mathrm{m}} \times 5 \times 10^3\,\frac{\mathrm{V}}{\mathrm{m}} \times \frac{1}{5 \times 10^{-3}\,\mathrm{s}} \\ &= 7.2 \times 10^{-4}\,\frac{\mathrm{A\,s}}{\mathrm{V\,m}} \times \frac{\mathrm{V}}{\mathrm{m\,s}} = 7.2 \times 10^{-4}\,\frac{\mathrm{A}}{\mathrm{m}^2} \\ &= 7.2 \times 10^{-8}\,\frac{\mathrm{A}}{\mathrm{cm}^2} \approx 0.1\,\mu\mathrm{A/cm}^2\ . \end{aligned}$$

Problem 2

The electrical field of a conductor with respect to the Earth's surface (assumed to be flat) can be reasonably well approximated by:

$$E = \frac{2}{\ln(2h/r_\mathrm{D})}\frac{U}{h} \ .$$

The electrical field of a free wire varies with distance from the wire like $1/r$. The related potential can be worked out by integration from the surface of the wire (Radius $r_\mathrm{D} \ll h$, height h of the wire above ground) effectively up to twice the height h (because of the mirror charge, one has voltage zero on the ground; the mirror charge also causes the factor of 2 in the numerator). For an assumed wire radius of $r_\mathrm{D} = 1\,\mathrm{cm}$ we get

$$\begin{aligned} E &= \frac{2}{\ln(2 \times 30\,\mathrm{m}/1\,\mathrm{cm})} \times \frac{220 \times 10^3\,\mathrm{V}}{30\,\mathrm{m}} = \frac{2}{8.7} \times 7.3\,\mathrm{kV/m} \\ &\approx 1.7\,\mathrm{kV/m} \ . \end{aligned}$$

In many countries the allowed limit is at $20\,\mathrm{kV/m}$, well above the obtained result.

The magnetic field strength is worked out from

$$\oint \boldsymbol{H} \cdot \mathrm{d}\boldsymbol{s} = I$$

to be ($r = h$)

$$H = \frac{I}{2\pi r} = \frac{10^3\,\mathrm{A}}{2\pi \times 30\,\mathrm{m}} = 5.3\,\mathrm{A/m} \ ,$$

corresponding to

$$B = \mu\mu_0 H = 4\pi \times 10^{-7}\,\frac{\mathrm{N}}{\mathrm{A}^2} \times 5.3\,\frac{\mathrm{A}}{\mathrm{m}} = 6.7 \times 10^{-6}\,\frac{\mathrm{V\,s}}{\mathrm{m}^2} = 6.7\,\mu\mathrm{T} \ ,$$

well below the natural magnetic field of the Earth.

Problem 3

$$\oint \boldsymbol{H} \cdot \mathrm{d}\boldsymbol{s} = \int \boldsymbol{j} \cdot \mathrm{d}\boldsymbol{A} \ \Rightarrow \ H = \frac{I}{2\pi r} \ ,$$

$$P = 100\,\mathrm{W} = U\ I \ ,$$

$$I = \frac{P}{U} = \begin{cases} 8.33\,\mathrm{A} & \text{, halogen lamp} \\ 0.455\,\mathrm{A} & \text{, 220 V bulb} \end{cases} \ ,$$

$$\Rightarrow \quad H = \begin{cases} 1.33\,\mathrm{A/m} \ \widehat{=}\ 1.67\,\mu\mathrm{T} & \text{, halogen lamp} \\ 0.072\,\mathrm{A/m} \ \widehat{=}\ 90.5\,\mathrm{nT} & \text{, 220 V bulb} \end{cases} \ .$$

In both cases the magnetic field strength is acceptable.

Formulary

activity

1 becquerel (Bq) = 1 decay per second
1 curie (Ci) = 3.7×10^{10} Bq
1 Bq = 27×10^{-12} Ci = 27 pCi

energy dose

(or simply **dose**) D (Gy), $\quad 1\,\mathrm{Gy} = 1\,\mathrm{J/kg}$

dose equivalent

H (Sv), $\quad H = w_R\, D$

w_R – radiation weighting factor (see Table 2.1)

ion dose

$I = 1\,\mathrm{C/kg}$

1 roentgen (R) = 2.58×10^{-4} C/kg $\widehat{=}$ 8.8 mGy

dose

$$D = \Gamma\, \frac{A}{r^2}\, t \quad \text{(for a pointlike emitter)}$$

Γ – dose constant in units of Sv m^2/(Bq h)
A – activity in Bq; t – time in hours (h);
r – distance in meters (m)

dose rate

$$\dot{D} = \Gamma\, \frac{A}{r^2} \quad \text{(for a pointlike emitter)}$$

decay law

$$N = N_0\, \mathrm{e}^{-\lambda t}$$

λ – decay constant in s^{-1}; $\lambda = \ln 2 / T_{1/2} = 1/\tau$
$T_{1/2}$ – half-life
τ – lifetime

effective half-life

$$T_{1/2}^{\mathrm{eff}} = \frac{T_{1/2}^{\mathrm{phys}}\, T_{1/2}^{\mathrm{bio}}}{T_{1/2}^{\mathrm{phys}} + T_{1/2}^{\mathrm{bio}}}$$

$T_{1/2}^{\mathrm{phys}}$ – physical half-life
$T_{1/2}^{\mathrm{bio}}$ – biological half-life

effective whole-body dose equivalent

$$E = H_{\mathrm{eff}} = \sum_T w_T \sum_R w_R D_{T,R}$$

w_T – tissue weighting factor (see Table 2.2)
w_R – radiation weighting factor (see Table 2.1)
One has to sum over the relevant radiation fields R and tissues T.

$k = \frac{\Delta E}{\Delta m}$ **kerma**

ΔE – sum over the initial kinetic energies of all charged particles liberated in a volume element by indirectly ionizing radiation
$\Delta m = \rho \, \Delta V$ – mass element (ρ – density)

$I = I_0 \, \mathrm{e}^{-\mu x}$ **attenuation law for γ rays**

μ – mass attenuation coefficient

$I = I_0 \, \mathrm{e}^{-\mu_\mathrm{a} x}$ **absorption law for γ rays**

μ_a – mass absorption coefficient

$N = N_0 \, \mathrm{e}^{-\kappa x}$
$\kappa = 15/E_{\beta_\mathrm{max}}^{1.5}$ (E_{β_max} in MeV, κ in $(\mathrm{g/cm^2})^{-1}$) **empirical absorption law for β rays**

$R[\mathrm{g/cm^2}] = 0.526 \times E_\mathrm{kin}[\mathrm{MeV}] - 0.095$ **empirical range for electrons**

$$A = \frac{\text{measured activity} - \text{background rate}}{\text{detection efficiency}}$$ **activity determination**

$$\sum_i \frac{A_i}{A_i^\mathrm{max}} \leq 1$$ **exemption limit for several radioactive sources**

A_i – activity of material i
A_i^max – exemption limit of material i

$$x_{1/2} = \frac{\ln 2}{\mu}$$ **half-value thickness**

$$x_{1/10} = \frac{\ln 10}{\mu}$$ **tenth-value thickness**

$N_\mathrm{true} = \frac{N}{1 - N\,\tau}$ **dead-time correction**

N – measured count rate
τ – dead time

$f(N, \mu) = \frac{\mu^N \mathrm{e}^{-\mu}}{N!}$ **Poisson distribution**

μ – average value, $\mu = \frac{1}{k} \sum_{i=1}^{k} N_i$

$f(N, \mu) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(N-\mu)^2}{2\sigma^2}\right)$ **Gaussian distribution**

σ – root-mean-square deviation

17 Written Test on Radiation Protection

17.1 Problems

allowed resources: pocket calculator

Problem 1

What is the maximum permitted dose equivalent for the effective whole-body dose per year for radiation-exposed workers (over 18 years) of category A according to the ICRP recommendations?

1. 50 mGy
2. 20 mSv
3. 5 rem
4. 3.7×10^{10} Bq

◯ only (1.) is correct
◯ only (2.) is correct
◯ only (1.) and (4.) are correct
◯ only (2.) and (3.) are correct
◯ only (4.) is correct

Problem 2

What characterizes an exclusion area according to the ICRP recommendations?

1. possible effective dose > 50 mSv/yr
2. possible area-dose rate > 3 mSv/h
3. maximum activity $> 3.7 \times 10^{13}$ Bq
4. possible area-dose rate > 3 mGy/h

◯ only (1.) and (2.) are correct
◯ only (2.) is correct
◯ only (1.) and (4.) are correct
◯ only (3.) is correct

C. Grupen, *Introduction to Radiation Protection*,
Graduate Texts in Physics, DOI 10.1007/978-3-642-02586-0_17,

Problem 3

What is the best shielding against 5-MeV γ rays?

1. lead
2. aluminum
3. plastics
4. a sandwich of plastics and lead (first plastics, followed by lead)
5. a sandwich of plastics and lead (first lead, followed by plastics)

◯ only (1.) is correct
◯ only (2.) is correct
◯ only (3.) is correct
◯ only (4.) is correct
◯ only (5.) is correct
◯ all is wrong

Problem 4

γ rays are attenuated by the following processes:

1. bremsstrahlung, i.e. deceleration of γ rays in the Coulomb field of a nucleus
2. pair production
3. Compton scattering
4. photoelectric effect

◯ only (2.) is correct
◯ only (4.) is correct
◯ only (1.), (2.), and (4.) are correct
◯ only (2.), (3.), and (4.) are correct
◯ only (3.) is correct
◯ all are correct

Problem 5

Suitably sensitized films can be blackened by

1. infrared light
2. ultra sound
3. β rays

◯ only (1.) is correct
◯ only (1.) and (2.) are correct
◯ only (1.) and (3.) are correct
◯ only (2.) and (3.) are correct
◯ only (3.) is correct
◯ all are correct

Problem 6*

The dependence of the number N of nuclei of a certain radioisotope which have not decayed is described by an exponential law. What does the curve look like for the total number of nuclei that has decayed (all scales are linear)?

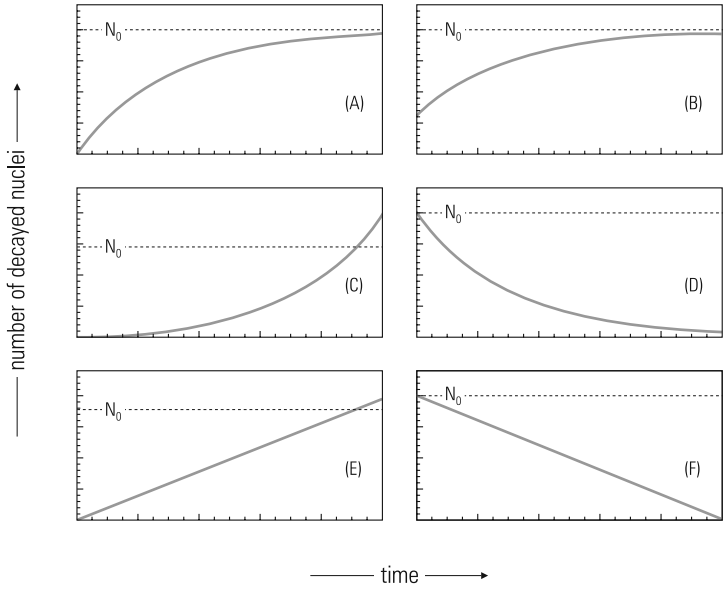


Figure 17.1
'Possible curves' for the number of decayed nuclei M as a function of time t

◯ (A) is correct
◯ (B) is correct
◯ (C) is correct
◯ (D) is correct
◯ (E) is correct
◯ (F) is correct

* These problems – partially with minor modifications – have been taken from the course "GK1 Physik für Mediziner" ("Basic physics course for physicians"), edition Medizin, VCH Verlagsgesellschaft, Weinheim (with kind permission of the editor Chapman & Hall GmbH).

Problem 7

The decay constant λ $\left(N = N_0\,\mathrm{e}^{-\lambda t}\right)$, the average lifetime τ, and half-life $T_{1/2}$ are related by the following equations:

1. $T_{1/2} = \tau \times \ln 2$ ◯
2. $\lambda\, T_{1/2} = 1$ ◯
3. $T_{1/2} = \ln \tau$ ◯
4. $\lambda\, \tau = T_{1/2}$ ◯
5. $\lambda\, \tau = 1$ ◯

Problem 8

The half-life of the radioisotope ^{42}K is 12 hours. Its activity has decayed from the original value of 1 mCi to 1 μCi after

1. 24 hours ◯
2. 48 hours ◯
3. 120 hours ◯
4. 10 days ◯
5. 20 days ◯

Problem 9

Photons created in an X-ray tube (acceleration voltage of the tube 100 kV) differ from photons coming from a tube operated with an acceleration voltage of 50 kV by

1. their maximum energy
2. their maximum velocity
3. their maximum frequency
4. their minimum wavelength

◯ only (1.) and (2.) are correct
◯ only (1.) and (3.) are correct
◯ only (1.), (3.), and (4.) are correct
◯ only (2.), (3.), and (4.) are correct
◯ all are correct

Problem 10[†]

Which of the following diagrams (see Fig. 17.2) represents the correct spectral distribution of bremsstrahlung photons from an X-ray tube best (all scales are linear, P – spectral radiation power, λ – wavelength)?

[†] See Footnote ∗ on page 274.

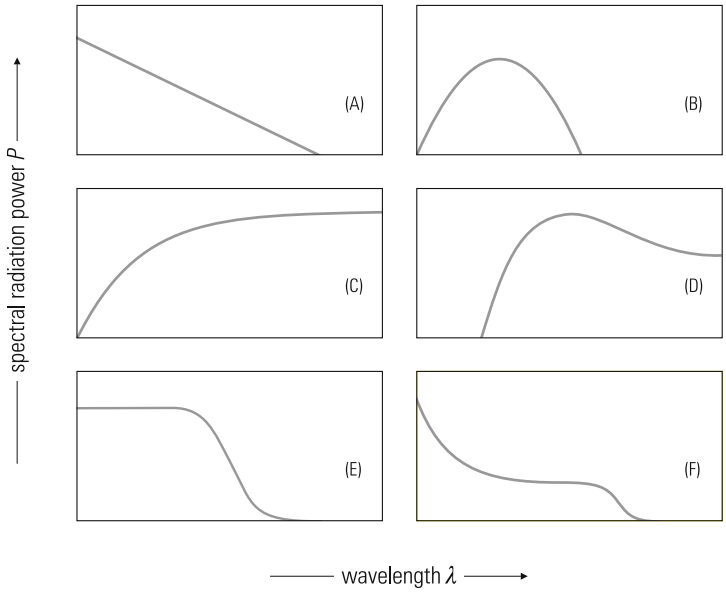


Figure 17.2
'Possible curves' for the spectral distribution of photons from an X-ray tube

Problem 11‡

The absorption of ^{60}Co γ rays in aluminum is measured with a Geiger–Müller counter. The result is plotted in semilogarithmic scale in Fig. 17.3 (lowest straight line in gray). The constant background rate of 500 counts/min in this experiment has already been subtracted. What was the original uncorrected count rate?

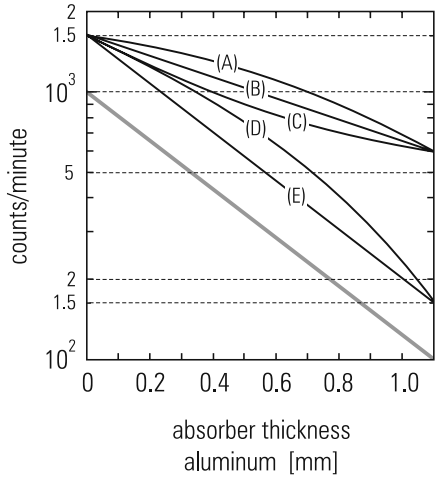


Figure 17.3
Absorption of X rays by Al on semilogarithmic paper

‡ See Footnote ∗ on page 274.

Problem 12

In an X-ray facility (path of rays in air, absorption in air can be neglected) an energy-dose rate of 4 Gy/min is measured at a focal distance of 50 cm. Which focal distance is required for an energy-dose rate of 1 Gy/min if one can assume that the X-ray tube emits the photons isotropically?

1. 12.5 cm ◯
2. 25 cm ◯
3. 100 cm ◯
4. 200 cm ◯
5. 2500 cm ◯

17.2 Solutions for the Written Test

Problem 1 Only (2.) is correct.

Problem 2 Only (2.) is correct.

Problem 3 Only (1.) is correct: lead has the largest attenuation coefficient.

Problem 4 Only (2.), (3.), and (4.) are correct; bremsstrahlung can only be generated by charged particles.

Problem 5 Only (1.) and (3.) are correct.

Problem 6 Only (A) is correct; for the number of remaining nuclei one gets

$$N = N_0 \, \mathrm{e}^{-\lambda t} \ ,$$

the number of decayed nuclei is obtained from

$$M = N_0 - N = N_0 \left(1 - \mathrm{e}^{-\lambda t}\right) \ .$$

Problem 7 Only (1.) and (5.) are correct.

Problem 8 Only (3.) is correct.

Problem 9 Only (1.), (3.), and (4.) are correct. Photons always travel at the velocity of light, irrespective of their energy.

Problem 10 Only (D) is correct, the cutoff wavelength (minimum wavelength) is obtained from

$$e\,U = h\,\nu = \frac{h\,c}{\lambda} \quad \text{to be} \quad \lambda = \frac{h\,c}{e\,U}$$

(h – Planck constant, U – acceleration voltage, ν – frequency, λ – wavelength).

Problem 11 Only (C) is correct. Due to the constant background contribution the original count rate must level off for large absorber thicknesses. Therefore the correct curve must be concave, i.e. (C).

Problem 12 Only (3.) is correct. It is just the inverse-square law.

18 Radiation-Protection Glossary[1]

"A good notation has a subtlety and suggestiveness which at times make it almost seem like a live teacher."

B. Russell 1872–1970

absorber

Material for shielding against ionizing radiation. X rays and γ rays are best absorbed with high-Z materials (e.g. lead or tungsten). The absorption of neutrons is best done with substances containing a high fraction of hydrogen. Neutrons can also be captured in boron or cadmium. α rays are of very short range and can be stopped even with thin foils. β rays should be absorbed with low-Z materials (1 cm aluminum or 2 cm plastic) to avoid bremsstrahlung.

absorber rod

Synonym for control rod.

absorption coefficient for photons

The photon intensity is exponentially absorbed in matter, $I = I_0\,\mathrm{e}^{-\mu_\mathrm{a} x}$, if I_0 is the initial intensity and I the intensity behind an absorber of thickness x. μ_a is called mass absorption coefficient and considers the photoelectric effect, Compton absorption, and pair production.

accelerator

A device which uses electric and magnetic fields to speed up electrically charged particles to high velocities. Electron linear accelerators and ion accelerators are used in tumor therapy.

accident

See radiation accident.

accident dosimetry

Body doses after radiation accidents can be determined via the activation of suitable substances in the human body (e.g. ^{23}Na, ^{32}S) and the measurement of their activity.

actinides

Elements with atomic numbers 90 to 103.

activation

Material under bombardment of neutrons, protons, or α particles can become radioactive. The activation cross sections for γ and β rays are rather small.

[1] Translated from the German edition; also using information from "The language of the nucleus", www.dataenabled.com/nuclearglossary/abcs/nuclearglossary_T.html; ONDRAF/NIRAS Radioactivity Glossary, www.nirond.be/engels/4_jargon_eng.html; "Glossary of Radiation terms", www.hps.org/documents/glossary.pdf, www.epa.gov/rpdweb00/marssim/docs/marsame/gl_prd.pdf, and www.who.int/ionizing_radiation/pub_meet/en/Depluranium7.pdf

C. Grupen, *Introduction to Radiation Protection*,
Graduate Texts in Physics, DOI 10.1007/978-3-642-02586-0_18,

activation analysis Traces of certain elements can be identified by their characteristic γ rays after activation (mostly with neutrons: neutron-activation analysis).

activation product An isotope formed through the process of activation.

activity Number of nuclear transformations per second. The unit of activity is becquerel. $1\,\mathrm{Bq} = 1$ decay/s. The old unit of the activity (still in use in some countries) was curie; 1 curie corresponds to the activity of 1 g radium 226. $1\,\mathrm{Ci} = 3.7 \times 10^{10}\,\mathrm{Bq}$, $1\,\mathrm{Bq} = 27\,\mathrm{pCi}$.

activity concentration Activity per unit volume.

activity, specific Activity per unit mass.

aerosol A suspension of small liquid or solid particles in a gas.

aerosol filtering Retention of radioactive aerosol particles by using appropriate filters for the air discharged from nuclear power plants.

air pollution Toxic or radioactive gases and aerosols introduced into the atmosphere by nuclear facilities and also by coal-fired power plants.

area of airborne radioactivity Area in which airborne radioactive materials exceed the air concentration limits. In emergency situations respiratory protection might be needed.

ALARA principle It is recommended to keep the radiation exposure 'as low as reasonably achievable' when handling radioactive material or working in nuclear facilities. Some national regulations even require to keep the radiation exposure 'as low as possible'. However, it does not make sense to reduce the radiation level well below the dose received from the natural environment.

albedo factor The albedo factor denotes the ratio of backscattered particles (scattering angle larger than 90 degrees) from a reflector to the number of incident particles. Albedo factors depend on the radiation type (e.g. n or γ), the energy, and the reflector material. Typical neutron albedos are around 80% while γ albedos are significantly smaller ($\approx 1\%$).

α decay Emission of a helium nucleus from a heavy nucleus. In α decay the nuclear mass changes by 4 units, the atomic number by 2 units, e.g. $^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + \alpha$.

ambient dose A measurement of the ambient or 'area' dose allows an estimate of the whole-body dose equivalent.

ambient-dose rate Ambient dose per unit time.

angiography X-ray examination of the heart and the coronary arteries using a contrast agent (mostly iodine).

annihilation

The destruction of a particle and its antiparticle as a result of a collision between them, e.g., an electron (e^-) and a positron (e^+) may interact resulting in the creation of two (or three) photons ($e^+e^- \rightarrow \gamma\gamma$). Annihilation radiation is used in medical diagnosis (Positron-Emission Tomography (PET)).

annihilation radiation

See annihilation.

annual intake

The amount of radioactive material taken into the body of an adult worker as a result of inhalation or ingestion in a year. The national radiation-protection regulations limit the intake of radioactive substances that might be discharged from nuclear facilities. According to German regulations radioactive material released from nuclear power plants or recycling facilities via air or water must not expose individuals to more than 0.3 mSv per year.

antimatter

For each charged particle (e.g. e^-) there is a particle with opposite charge (e^+) with otherwise identical properties.

aquifer storage

Storage of tritium-containing water in layers of rock or soil able to hold water (aquifers).

atom

The smallest possible unit of an element. It consists of an atomic nucleus and a number of electrons in the atomic shell corresponding to the number of protons in the nucleus. A typical atomic size is in the range between 10^{-10} m and 10^{-9} m.

atomic bomb

Nuclear-fission bomb, in which fissionable material like ^{235}U or ^{239}Pu is merged by a mechanical implosion into a super-critical mass, so that an uncontrolled chain reaction starts (see also hydrogen bomb).

atomic energy

Energy released in nuclear reactions. The process in which a neutron splits an atomic nucleus is called fission. The merging of two light nuclei at very high temperatures is called fusion.

atomic legislation

Atomic legislation regulates the peaceful use of nuclear energy and the protection against its dangers.

atomic nucleus

The positively charged nucleus of an atom. The nucleus consists of Z protons and N neutrons. The atomic number of a nucleus is $A = Z + N$. The constituents, nucleons, are bound by strong interactions, which are stronger than the repulsive force acting between the positively charged protons. Nuclei typically have a diameter of several femtometer (10^{-15} m).

atomic pile

A nuclear reactor constructed by stacking uranium as fuel and graphite blocks as moderator using water as coolant.

attenuation coefficient for photons

The photon intensity is exponentially attenuated in matter, according to $I = I_0\,\mathrm{e}^{-\mu x}$, if I_0 is the intensity at $x = 0$ and I the intensity of photons with the initial energy after a thickness x of absorber. μ is called the mass attenuation coefficient and considers the photoelectric effect, Compton scattering, and pair production.

Auger effect After the photoionization of an atom, the excitation energy of the atomic shell can be emitted in the form of characteristic X rays. The excitation energy can also be directly transferred to an electron further out in the atomic shell, which then might leave the atom as a so-called Auger electron.

authorized physician The competent authority authorizes physicians to perform precautionary occupational health examinations. The physician is required to possess the requisite qualification in the field of radiation protection.

averted dose Dose avoided by implementing protective actions, e.g. by sheltering or relocation of the population after a severe radiological emergency.

background radiation Cosmic rays and radioactivity in soil, water, and air are forms of ambient radiation that often interfere with low-count-rate measurements.

background rate Each detector counts a certain rate even if it is not exposed to a radioactive substance. This background originates from environmental radiation (cosmic rays and terrestrial radiation) and has to be subtracted from the measured activity.

backscatter peak The backscatter peak is caused by Compton-backscattered photons from shielding material surrounding the detector which then enter the sensitive volume of the detector and are recorded there via the photoelectric effect.

becquerel Unit of activity; 1 Bq = one decay per second; 1 Bq = 27 pCi, 1 Ci = 3.7×10^{10} Bq.

beta decay A type of radioactive decay in which a nucleus transforms into another one, differing in charge by ± 1 unit. There are three types of β decay: β^- decay, β^+ decay, and electron capture ($p + e^- \rightarrow n + \nu_e$).

β radiation (β^+, β^-) Electron emission from the atomic nucleus, in which a neutron transforms into a proton ($n \rightarrow p + e^- + \bar{\nu}_e$). In this three-body decay the transition energy is essentially shared between electron (e^-) and the electron antineutrino ($\bar{\nu}_e$). Therefore the electron energy spectrum is continuous up to a maximum energy. This maximum energy, which is characteristic for the emitting nucleus, is usually given in nuclear data sheets. The most probable energy amounts to about one third of the maximum energy. Positron emission ($p \rightarrow n + e^+ + \nu_e$) is also classified as beta radiation.

betatron A particle accelerator used to accelerate electrons. The betatron is essentially a transformer where a torus-shaped vacuum pipe is used as secondary coil. An alternating current in the primary coils accelerates electrons in the vacuum on a circular path.

Bethe–Bloch relation Describes the energy loss of charged particles by ionization and excitation while traversing matter.

Bethe–Weizsäcker formula
Describes the nuclear binding energy in the liquid-drop model. The binding energy varies between 7 and 8 MeV per nucleon for most nuclei.

beyond-design accident
For nuclear facilities, exposure limits have to be established which must not be exceeded even in case of accidents; e.g. 50 mSv according to German radiation-protection regulations. The severe catastrophe in Chernobyl 1986 was certainly a beyond-design accident.

binding energy
See nuclear binding energy.

biodiversity
A large number and wide range of species of animals, plants, fungi, and microorganisms; possibly advanced by low-level radiation.

biokinetics
The study of the movement of radioactive substances within organisms.

biological half-life
Time required for the concentration of a radioactive substance in a biological system to be reduced by a factor of two by metabolic processes. The biological half-life does not include radioactive decay.

biological shield
A radiation shield around a reactor or other radiation facility to reduce dose rates to safe levels.

bituminization
Encapsulation in bitumen (tar, asphalt). A method used to confine certain types of radioactive waste.

blood activation
^{23}Na contained in human blood can be activated by neutrons. This activation leads to radioactive ^{24}Na. The ^{24}Na activity of the blood allows a dose determination even when the irradiated person was not carrying a dosimeter (accident dosimetry).

body counter
Whole-body counters measure the radioactivity within the human body. The technique is most effectively applied to radioactive material that emits γ rays, although (with less efficiency), β emitters can also be measured. Whole-body counters require effective shielding with ultrapure absorbers free of any radioactive contamination.

body dose
Collective term for the effective whole-body or partial-body dose. The body dose is the sum of external and internal exposure.

boiling-water reactor
Power-plant design in which the water flows to the nuclear core where it is heated and allowed to boil. The steam produced is passed through a heat exchanger and eventually creates an electric current in a generator.

bone seeker
Some radioisotopes (e.g. ^{90}Sr, which is chemically similar to calcium) are preferentially accumulated in bones after incorporation.

Bragg peak
The ionization density increases towards the end of the range of a charged particle (see Bethe–Bloch relation). This feature is exploited in hadron therapy.

breeder Nuclear reactors in which, as well as electricity is being generated, transuranic elements are bred by neutron attachment with subsequent β^- decay (e.g. weapons-grade plutonium).

bremsstrahlung Emission of electromagnetic radiation by deflection or deceleration of charged particles (usually electrons) in the Coulomb field of a nucleus. The energy loss due to bremsstrahlung is proportional to Z^2 and increases linearly with energy.

burn-up The amount of fissionable nuclei in fuel rods in a nuclear reactor is continuously reduced during operation. The burn-up is defined as the ratio of the fissile material consumed to that originally present.

^{14}C method Dating method for archeological objects by measuring their remnant ^{14}C activity. In living beings the isotopic ratio $^{14}\mathrm{C}/^{12}\mathrm{C}$ is constant due to the intake of carbon from the air (plants) or by consumption of organisms which have this ratio. Carbon in living biomass has a specific activity of 50 Bq per kg. With the death of a plant or animal the isotopic ratio decreases by radioactive decay of ^{14}C (see also dating method).

calcination Thermal treatment process applied to solid radioactive materials in order to remove the volatile fraction.

calibration radiation Radiation from calibration sources with well-defined intensity and energy, e.g. γ rays of energy 662 keV from a cesium-137 source.

cancer incidence Radiation can induce cancer by stochastic processes. (A stochastic process, or random process, is the counterpart to a deterministic process. The outcome of such a process is governed by a probability distribution. Individual events cannot be predicted.) The latency period for cancer incidence can be very large ($\approx$ 20 years, see delayed radiation effects).

capture cross section Measure of the probability that an incident particle or photon will be absorbed by a target isotope.

carbon 14 Naturally occurring radioactive isotope of carbon that has a half-life of 5730 years.

carcinogens Substances that can cause cancer, such as radioactive materials.

cask Heavily shielded container used to store or ship radioactive material.

cataract An opacity that develops in the crystalline lens of the eye or in its envelope, sometimes as a consequence of radiation exposure.

cellular phone Mobile phone.

cellular-phone network
Mobile-radio-telephone service for cellular phones. The signal transmission uses the frequency range between 1 and 2 GHz.

cementation
Encapsulation in cement or concrete to confine certain types of radioactive waste for final disposal.

cesium 137
Well-known radioisotope which is produced in nuclear fission. ^{137}Cs is a β and γ emitter with a half-life of 30 years.

chain reaction
A sequence of reactions where a reactive product causes additional reactions to take place. An example is the chain reaction initiated by neutrons in a nuclear reactor.

chart of nuclides
Map containing all important information on radioisotopes (type of decay, decay energy, half-life, isotopic abundance, ...); also called table of isotopes.

chelating agent
Chemical agent which increases the elimination of potentially poisonous substances from the human body. Chelating agents are applied after accident-caused incorporations of radioactive material, e.g. ethylenediamine tetraacetate (EDTA).

chemical dosimetry
Radiation-induced reactions in liquids, solids, or gases with known yield (e.g. of photons) are used to measure radioactive exposure or contamination.

Cherenkov counter
Particle detector based on the Cherenkov effect.

Cherenkov effect
Cherenkov radiation in media with index of refraction n is emitted by charged particles which move with velocities faster than the speed of light in the medium, c/n. Cherenkov radiation of fast electrons is responsible for the blue color of the water in water-cooled reactors ('swimming-pool reactor').

Chernobyl accident
Most severe reactor accident in history in the Ukraine in 1986, causing global radioactive pollution.

chromosome
Part of the cell nucleus. Chromosomes form helix-like structures which consist of proteins strung together. They contain the genes.

cleanup
Treatment, elimination, or destruction of contaminated material.

clearance
If the activity of radioactive material released from a nuclear facility falls below a certain level (clearance level), it may be exempted from the regulations of radiation protection, and can then be handled freely. The clearance levels are defined in national regulations for each radioisotope separately. They refer, e.g., to limits of the specific activity and limits for surface contaminations (for examples, see Appendix D).

clinical dosimetry
Dosimetry in radiation therapy to monitor the applied radiation doses.

cloud chamber In a supersaturated gas–vapor mixture, droplets will form along the track of charged particles. The positively charged ions produced by ionization of charged particles act as condensation nuclei. The state of supersaturation is achieved by a rapid expansion of the chamber or by a suitable temperature gradient. See also ‘expansions cloud chamber’.

cobalt 60 The two γ rays (1.17 MeV, 1.33 MeV), which are emitted after the decay of ^{60}Co into ^{60}Ni, are used for radiation therapy of tumors.

collective dose Sum of individual doses received in a given period of time by a specified population from exposure to radiation.

collective effective dose equivalent Product of the average effective dose $\langle H \rangle$ in a population group and the number of people exposed, measured in man-sievert.

committed dose equivalent Dose equivalent that will be received from an intake of or exposure to radioactive material by an individual during the 50-year period following the intake or exposure.

compaction Technique which consists of crushing radioactive or contaminated material using a press in order to reduce its volume.

compressed-air breathing apparatus If during rescue operations the air in a particular area is polluted with radioactive gases or vapors, the use of suitable respiratory equipment might be required. A compressed-air breathing apparatus adequate for a period of 40 to 50 minutes has a weight of 16 kg.

Compton backscattering Scattering of X rays or γ rays in a direction opposite to that of the incident radiation by the Compton effect.

Compton edge The Compton edge is caused by the maximum possible energy transfer of a photon to a free electron which occurs in backscattering.

Compton effect Scattering of energetic photons off quasi-free electrons. The scattering off atomic electrons can be considered as pure Compton effect if their binding energy is small compared to the photon energy.

compulsory cover The handling of radioactive material requires financial precautions, e.g. in the form of casualty insurance, to cover potential damages.

computed tomography (CT) Also computer tomography. X-ray technique for establishing and examining cross-sectional areas of the human body.

conditioning Technique to obtain a solid, compact material, which allows transport and storage of waste awaiting its final disposal. One important aspect of conditioning is immobilization of radioactive waste.

confidence level
Probability that the given uncertainty interval will contain the measured value. The standard root-mean-square error $1\,\sigma$ corresponds to a confidence level of 68.3%, $2\,\sigma$ to about 95.4%. A confidence level of 99% corresponds to $2.58\,\sigma$.

containment
The prevention of the escape of radioactive materials from a nuclear reactor by appropriate provisions, e.g. after accidents or failures.

contamination
Pollution by radioactive substances.

contrast agent
Contrast agents, or radiocontrast agents, are compounds used to improve the visibility of internal structures of the human body in X-ray imaging.

control rod
Component of a reactor that contains strong neutron absorbers, like boron or cadmium, and which is used to control the reactor reactivity.

controlled area
Radiation area, in which persons (category A) might receive a whole-body dose of more than 6 mSv/yr. The maximum annual dose is 20 mSv/yr. For persons of category B who work in controlled areas, the maximum annual dose is 6 mSv/yr (these limits refer to European regulations).

conversion
An excited nucleus can transfer its excitation energy *directly* to an atomic electron (without intermediate radiation). The energy is normally quite high, so that the electron will leave the atom. This electron is called a conversion electron.

conversion coefficient
Ratio of the number of emitted conversion electrons to the total number of nuclear transitions after K capture ($\eta = N_{\text{conversions}}/(N_{\text{conversions}} + N_{\text{photon emissions}})$).

cooldown
Even after reactor shutdown the fuel rods must be cooled by circulation of coolant through the reactor core.

core meltdown
If the core cooling and the emergency core cooling system fail simultaneously in a nuclear reactor, the residual heat created by the decay of the fission products heats up the reactor core, until it melts.

cosmic rays
Energetic particles originating from the Sun, the Milky Way, and beyond that hit the Earth's atmosphere. About 85% of all incoming cosmic-ray particles are protons, about 12% are helium nuclei (α particles), and 3% are nuclei heavier than helium. In addition, there are electrons at the 1% level. Primary cosmic rays generate secondary cosmic rays by interactions in the atmosphere.

cosmogenic isotopes
Isotopes produced by interactions of cosmic rays with nuclei of the Earth's atmosphere, e.g. ^{14}C, ^{21}Ne, ^{26}Al, ^{32}Si, ^{36}Cl, ^{39}Ar, ^{41}Ca, ^{81}Kr.

counter
See Geiger–Müller counter and proportional counter.

critical mass Smallest amount of fissile material needed for a sustained nuclear chain reaction.

critical organ Organ which is most sensitive to radiation damage by an incorporated radioactive nuclide or by external radiation. For example, ^{131}I accumulates in the thyroid gland and ^{90}Sr is a bone seeker.

criticality A critical amount of fissile material is needed for a sustained nuclear chain reaction. For stable operation the neutron amplification factor must be 1. In that case the reactor is called critical.

cross section Effective area of a particle or nucleus which an assumed pointlike particle is modeled to hit to initiate an interaction.

cumulative dose Total whole-body dose due to repeated exposure to radiation.

curie (Ci) One curie corresponds to the activity of 3.7×10^{10} becquerel. Originally it was defined to be the activity of one gram of radium 226. The old activity unit curie is still used in some countries.

cyclotron In a cyclotron accelerator charged particles are guided along spiral orbits. The acceleration is achieved by high-frequency electromagnetic fields.

dating method Living beings exhibit a certain ratio of ^{14}C to ^{12}C. With the death of an organism the intake of ^{14}C from the biosphere stops, and the radio-carbon decays with its half-life of 5730 years. The ratio of the radio-carbon activity of formerly living material to currently living material makes it possible to date their age (see ^{14}C method). For geological or cosmological dating, the long-lived radioisotopes ^{40}K, ^{232}Th, and ^{238}U are mainly used.

decay A process in which an atomic nucleus spontaneously emits one or more α, β, or γ particles or neutrons, thereby changing its identity.

decay chain Series of isotopes linked in a chain by radioactive decay. The isotopes in the chain decay until a stable nuclide is reached. See also decay series.

decay constant (λ) Describes radioactive decay according to $N = N_0\,\mathrm{e}^{-\lambda t}$. $\lambda = 1/\tau$, where τ is the lifetime, and $\lambda = \ln 2/T_{1/2}$, where $T_{1/2}$ is the half-life.

decay law Describes the decreasing number of nuclei in time by radioactive decay: $N = N_0\,\mathrm{e}^{-\lambda t}$, where λ is the decay constant.

decay level Radioactive decays can be described by level schemes which denote the parent nuclide, the daughter nuclide, the decay energy, the branching fraction, and the type of decay.

decay method A certain storage time in containers allows short-lived radioactive waste to decay, thereby simplifying its disposal.

decay mode

Occasionally an isotope can decay via different channels, which are characterized by branching fractions. Examples include β^-, β^+, α, or γ decay, but also internal transitions or spontaneous fission.

decay series

Series of decays of heavy radioactive nuclei eventually decaying into stable isotopes. Since heavy nuclei are predominantly α emitters and an α particle has a mass number of $A = 4$, there are exactly four possible decay chains. The uranium–radium series, the uranium–actinium series, the thorium series, and the neptunium series. The latter no longer occurs in nature on Earth because of the relatively short half-life of neptunium 237 ($\approx$ 2 million years).

decommissioning

Process of dismantling a reactor or any nuclear facility. It includes the removal of fuel, contaminated water, and contaminated structure material with subsequent safe storage.

decontamination

Elimination or reduction of a contamination.

decorporation

Removal of radioactive material from the human body by elimination or emesis (vomiting) (see also chelating agent).

delayed radiation effects

Radiation effects observed after a long latency.

deleptonization

Neutron formation by merging protons and electrons at high densities and pressures, e.g. during the formation of neutron stars.

delta rays

In the process of ionization by charged particles, occasionally a large amount of energy can be transferred to atomic electrons ($\geq$ keV range). Such electrons are called δ electrons or knock-on electrons.

depleted uranium

Uranium with a fraction of ^{235}U smaller than the 0.7% fraction found in natural uranium, e.g. spent uranium or uranium intentionally depleted so that it can be used for other purposes.

derivative

The slope of a mathematical function $f(x)$ can be characterized by its difference quotient $\Delta f/\Delta x$. For non-linear and rapidly changing functions the intervals Δf and Δx must be infinitesimally small. The slope $\mathrm{d}f/\mathrm{d}x$ thus defined is called the derivative of the function $f(x)$ with respect to x.

design-based accident limit

The design of a nuclear facility has to consider possible consequences of operation failures. According to European regulations the exposure limit due to such an occurrence must stay below 50 mSv for the population living in the vicinity of the nuclear facility.

design-basis accident

A nuclear facility must be designed to conform to a certain standard in case of an accident. The maximum exposure to the public in case of an accident must be kept below the levels as defined in the national radiation-protection regulations.

detection efficiency Probability that an ionizing particle is registered in a detector. Charged particles are usually recorded with 100% efficiency. A Geiger–Müller counter measures γ rays with an efficiency of only 1%. Neutrons in certain scintillators are detected with an efficiency of around 10%.

deuterium Isotope of hydrogen with one neutron in addition to the proton in the nucleus ('heavy hydrogen').

deuterium–tritium fusion Main fusion mechanism for the planned man-made hydrogen fusion.

deuteron Nucleus of the deuterium atom.

diffusion cloud chamber See cloud chamber.

discharge Release of radioactive material via air or water.

disposal Removal of radioactive waste for final storage in a dump or disposal site.

disposal facility Land, structures, cavities, and equipment used for the disposal of waste.

distance law Indicates that the radiation dose per unit area decreases with the square of the distance from the radiation source.

DNA Deoxyribonucleic acid, genetic material of most living organisms, which is a major constituent of the chromosomes within the cell nucleus.

dose (D) The energy dose is the energy transfer per unit mass. Its unit is $1\,\mathrm{J/kg} = 1\,\mathrm{gray} = 100\,\mathrm{rad}$.

dose alerter Radiation detector providing an alarm if a preselected dose level is exceeded.

dose commitment Dose equivalent received by a person during one calendar year due to uptake of a radioisotope.

dose constant Γ The dose-equivalent rate $\dot{H}$ from a pointlike emitter depends on its activity A and distance r as $\dot{H} = \Gamma\, A/r^2$. The value of the dose constant depends on the isotope, and is different for β and γ emitters.

dose–effect relation In radiation protection one assumes that there is a linear relation between received dose and biological effect.

dose equivalent (H) Absorbed energy measured in joule per kilogram weighted with the radiation weighting factor. The unit of the dose equivalent is the sievert (Sv); $1\,\mathrm{Sv} = 100\,\mathrm{rem}$.

dose equivalent, effective (H_{eff} or E)

Dose equivalent derived from the exposure of different parts of the human body by weighting with the corresponding tissue weighting factors, which consider the different radiation sensitivity of irradiated organs or tissue: $H_{\text{eff}} = \sum_T w_T H_T$, where H_T are the individual organ doses and w_T the radiation weighting factors.

dose rate

Absorbed dose per unit time. Common units for the energy-dose rate are µGy/h or mGy/h. The dose-equivalent rate is measured in µSv/h or mSv/h, respectively.

dose-rate alerter

Radiation detector providing an alarm if a preselected dose-rate level is exceeded.

dosimeter

Detector for measurement of the received dose.

double beta decay

For certain long-lived isotopes, where single beta decay is prevented by energy considerations, a double β^- decay may occur. An example is ^{76}Ge decaying to ^{76}Se, where the intermediate ^{76}As cannot be reached for energy reasons. All double β emitters have half-lives longer than 10^{19} years. In certain particle physics theories, neutrino-less double β decay is also possible.

dump sites

Waste disposal grounds.

duty to give notice

The competent authorities have to be informed about exceptional radiation exposures and also when radiation limits have been violated. The possession and the handling of radioactive material exceeding the exemption limits must be authorized.

early radiation effect

Immediate radiation effect as a consequence of exposure to high-level radiation over a short time. Examples of immediate radiation effects are erythema (superficial inflammation of the skin exhibiting abnormal redness) or alopecia (loss of hair). The harm due to immediate radiation effects is assumed to be proportional to the received dose.

ecosystem

Natural environment including ground, water, air, climate, animals, and plants.

effective dose

Measure of dose which takes into account the type of radiation and the sensitivity of particular tissues and organs to that radiation.

effective dose equivalent

Sum of the dose equivalents to the organ or tissue considering the tissue weighting factors for each of the body organs or tissues that are irradiated.

effective half-life

Time required for the concentration of a radioisotope in a biological system to be reduced by a factor of two. The effective half-life includes all processes of elimination, including radioactive decay.

efficiency See detection efficiency.

electromagnetic interactions Interactions of particles due to their electric charge. This type of interaction also includes magnetic effects.

electron (e) The lightest electrically charged particle. As a consequence it is stable, because there are no other charged particles lighter than the electron, into which it could decay. Electrons have the electric charge -1 in units of the elementary charge.

electron capture (EC) Interaction of an atomic electron with the nucleus. A proton captures an atomic electron and transforms into a neutron and an electron neutrino ($p + e^- \rightarrow n + \nu_e$). EC is a form of β decay in competition to β^+ emission.

electron volt (eV) Unit for the energy *and* mass of a particle. One eV is the energy gained by a singly charged particle if accelerated in a potential of one volt. Typical energies of α, β, and γ rays in the field of radiation protection are in the MeV range. X rays have energies around 10–100 keV.

electrosmog Term coined to describe the pollution due to static and dynamic electromagnetic fields. The word is a contraction of electromagnetic radiation, smoke, and fog.

electroweak interaction In the Standard Model of elementary particles, electromagnetic and weak interactions are unified: electroweak interactions. In the extended Standard Model strong interactions, described by quantum chromodynamics, are also included.

elementary charge Electrical charge of the proton $q = 1.6 \times 10^{-19}$ C. The electrical charge of the electron is $q_e = -q$.

emanation See exhalation.

energy dose (D) Amount of absorbed energy per unit mass. The unit of the energy dose is 1 gray (Gy) = 1 joule/1 kg. 1 Gy = 100 rad.

energy-dose rate Absorbed energy per unit mass and unit time. Common energy-dose rates are μGy/h or mGy/h.

energy fluence Time-integrated energy flux density, measured in $\mathrm{J/m^2}$.

energy flux density Sum of energies of particles passing through a unit area per time.

energy loss Energy reduction of charged particles on passing through matter, by ionization, excitation, or the production of bremsstrahlung.

energy resolution Ratio of the measurement uncertainty ΔE with respect to the energy of the incident particle E in a detector.

energy absorption coefficient

The energy absorption coefficient of a substance for photons of energy E is $\mu_{\mathrm{en}} = \mu_{\mathrm{a}}(1 - G)$, where μ_{a} is the mass absorption coefficient, and G is that relative energy fraction of the created charged particles in the photon interaction process which is transferred to bremsstrahlung photons.

enriched uranium

Uranium in which the fissionable ^{235}U isotope has an abundance larger than that found in nature.

enrichment

Technique to modify the natural isotopic abundance of a material in such a way as to increase the fraction of easily fissionable isotopes.

Environmental Protection Agency

The object of the U.S. Environmental Protection Agency is to protect human health and to safeguard the natural environment – air, water, and land – upon which life depends.

epithermal neutrons

Neutrons in the energy range from 1 eV to 1 keV.

erythema

Superficial inflammation of the skin (erythrodermia) caused by the absorption of a large dose of β or γ radiation or also by ultraviolet light.

excited state

Atomic or nuclear state of energy higher than the ground state. The excess energy is emitted in the form of γ rays characteristic for the emitting radioisotope after the nuclear lifetime, which depends on the isotope, e.g. $^{60}_{28}\mathrm{Ni}^{**} \rightarrow {}^{60}_{28}\mathrm{Ni}^{*} + \gamma \rightarrow {}^{60}_{28}\mathrm{Ni} + \gamma + \gamma$. The asterisk denotes the excited state. Ni^{**} is doubly excited.

excluded area

See exclusion area.

exclusion area

Area surrounding a reactor in which the reactor licensee has the authority to determine all activities. This includes limiting or excluding access to the area by personnel or property. According to the ICRP recommendations an area is called excluded if the dose rate exceeds 3 mSv/h.

exemption limit

If the activity of radioactive material falls below a certain level (exemption limit), it may be exempted from the regulations of radiation protection and can be handled freely. The exemption limits are defined in national regulations for each radioisotope separately (for examples, see Appendix B).

exhalation

Emanation or evaporation of gaseous radioactive substances (e.g. radon) from rock or building material.

exponential function

Exponentials always occur when the rate of change of some quantity is proportional to the quantity itself. Examples for exponentials are radioactive decay, the absorption of γ rays in matter, and the capital growth by interest on interest. The inverse of the exponential function e^x is the natural logarithm $\ln x$.

exposure dose Ratio of the created charge Q by X rays per unit mass m_{air} in air. The unit of the exposure dose (or ion dose) is roentgen R. $1\,\text{R} = 2.58 \times 10^{-4}\,\text{C/kg}$. Converted to an energy dose one has $1\,\text{R} \approx 0.88\,\text{rad} = 8.8\,\text{mGy}$.

external radiation exposure Radiation exposure from the natural environment (cosmic rays, terrestrial radiation) or from nuclear facilities.

fallout Radioactive substances or dust injected into the biosphere by nuclear-weapon tests or reactor accidents can be washed out by rain ('washout') or simply sink to the ground, thereby presenting a radiation risk for the population.

fast breeder Reactor type in which transuranic elements are bred using fast neutrons. Fast breeders have a high yield, but are delicate to handle technically.

Fermi–Kurie diagram Also called Kurie diagram. β transitions are three-body decays. They lead to continuous energy spectra. If the square root of the decay rate N, normalized to the square of the electron momentum p^2, and divided by the Fermi correction function F, i.e. $\sqrt{\frac{N}{p^2 \cdot F}}$, is plotted against the electron energy, one gets a straight line for allowed decays, which makes it possible to read the transition energy very precisely.

50-years commitment dose equivalent Dose equivalent that an organ or tissue receives over a period of 50 years after a single incorporation of radioisotopes.

film badge Small badge containing photographic films that is worn by personnel to monitor radiation exposure. Modern film badges with different filters measure the received dose, and can even distinguish γ rays from β particles and neutrons.

film dosimeter X-ray film for the measurement of energy doses. The reading presents a formal documentation of the energy dose (see also film badge).

final disposal Permanent storage of nuclear waste in such a way that dangers for humans and the environment are excluded.

final disposal facility Dump to contain radioactive waste for long-term storage; usually in deep geological layers.

fire detector Older fire or smoke detectors use a small amount of an α-emitting radioisotope (e.g. ^{241}Am or ^{226}Ra), which generates a certain current in a capacitor. Smoke or fire changes the conductivity in the fire detector, which in turn triggers an alarm. Modern fire detectors are optical devices, measuring the light scattered off smoke particles with a photodiode.

fission Heavy nuclei (like uranium) can be split into smaller fragments by neutron bombardment. For very heavy nuclei ($Z \geq 90$) also spontaneous fission can occur.

Gives the probability that a fission reaction will occur.	**fission cross section**
Nucleus formed as a direct result of nuclear fission.	**fission fragment**
Highly radioactive fragments produced as a result of spontaneous or induced fission.	**fission product**
The effective dose caused by cosmic rays has to be recorded for flight personnel, if it might exceed 1 mSv/yr.	**flight personnel**
See gas flow counter.	**flow counter**
Time integral of the flux density, measured in m^{-2}.	**fluence**
Particle flux per unit area and unit time ($m^{-2}\,s^{-1}$).	**flux density**
The ionizing effect of strong radiation will kill viruses and spores, and destroy enzymes. The irradiated food will *not* become radioactive, however, its taste may suffer.	**food irradiation**
Large-area counter mounted in a support plate for the measurement of possible contamination of feet or shoes.	**foot monitor**
Split-dose irradiation. Higher radiation doses can be tolerated by tissue if they are applied in fractions rather than on a single occasion. This is related to the body's own repair mechanisms. In tumor treatment by γ rays, one takes advantage of the fact that healthy tissue heals more quickly and effectively than cancerous tissue.	**fractionated irradiation**
Breakup of a heavy nucleus into smaller fragments in a collision.	**fragmentation**
All steps in the processing of fissionable material as fuel for a reactor, including mining, purification, isotopic enrichment, fuel fabrication, storage of irradiated fuel, reprocessing of spent nuclear fuel, and disposal.	**fuel cycle**
Fuel rods are the central elements of a nuclear reactor. They mostly consist of uranium enriched in the isotope ^{235}U and form the so-called reactor nucleus.	**fuel rods**
See photopeak.	**full-absorption peak**
Design-approved X-ray device, with multiple security systems.	**fully protected tube housing**
Nuclear reactor, where the energy generation is based on hydrogen fusion.	**fusion reactor**
Full width of the energy resolution of a detector at half of the maximum value.	**FWHM**

γ radiography Non-destructive test of materials based on absorption measurements of γ rays.

γ rays Energy quanta of electromagnetic radiation in the MeV range. γ rays can best be shielded with materials of high atomic number (e.g. lead or tungsten).

gas flow counter Low-energy β rays or α particles have a very short range. Their measurement requires very thin entrance windows or even windowless gas ionization detectors. Samples are placed inside the detector and its volume is flushed with a suitable counting gas, e.g. methane (methane flow counter).

gas-cooled reactor Nuclear-reactor design which uses gas as a coolant, e.g. the pebble-bed reactor.

Gauss distribution (normal distribution) Symmetric distribution of a continuous random variable. For large average values, the Poisson distribution approaches a Gaussian shape.

Geiger–Müller counter Also called GM counter. Radiation detector which measures charged particles and γ rays by their ionization in a cylindrical volume with subsequent gas amplification. The output signal of a GM counter does not depend on the type of the incident particle and not on the energy loss in the detector.

genetic radiation effects See mutation.

geomagnetic latitude Location on Earth if its magnetic field were to be replaced by a dipole field closely approximating it. The magnetic poles do not coincide with the geographic poles. The deviation of the magnetic poles from the geographic poles varies in time. Presently the distance is around 1000 km, corresponding to about 9 degrees deviation. Also it has to be remembered that the geographic North Pole lies near the geomagnetic south pole, and the geographic South Pole near the geomagnetic north pole.

germanium crystal Solid-state detector, perfectly suited for high-resolution measurement and identification of γ-ray emitting radioisotopes.

gluon Exchange particle mediating the interaction of quarks and other strongly interacting particles.

gonad dose Dose at the sexual organs.

graphite Naturally occurring form of carbon. Graphite is an excellent neutron moderator because it has a very low neutron-capture cross section and a large scattering cross section.

graphite reactor In this reactor type graphite is used as moderator and water as coolant. If some or all of the coolant is lost, the reactor can go supercritical, possibly leading to a core meltdown. (The reactor at Chernobyl was of this type, and its fate is well-known. Such hybrid reactors are considered inherently unsafe.)

gray (Gy)

The energy absorption of 1 joule per kg. One gray is 100 rads (radiation absorbed dose). The gray and the rad are measures for the energy transfer by radiation to an absorber. 1 rad = 100 erg per g.

hadron therapy

Tumor irradiation with protons or heavy nuclei, taking advantage of the Bragg peak at the end of their range. Hadron therapy is particularly useful as it can be applied with less damage to healthy tissue compared to other methods.

hadrons

Strongly interacting particles, like protons, neutrons, or charged pions.

hair activation

Hair contains a small amount of sulphur, which can be activated by neutrons according to $n + {}^{32}\mathrm{S} \rightarrow p + {}^{32}\mathrm{P}$. The activity determination of the radioactive ^{32}P isotope allows a dose determination after an irradiation, even if no standard dosimetric information was available (see also accident dosimetry).

half-life

Time after which half of the number of nuclei of some radioactive substance has decayed. The decay is described by $N = N_0\,\mathrm{e}^{-t/\tau} = N_0\,\mathrm{e}^{-\lambda t}$. The half-life $T_{1/2}$ is related to the lifetime τ according to $T_{1/2} = \tau \times \ln 2$ and to the decay constant λ as $T_{1/2} = \ln 2/\lambda$.

half-life, biological ($T^{\mathrm{bio}}_{1/2}$)

Time required for the concentration of a radioactive substance in a biological system to be reduced by one half by biological processes only.

half-life, effective

If $T^{\mathrm{phys}}_{1/2}$ is the physical and $T^{\mathrm{bio}}_{1/2}$ the biological half-life, the effective half-life is $T^{\mathrm{eff}}_{1/2} = T^{\mathrm{phys}}_{1/2}\, T^{\mathrm{bio}}_{1/2} \Big/ \left(T^{\mathrm{phys}}_{1/2} + T^{\mathrm{bio}}_{1/2}\right)$. The effective half-life includes biological processes for eliminating substances from the body *and* radioactive decay. E.g., the effective half-life for ^{241}Am in humans is 84 years ($T^{\mathrm{phys}}_{1/2} = 432$ yrs, $T^{\mathrm{bio}}_{1/2} = 104$ yrs).

half-thickness

The thickness of a particular material which reduces the intensity of radiation by a factor of two. If μ is the mass attenuation coefficient for γ rays, the half-thickness $x_{1/2}$ is $x_{1/2} = \ln 2/\mu$. For 1 MeV γ rays in lead, $x_{1/2} = 1.23$ cm; for 1 MeV electrons in aluminum, $x_{1/2} = 1.1$ mm.

handling license

Anyone handling radioactive substances exceeding the exemption limit or the clearance level requires a license. A license will be granted if no facts are known which could cast doubt on the reliability of the applicant or his legal representative. A license is also required for the operation of facilities which generate ionizing radiation (e.g. accelerators).

hazard category of lasers

Danger rating of lasers depending on the output power and operation mode (pulsed or continuous) of lasers.

health physics

Concerns the study of the effects of ionizing radiation on humans. It also deals with investigations on how to reduce the health risks associated with radiation exposure.

heat exchanger A device built for efficient heat transfer from one medium to another in such a way that the media never mix. In a nuclear reactor, the heat exchanger transfers heat from the primary reactor cooling system to a secondary system. This ensures that contaminated water or steam cannot be transferred to the generator turbines.

heat-up After reactor shutdown, the temperature of fuel rods will be kept high due the radioactivity of short-lived fission products generating heat. During normal reactor operation, or in an accident, the temperature of fuel rods may also rise because of an increased rate of fission in the reactor core.

heating with neutral particles Heating of a fusion plasma by injection of neutral particles, e.g. by neutrons, hydrogen, deuterium, or tritium atoms.

heavy-ion therapy See hadron therapy.

high-radiation area An area, accessible to individuals, in which radiation levels could result in a dose equivalent exceeding the limits defined by national radiation-protection regulations (e.g., a 3mSv/h limit defines an exclusion area according to the ICRP recommendations).

high-temperature reactor High-temperature reactors allow operation at very high temperatures (around 1000 degrees Celsius) by using special ceramic materials in the reactor core. These reactors use mostly helium gas as coolant instead of water. High-temperature reactors are intrinsically safe, and can also be built in smaller units (100 MW).

hormesis Term for generally favorable biological responses to exposures of low-level ionizing radiation.

hot particles Small dust particles of high activity have been observed in the radioactive fallout after nuclear-weapons tests. They are called ‘hot particles’.

hot spot Location where the radioactivity or radiation is higher than expected. For example, absorption of naturally occurring α-ray emitters by the tar in smokers’ lungs might produce hot spots on lung tissue and/or the bronchi.

hydrogen bomb Nuclear weapon deriving its power from the nuclear fusion of hydrogen isotopes, also called H-bomb or thermonuclear bomb.

hydrogen fusion Energy production mechanism in the Sun and stars. In this process hydrogen is fused to make helium.

hydrogen pellets Pellets of solid tritium and deuterium as starting material for inertial fusion (laser fusion).

ICRP The International Commission on Radiological Protection recommends regulations and limits for radiation protection.

identification

Proper identification and labeling must be used in areas where ionizing radiation is generated, or where radiation sources are handled. Examples for this are controlled, supervised, and exclusion areas.

impact parameter

The perpendicular distance between the velocity vector of a projectile and the center of the object (e.g. the target nucleus) it is approaching. For the scattering of particles which are not significantly deflected, the impact parameter coincides with the distance of closest approach.

incorporation

Intake of radioactive substances by eating or drinking, breathing, or via lesions.

indicator

Radioactive atoms can be integrated into chemical substances. This makes possible the studying of metabolic processes in the human body using these tagged tracers.

induced radioactivity

Radioactivity that is produced by bombarding a substance with radiation. Induced radioactivity is an issue in nuclear power plants and at hadron accelerators.

inertial fusion

Compacting of solid tritium and deuterium in a pellet, which is omnidirectionally irradiated with powerful pulsed lasers or heavy ions, and in this way brought to fusion.

ingestion

Intake of radioactive substances by eating or drinking.

inhalation

Intake of radioactive substances by breathing (also by cutaneous respiration).

interaction

A process in which a particle or nucleus collides with another particle or nucleus. If this collision is inelastic, new particles may be created.

internal exposure

The natural body radioactivity of humans is about 9000 Bq. It is caused mainly by the potassium isotope ^{40}K (4200 Bq) and the carbon isotope ^{14}C (3800 Bq). The annual body dose due to internal exposure is about 0.2 mSv.

intervention level

Level of avertable dose at which specific actions or remedies are taken in a radiological emergency situation. The recommended value of the intervention level for sheltering is 10 mSv, and for evacuation 50 mSv. This implies that exposures of 10 mSv or 50 mSv can be avoided or significantly reduced by sheltering or evacuation, respectively.

inverse Compton effect

Scattering of energetic electrons off low-energy photons, transferring energy from the electron to the photon, resulting in a blueshift.

iodine incorporation

Stable iodine as well as radioactive iodine (^{131}I) accumulate predominantly in the thyroid gland. ^{131}I is used as diagnostic tool in the diagnosis of diseases of the thyroid gland. The effects of exposure to ^{131}I after nuclear accidents can be mitigated by the timely intake of tablets containing large doses of stable iodine.

ion Electrically charged atomic or molecular particle, which is created by separating or attaching one or more electrons (e.g. Na^+, Cl^-, Ca^{++}, ...).

ion dose (I) Creation of a certain amount of charge per kilogram by ionizing radiation. 1 roentgen corresponds to an ion dose of 2.58×10^{-4} C/kg in air.

ion-dose rate Absorbed ion dose per unit time. The unit of the ion-dose rate is coulomb per kg and per second, i.e. ampere per kilogram.

ionization Separation of atomic electrons by photons (photoionization) or by charged particles (ionization by collision).

ionization chamber Particle detector for ionizing radiation based on the ionizing power of α, β, and γ rays. The ionization created is collected in a constant electric field.

ionizing radiation Radiation from radioactive substances which produces ions in a direct or indirect way.

irradiation facilities Instruments containing radioactive sources which provide beams of ionizing radiation for an adjustable time. The activity of the sources used in medicine and engineering can be rather high (2×10^{13} Bq or even more). Electron and ion accelerators, as well as X-ray facilities, also belong to this category.

irradiation pathway Path and spread of radioactive substances in the environment after discharge from a nuclear facility. Eventually it will lead to an exposure of humans to radiation.

isobar Nuclei of equal mass, i.e. nuclei, in which the sum of the number of neutrons and protons is constant.

isomer Isotopes with equal proton and neutron number, but different excited states (e.g. ^{99}Tc and ^{99m}Tc).

isotone Nuclei with equal neutron number.

isotope Nuclei of equal electric charge, representing the same chemical element, but with differing neutron number.

isotope battery See radioisotope thermoelectric generator.

isotope chart Chart of nuclides, which shows all known isotopes, along with their decay modes, half-lives, and other characteristic features.

isotopic abundance Concentration of a certain isotope in a sample relative to the other isotopes of that element.

isotopic enrichment
Process of increasing the concentration of one isotope in a sample relative to that of the other isotopes of that element, e.g. enrichment of ^{235}U (compared to the occurrence of this isotope in uranium of natural abundance) for fuel in nuclear reactors.

ITER
International Thermonuclear Experimental Reactor to be built in Cadarache, France. This test facility will use the tokamak principle to create nuclear fusion.

JET
Joint European Torus: prototype of a fusion reactor (Culham, UK) based on the tokamak principle.

kerma
Kerma ('kinetic energy released in matter' or 'kinetic energy released per unit mass') is the ratio of the kinetic energies of all charged particles which are generated in a volume element by indirectly ionizing radiation (γ rays or neutrons), to the mass of the volume element.

Klein–Nishina formula
The Klein–Nishina formula describes the cross section for Compton scattering of photons off quasi-free electrons.

knock-on electrons
See delta rays.

K capture (EC)
Capture of an electron from the K shell by a proton ($p + e^- \rightarrow n + \nu_e$) with subsequent emission of characteristic X rays or Auger electrons.

Kurie diagram
See Fermi–Kurie diagram.

Landau distribution
Asymmetrical probability distribution. It describes e.g. the energy-loss distribution of charged particles in thin targets.

laser fusion
Nuclear fusion with pulsed high-power lasers.

laser pointer
Handy, small low-power laser as pointer for presentations.

latency
Period of time between irradiation and the first signs of response. The latency period for leukemia is shorter (15–20 years) than that for the development of other tumors (25–30 years).

lepton
Light particle with half-integer spin. The family of leptons consists of the electron (e^-), the muon (μ^-), the tau (τ^-), and the associated neutrinos (and all their antiparticles).

LET
A measure of the energy transfer to material by an ionizing particle. The linear energy transfer (LET) is used to quantify the effects of ionizing radiation on biological systems and electronic devices. LET only considers energy transfer processes with transferred energies below a cut parameter (usually taken as 100 eV).

lethal dose The median lethal dose LD_{50}^{30} of radiation is the dose corresponding to a mortality of 50% within 30 days without medical treatment. The lethal whole-body dose for humans is around 4 Sv.

leukemia Disease in which there is an excess of white corpuscles (leucocytes) in tissue and blood. The risk factor for radiation-induced leukemia as a consequence of a whole-body exposure is 5×10^{-4} per 100 mSv (ICRP figure).

level diagram Diagram showing the excited states of a nucleus and its nuclear transitions. Given also are the type of decay, the transition energies, and the branching fractions.

lifetime Time period in which the number of nuclei has decayed to a level of $1/\mathrm{e}$ of its initial value ($\approx 37\%$). The lifetime τ is inversely proportional to the decay constant, $\tau = 1/\lambda$, and it is related to the half-life according to $\tau = T_{1/2}/\ln 2$.

lifetime irradiation dose The integrated dose equivalent up to the age of N years is limited according to the ICRP recommendations to $(N - 18) \times 20$ mSv. Under most national regulations, individuals below the age of 18 are not allowed to work in radiation areas. The full lifetime irradiation dose must not exceed 400 mSv (European regulations).

light-water reactor Reactor that uses ordinary water as a coolant *and* moderator.

LINAC Short for linear accelerator. It is an electrical device for the linear acceleration of subatomic particles (mostly electrons or protons) without magnetic deflection (like in synchrotrons). Electrostatic or magnetic lens elements may be included to ensure that the beam is confined to the center of the vacuum pipe. LINACs are used in radiology for tumor irradiation and as injectors for synchrotrons.

liquid-drop model This nuclear model assumes that the nucleons in a nucleus are bound in a similar way as water molecules in a drop. The volume binding energy has to be modified by surface effects, Coulomb repulsion, and asymmetry effects.

liquid scintillator Liquid organic scintillating material. The shape of liquid scintillators can be adapted to fit the measurement. The liquid can also easily be replaced should there be radiation damage or aging problems.

LNT hypothesis Hypothesis that the risk factor for stochastic radiation damage depends linearly on the dose, and that there is no threshold effect ('Linear No-Threshold').

logarithm (natural) See also exponential function. If $\mathrm{e}^x = a$, then x is called the natural logarithm of a: $x = \ln a$. The natural logarithm describes many relations in physics and biology. The Weber–Fechner law states that the perception due to a stimulus is proportional to the logarithm of the stimulus. The exponential function and the logarithm simplify many mathematical relations.

magic numbers

A magic number is a number of nucleons (either protons or neutrons) arranged into complete shells within the atomic nucleus. The magic proton and neutron numbers are 2, 8, 20, 28, 50, 82, 126. Nuclei where both the proton and neutron number are magic, are called doubly magic (e.g. ^{16}O or ^{40}Ca).

mammography

Examination of the female breasts by X rays. Using modern techniques typical partial-body exposures of the tissue are – depending on the radiographic technique – between 2 and 10 mSv, corresponding to a whole-body dose equivalent of 100 µSv–500 µSv (the tissue weighting factor for the chest is 0.05).

man-sievert

Unit for the collective dose, which is the product of the total number of persons N by one person's average dose $\langle H \rangle$ in sievert or, more generally, the collective equivalent dose S is

$$S = \sum_k P_k \, \langle H_k \rangle \ ,$$

where $\langle H_k \rangle$ is the per capita equivalent dose in an interval $H_k \ldots H_k + \mathrm{d}H_k$ and P_k the number of persons with radiation exposures in this interval.

mA s product

Product of the tube current (mA) and exposure time (s) for X-ray examinations. The mA s product is an important quality factor in medical imaging.

mass absorption coefficient

See absorption coefficient for photons.

mass attenuation coefficient

See attenuation coefficient for photons.

mass defect

Mass deficit between the mass of an isotope and the sum of the masses of its constituent nucleons or fragments.

Maxwell–Boltzmann distribution

Describes the energy or velocity distribution for particles, atoms, or molecules in thermal equilibrium at a temperature T.

medical physics expert

Specially trained scientist with the necessary qualifications in radiation protection.

medical supervision

Medical supervision is mandatory for radiation-exposed workers of category A in controlled areas, and for radiation-exposed workers of category B if handling unsealed radioactive sources.

metastable state

Excited nuclear state with relatively long lifetime. Metastable nuclear isomers have half-lives at least 100 times longer than typical gamma-decay times ($\approx 10^{-14}$ s). The lifetimes of some metastable nuclei can be extremely large (e.g. 10^{15} years for $^{180\mathrm{m}}$Ta).

methane flow counter

See gas flow counter.

mineral spring Drinking, or swimming in, water from mineral springs, which contains α emitters, may alleviate some diseases (such as rheumatism). However, the usefulness and effectiveness of such spas is a matter of debate. Also the effect of inhaling radon-rich air is debatable.

moderation The fission cross section for thermal neutrons is particularly large. Neutrons liberated in nuclear fission have much higher than thermal energies. They have to be slowed down by suitable moderators, like water or graphite.

Møller scattering Elastic electron–electron scattering.

Mössbauer effect Emission or absorption of nuclear-resonance photons without recoil.

monitoring Measurement of radiation levels, concentrations, and surface area contaminations to evaluate potential exposures and doses.

Moseley law The frequency of atomic X rays is proportional to $(Z-1)^2$, where Z is the atomic number.

MOX Nuclear fuel consisting of a mixture of oxides of uranium and plutonium.

multiple scattering Scattering of charged particles in Coulomb fields during their passage through matter.

muon (μ) Unstable elementary particle generated, e.g. by the decay of pions produced in cosmic rays. The lifetime of the muon is 2.2 µs. Its mass is 105.7 MeV/c^2.

mutation The replacement of a single base nucleotide (of DNA) with another nucleotide. Mutations may arise spontaneously, but can also be caused by ionizing radiation. These genetic effects of radiation can be heritable.

natural reactor A high level of uranium isotopes in ores can lead to natural fission processes under favorable weather conditions (availability of water). See Oklo.

neutrino A lepton without charge and very small mass (< 1 eV). For each charged lepton (electron, muon, tau) there is a different neutrino (ν_e, ν_μ, ν_τ). Electron neutrinos (ν_e, $\bar{\nu}_e$) are emitted in nuclear β decay.

neutron Nuclear building block. Free neutrons are unstable and decay according to $n \rightarrow p + e^- + \bar{\nu}_e$ with a lifetime of about 15 minutes.

neutron activation Activation of substances by neutron bombardment. Neutron activation may present a problem for fusion reactors.

neutron amplification factor In a fission chain reaction, the number of neutrons from each nuclear fission which remains available to cause further fission. For stable operation of a nuclear reactor, the neutron amplification factor has to be 1.

neutron capture
Certain materials have large cross sections for neutron capture. These materials are often used for control rods in nuclear reactors (e.g. cadmium).

neutron counter
Boron-trifluoride counter, in which incident neutrons create easily detectable charged particles in interactions with boron ($n + {}^{10}_{5}\mathrm{B} \rightarrow \alpha + {}^{7}_{3}\mathrm{Li}$).

neutron deceleration
Neutrons are best decelerated using substances of low mass number (e.g. H_2O, D_2O, Be, graphite, paraffin); see also moderation.

neutron fluence
Time-integrated neutron flux per cm^2.

neutron flux
Number of neutrons per cm^2 and second.

neutron poison
Materials with large neutron-capture cross sections will reduce the reactor reactivity, thereby creating a problem for energy production. Such materials have to be avoided if the power station is to operate efficiently. Some neutron-capturing isotopes may even be created as fission products, which then will have an impact on the reactor performance.

neutron reflector
A material with a large neutron scattering cross section. Beryllium is very useful as neutron reflector because it has an extremely high scattering cross section and at the same time a very low capture cross section.

neutron source
Radium–beryllium source. α particles from radium decay produce neutrons on interacting with beryllium according to $\alpha + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{12}_{6}\mathrm{C} + n$. Instead of radium, other α emitters (Po, Am, ...) may be used.

neutrons, epithermal
Neutrons with energies in the eV range.

neutrons, fast
Fission neutrons with energies of more than 0.1 MeV.

neutrons, thermal
Neutrons in thermal equilibrium with the environment. Neutrons of room temperature (300 kelvin) have an energy of $25\,\mathrm{meV} = (1/40)\,\mathrm{eV}$.

NIR
Non-ionizing radiation, i.e. electromagnetic radiation below the ionization level ($\leq$ several eV).

nuclear binding energy
Energy which would be needed to decompose an atomic nucleus into its constituents. Typical binding energies per nucleon are 7 to 8 MeV.

nuclear bomb
A weapon in which a nuclear chain reaction occurs in a fraction of a second causing an uncontrolled explosion. The nuclear chain reaction is initiated by bringing together two subcritical amounts of fissile material by a mechanical implosion (see also hydrogen bomb).

nuclear emulsion
Particle detector recording tracks of charged particles in a silver-bromide emulsion. The tracks can be made visible by developing the emulsion like a photographic film.

nuclear fission Fission of a nucleus, mostly into two fragments. The fission products usually have different masses. The fission yield shows a double peak structure with maxima around masses of 95 and 140, corresponding to the magic neutron numbers of 50 and 82.

nuclear fluorescence (resonance absorption) γ rays are preferentially absorbed by nuclei if their energy corresponds to an excitation energy of the nucleus.

nuclear fuel Fissile material used in a reactor.

nuclear fusion Light nuclei may be combined, making heavier ones, thereby releasing nuclear binding energy. In this way protons can be merged, eventually to form helium. In fusion experiments conducted so far on Earth, deuterons and tritons are used. The Sun fuses protons via deuterons and tritons to helium.

nuclear incident Unexpected event in a nuclear facility, resulting in an increase in the possibility of radioactive contamination of the environment.

nuclear pharmaceuticals In clinical diagnostics, patients are occasionally administered compounds tagged with radioisotopes, either orally or by injection. Such tagged pharmaceuticals are also used in radiotherapy.

nuclear photoelectric effect Nuclear reaction by which a nucleon is liberated from a nucleus by a photon.

nuclear power plant A facility which converts nuclear energy into electrical power. Current nuclear power plants use the energy from fission to produce steam, which drives a generator and generates electrical power.

nuclear reaction A process in which two nuclei or elementary particles collide to produce fragments different from the initial particles. If the particles collide and separate without changing, the process is called an elastic collision, otherwise inelastic.

nuclear reactor Device in which a nuclear chain reaction is initiated, controlled, and sustained.

nuclear security class Identifies nuclear packages depending on possible radiation hazards.

nuclear waste Radioactive material as waste product from nuclear power plants, from the nuclear-fuel cycle, or from recycling facilities. Such waste has be to disposed of by safe long-term storage.

nucleon Collective name for proton and neutron.

nucleotide Organic compound consisting of a nitrogen-containing base linked to a sugar and a phosphorus group. DNA and RNA are made up of long chains of nucleotides.

nucleus
An ensemble of protons and neutrons forming the center, the core of an atom.

nuclide
Isotope defined by its proton number, neutron number, and its energy state. Radioactive nuclides are called radionuclides or radioisotopes.

Oklo
A high level of uranium isotopes in ores can lead to natural fission processes under favorable weather conditions (availability of water). These conditions were met in Oklo, Gabon, in Central Africa, where a natural reactor was operating over millions of years. A large amount of ^{235}U was processed before the reactor went subcritical. Therefore this natural reactor will not restart.

organ, critical
See critical organ.

packaging
Encasing of radioactive material required to ensure compliance with the packaging and transport requirements. Depending on the type and activity of the radioactive material, it will consist of some combination of absorbing materials, thermal insulation, radiation shielding, and devices for cooling.

pair annihilation
See annihilation.

pair production
Production of e.g. electron–positron pairs by γ rays in the Coulomb field of nuclei.

partial-body dose
Average of the dose equivalent over part of the body or organ.

particle therapy
See hadron therapy.

pebble-bed reactor
See high-temperature reactor.

pendulum irradiation
Special tumor irradiation treatment where the patient rests on the treatment couch while the X-ray tube swings at a fixed angle about an axis passing through the tumor. Rotational treatment and the swinging-pendulum irradiation spares healthy tissue from unnecessary exposure.

pen-type dosimeter
See pocket dosimeter.

personal dose
Dose equivalent for tissue measured at a representative part of the body.

personal dosimeter
Personal exposure meter.

PET
Positron-emission tomography is a medical imaging technique using the annihilation of positrons. e^+e^- annihilation leads to two anticollinear photons (i.e. making an angle of 180 degrees) of 511 keV each, which are measured by the PET camera to provide an image of the tissue or organ being examined.

phosphate fertilizer Phosphate fertilizers contain among others the radioisotopes ^{226}Ra, ^{232}Th, and ^{40}K. The potassium activity alone can be as high as 40 kBq/kg.

phosphate-glass dosimeter Silver-activated phosphate glass emits an orange fluorescence radiation on irradiation with UV. The intensity of the fluorescence radiation is proportional to the absorbed energy dose. The reading of the dose with UV radiation does not erase the dose information.

photoelectric effect Separation of electrons from atoms by X rays or γ rays

photofission Nuclear fission induced by energetic photons.

photon Energy quantum of electromagnetic radiation.

photopeak Total-absorption peak of X rays or γ rays in a particle detector. This peak is mostly caused by the photoelectric effect. However, the full-absorption peak of photons due to Compton scattering, with subsequent simultaneous absorption of the Compton-scattered photon via the photoelectric effect, is sometimes also called photopeak.

pion (π) Unstable elementary particle with a lifetime for charged pions of 26 ns.

pitchblende Uranium-containing mineral.

planned special exposure Exposure to radiation, separate from and in addition to the annual dose limits, e.g. as a consequence of nuclear incidents.

plasma Ionized gas with a high fraction of free electrons and ions.

plasma heating The heating of a plasma can be achieved either by induced currents, high-frequency radiation, or injection of neutral particles.

plastic detector Charged particles passing through plastic material create local radiation damage which can be made visible by etching (also called nuclear-track detector or track-etch detector).

plastic scintillators Polymerized organic scintillating substances.

plateau Above a certain voltage, the count rate in a gaseous particle detector becomes nearly independent of the voltage. The stable working point is best chosen in the central part of this plateau.

pocket dosimeter Ionization chamber built as pen-type dosimeter, which enables an instant reading of the received dose.

Poisson distribution A distribution of a discrete random variable. See also statistics.

positron (e^+) Antiparticle of the electron.

positronium

Atom-like system consisting of an e^+e^- pair. The spin of this system can be 0 or 1 depending on the relative spin orientation of the electrons. The spin-0 positronium ('para-positronium') decays into two photons, and the spin-1 positronium ('ortho-positronium') into three photons.

***pp* cycle**

See proton–proton fusion.

pressurized-water reactor

Reactor design with normal or heavy water flowing through the core at very high pressure in a closed loop. The water is not allowed to boil in the core but rather produces steam behind a heat exchanger to feed a generator. The water is used as moderator *and* coolant.

primary cosmic rays

Cosmic radiation from outer space incident on Earth. The baryonic component consists predominantly of protons and α particles, but also heavier elements up to uranium are present in primary cosmic rays. In addition there are also primary electrons, photons, neutrinos, and even a few antiparticles.

primordial isotopes

Extremely long-lived isotopes which have been formed in the cosmological nucleosynthesis $\approx$ 13 billion years ago (or in supernova explosions) and which are still around. Examples are ^{40}K, ^{87}Rb, ^{147}Sm, ^{187}Re.

prompt fission neutron

Neutron emitted during the fission reaction, in contrast to a delayed fission neutron.

proportional chamber

Particle detector which measures the position of a particle's passage with a layer of parallel anode wires, and gives proportional amplification of the ionization produced by a charged particle or photon. In the field of radiation protection multi-wire proportional chambers are mainly used for the measurement of surface contaminations.

proton

Positively charged building block of the nucleus.

proton–proton fusion

Main fusion mechanism for energy generation in the Sun and most stars, leading to helium.

proton therapy

Precision radiation therapy for the treatment of well-localized deep-seated tumors with protons. This method relies on the increased energy loss of protons at the end of their range (Bragg peak). The surrounding tissue is spared from unnecessary exposure.

qualification

Knowledge concerning technical, academic, and practical abilities and skills developed through training, education, and practical experience. This kind of qualification in the field of radiation protection is a requirement for a radiation officer.

quality factor Measure of the effectiveness of a radiation at producing damage in a biological system. It depends on the linear energy transfer. The quality factor has been replaced by the radiation weighting factor in the conversion of the energy dose to the dose equivalent. The radiation weighting factor is 1 for X rays, γ rays, and electrons, and 20 for α particles and fission fragments. The corresponding factors for protons and neutrons lie between these values. The different biological effects on individual irradiated organs or tissue are taken into account by tissue weighting factors.

quantum Smallest discrete amount of any physics quantity. Planck's constant is the smallest possible amount of an action, and the elementary charge is the smallest amount of charge of free particles.

quark Basic constituent of matter. There are six different quark types, up, down, charm, strange, top, and bottom. These different quark types are called 'flavors'.

quencher In proportional counters the exponential amplification of charge carriers (avalanche development) has to be interrupted. This can be accomplished by the addition of a vapor to the noble-gas filling. The gas ions produced near the anode transfer their charge to the vapor molecules while drifting to the cathode. In contrast to the gas ions, the ionized vapor molecules are unable to liberate electrons from the cathode upon impact. Therefore further electron multiplication is stopped (i.e. the discharge is quenched).

rad Radiation absorbed dose: 100 erg per gram; 1 rad = 10 mGy.

radiation accident Situation after a nuclear accident in which the radiation limits to workers and/or the general public might be exceeded.

radiation areas Areas in which increased radiation levels are allowed to occur. There are three classes: exclusion areas, controlled areas, and surveyed areas.

radiation belt See Van Allen belt.

radiation cataract See cataract.

radiation effects Are divided into early, or immediate, and delayed radiation effects.

radiation-exposed worker Annual dose limits for radiation-exposed workers of categories A and B are defined in the radiation-protection regulations. For radiation-exposed workers of category A working in controlled areas, the annual dose limit in most countries is 20 mSv.

radiation exposure Radiation exposure from the environment amounts to about 2–3 mSv/yr. The average exposure from medical diagnostics, and the use of radioisotopes in medicine and industry, is around 2 mSv/yr.

radiation-induced cancer
Cancer can be caused by ionizing radiation; but also high-frequency non-ionizing radiation can induce cancer (especially of the skin).

radiation injury
Radiation damage as result of exposure to large doses of radiation.

radiation, ionizing
See ionizing radiation.

radiationless decay
Decay of an atom from an excited state without the emission of electromagnetic radiation (e.g. through Auger effect).

radiation limits
National radiation-protection regulations define limits for exemption, for clearance, for discharges from nuclear facilities to the environment, and for surface contaminations of work places, etc.

radiation officer
Short for radiation-protection officer, see there.

radiation-protection documentation
The exposures of personnel working in radiation areas have to be documented. The records for each individual have to be kept for 30 years or more, depending on the national regulations.

radiation-protection guide
Such a guide establishes that exposures from radiation facilities or devices which generate ionizing radiation should be kept as low as reasonably achievable (ALARA principle). In some countries it is even required to keep the exposures as low as possible.

radiation-protection officer
The radiation-protection supervisor has to appoint an appropriate number of radiation-protection officers for the control and surveillance of the work in radiation areas. This is done formally with a radiation-protection directive. The radiation-protection officer has to be qualified for his work in the field of radiation protection. He has to organize the radiation protection, and he has to make sure that the radiation-protection regulations are respected.

radiation-protection regulations
Define the rules for the handling of radioactive material and the operation of facilities which produce ionizing radiation.

radiation-protection supervisor
The radiation-protection supervisor has to appoint an appropriate number of radiation-protection officers by issuing a radiation-protection directive. In contrast to the radiation-protection officers, the supervisor need not be an expert in the field of radiation protection. The radiation-protection supervisor has to see that the radiation-protection regulations are respected. If there is a problem in the field of radiation protection, the responsibility rests with the radiation-protection supervisor.

radiation risk
See risk factor.

radiation sickness
Radiation syndrome as a result from an exposure to high-level radiation ($\geq$ 0.5 Sv). Early symptoms are nausea, vomiting, and diarrhea, followed for higher doses also by loss of hair and hemorrhage. For doses of more than 1 Sv, fatalities might occur.

radiation therapy Treatment of diseases (e.g. tumors) using methods from nuclear medicine and radiology (e.g. γ or hadron irradiation).

radiation weighting factor Weighting factor assessing the biological effectiveness of ionizing radiation. The energy dose D multiplied by the radiation weighting factor yields the dose equivalent.

radiopharmaceuticals In clinical diagnostics patients are occasionally administered compounds tagged with radioisotopes, either orally or by injections. Such tagged pharmaceuticals are also used in radiotherapy.

radioactive equilibrium If the half-life $T_{1/2}$ of the first isotope in a radioactive decay series is much larger than those of the half-lives of the decay products, a radioactive equilibrium is attained after a time $t \gg T_{1/2}$. In this situation, the number of nuclei of a certain type created by decay is identical to those that decay to other nuclei.

radioactive tracing By replacing a stable atom in a compound by a radioisotope of the same element, its path through a biological system can be traced by the radiation it emits; also called labeling.

radiobiology Branch of biology concerned with the effects of radioactive substances on living organisms.

radioisotope battery See radioisotope generator.

radioisotope generator (RTG) A Radioisotope Thermoelectric Generator produces electrical energy from the decay of radioisotopes.

radiological emergency situation After a radiation accident, plans must be provided to mitigate and eliminate the consequences of such an emergency. The population concerned must be instructed how to deal with such a situation, which might lead to exposures for the general public beyond the standard radiation limits.

radionuclide Radioisotopes of natural origin or produced by activation of stable elements or by fission.

radioprotective substance Chemical radioprotectors which reduce the radiation sensitivity, e.g. cystamine applied *before* a radiation exposure reduces the radiation sensitivity considerably.

radium–beryllium source α particles from radium decay produce neutrons on impact on beryllium according to $\alpha + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{12}_{6}\mathrm{C} + n$. Instead of radium, other α emitters (Po, Am, ...) can be used.

radon Radioactive noble gas. The isotopes ^{220}Rn and ^{222}Rn represent the main natural radiation exposure to the population (1.1 mSv/yr).

range

α rays from radioactive sources are of very short range (4 cm in air, in plastics $\approx$ 0.1 mm). The range of β rays corresponds to a maximum of 5 mm in aluminum. γ rays are only exponentially attenuated and cannot even be completely shielded by lead.

Rayleigh scattering

Elastic scattering of photons in the visible range off atomic electrons. The cross section for Rayleigh scattering is proportional to the fourth power of the frequency. Rayleigh scattering causes the blue color of the sky.

reactivity

Quantity to measure the departure of a reactor from criticality.

reactor poison

Materials with large neutron-capture cross sections will reduce the reactor reactivity, and therefore create a problem for energy production.

recycling

Reprocessing of unburnt nuclear material by chemical techniques for re-use in fuel rods.

reference man

Person assumed to have the anatomical and physiological characteristics of an average individual.

reflector

A material with a large neutron scattering cross section. Beryllium, graphite, and water are suitable reflector materials.

regulator rod

Control rods made of material with a large neutron absorption cross section, e.g. cadmium. Inserting or retracting the regulator rods allows to control the neutron-amplification factor in a nuclear reactor.

Relative Biological Effectiveness (RBE factor)

Measure of the effectiveness of a type of radiation at producing injury in a biological system. See also quality factor.

release

Removal of all regulatory radiological control of radioactive material below the clearance level, because the associated risk has become sufficiently low. Released material below the clearance level is no longer subject to any restriction or radiological control.

rem

Roentgen equivalent man; dose equivalent measured in 100 erg per gram, multiplied by the radiation weighting factor. 1 rem = 10 mSv.

repository

Facility for the permanent disposal of high-level radioactive waste.

reprocessing plant

Facility that processes spent nuclear fuel to enrich it again with fissile material for re-use in a reactor.

residual heat

After shutdown a nuclear reactor will still produce heat, which originates from the radioactivity of the fission products and a low level of further fission processes.

rest energy The energy equivalent of the mass of a particle according to $E = mc^2$. The rest energy of an electron is 511 keV, that of a proton is 938 MeV. Frequently also the masses of particles are given in energy units.

restricted area Area to which access is limited because of possible exposure to radiation.

retention Describes the time-dependent behavior of an incorporated radioactive substance in an organism.

ring accelerator Particle accelerator which uses (mostly alternating) electric fields to propel charged particles to high velocities (see also synchrotron, cyclotron).

risk–benefit estimate Radioisotopes are used for the treatment of tumors and in medical diagnosis. At the same time ionizing radiation may induce cancer. The use of radioisotopes in medicine requires that the therapeutical benefit must significantly exceed the radiation risk.

risk factor If N persons are irradiated by a dose equivalent H, the number of individuals contracting a stochastic radiation effect (e.g. leukemia) is $n = f\ N\ H$; f is the risk factor.

risk level Different radiation areas can be characterized by a risk level. This helps the fire brigade to wear appropriate protective shielding if there is a fire.

RNA Ribonucleic acid: carries the genetic code transcribed from DNA to specialized sites within the cell (ribosomes).

roentgen (R) One roentgen is the intensity of X rays or γ rays which produces one electrostatic unit each of ions and electrons in 1 cm^3 of dry air at standard pressure and temperature. For air: 1 R = 0.88 rad = 8.8 mGy.

safety rod Quickly movable control rod used to decrease the reactor reactivity in an emergency.

SAR value Short for specific absorption rate. The SAR value is a measure of the absorption of non-ionizing electromagnetic radiation (NIR) in tissue.

scintigram Nuclear technique to image internal organs: measurement of γ rays emitted by the radioisotope-tagged organs in the human body using modular scintillation counters. Metabolic processes of organs can also be imaged.

scintillation counter Particle detector based on the absorption of γ rays or on the energy loss of charged particles by excitation. Photons emitted during the transition of excited states into the ground state form the basis of particle detection.

secondary cosmic rays Secondary cosmic rays are a complex mixture of elementary particles, which are created in interactions of primary cosmic rays with nuclei in the Earth's atmosphere. At sea level, secondary cosmic rays consist mainly of muons (80%) and electrons (20%).

self absorption

Electrons from low-energy β emitters, and α rays can be significantly absorbed in the source itself.

semiconductor counter

Ionizing radiation can be measured in semiconductors (e.g. silicon or germanium) where electron–hole pairs are produced: these can be collected in an electric field. The number of electron–hole pairs produced is proportional to the energy deposited.

sensitizer

The effect of radiation on a biological system can be enhanced by certain compounds, e.g. oxygen, bromouracil, fluorouracil. The concentration of water also influences the sensitivity to radiation. Similarly, carcinogenic substances act as sensitizers.

sievert (Sv)

Dose equivalent in joules per kilogram. The dose equivalent is the energy dose in gray multiplied by the radiation weighting factor w_R. 1 Sv $= 100$ rem.

single-escape peak

Structure in the γ spectrum of a monoenergetic emitter, which originates from pair production and subsequent positron annihilation, where one photon (511 keV) escapes detection.

smoking

The inhalation of natural radon and its α-emitting decay products attached to aerosols increases the risk of lung cancer and cancer of the bronchi among smokers, and also for passive smokers. Possibly cancer of the throat is also caused by smoking.

soft tissue

Homogeneous material with a mass fraction of 10.1% hydrogen, 11.1% carbon, 2.6% nitrogen, and 76.2% oxygen.

somatic radiation effects

Biological radiation effects which manifest themselves in changes of the structure and dynamical behavior of non-sexual organs.

source strength

Activity of a radioactive source in Bq (in some countries still in the old unit Ci).

sources

Radioactive sources.

spallation

Nuclear transformation caused by high-energy particles, in which a large number of nuclear fragments, α particles, and nucleons are produced.

spallation neutron source

Facility for the production of an intense neutron flux by bombarding a target with energetic protons.

spectrometer

Detection system consisting of deflection magnets and particle detectors for the measurement of particle momenta.

spent nuclear fuel

Fuel withdrawn from a nuclear reactor after having been used as a source of energy. Spent fuel has not been chemically separated into its constituent elements by reprocessing.

spermiogenesis Sperm production is very sensitive to radiation both in quantity and quality.

spin Intrinsic angular momentum of a particle or nucleus in units of $\hbar$, where $\hbar = h/(2\pi)$ and h is Planck's constant.

spontaneous fission Spontaneous fission is a type of radioactive decay which is not caused by an incident particle (in contrast to induced fission). The half-lives for spontaneous fission decrease rapidly with increasing Z, e.g. $T_{1/2} = 4.5 \times 10^9$ years for ^{238}U, $T_{1/2} = 2.64$ years for ^{252}Cf, and $T_{1/2} = 5$ ms for ^{262}No.

statistics The rates in radioactive decay are subject to Poisson statistics. The root mean square of a Poisson distribution – a measure of its width – is equal to the square root of the average value.

stellarator Toroidal chamber for magnetic confinement of a hot hydrogen plasma. In the stellarator, the plasma containment is achieved with a sophisticated arrangement of magnetic coils.

sterilization See food irradiation.

sterility An exposure to radiation can induce sterility (possibly temporary).

stochastic process A stochastic process, or sometimes random process, is the counterpart to a deterministic process. The outcome of individual events in such a process is unpredictable. However, many events of this type follow a given probability distribution.

stochastic radiation effects Delayed radiation effects for which the seriousness of the disease does not depend on the dose, but the probability of occurrence is linearly dependent on it.

stopping power The linear stopping power of materials for charged particles is the energy deposition per unit length. The energy deposition can either be caused by ionization and excitation or by bremsstrahlung.

stray radiation X-ray production as an unwanted by-product of technical instruments (e.g. by TV sets of older design or by radar equipment).

strong interaction Short-range interaction binding quarks, antiquarks, and gluons in nucleons and hadrons. The nucleons are bound together in nuclei by the residual interaction of the strong forces.

subatomic particle Any particle smaller than an atom (e.g. proton, electron, pion).

subcritical mass Amount of fissile material which is incapable of sustaining a fission chain reaction. Subcriticality is the case when there is insufficient mass of fissile material, or when it does not have the required geometry.

State of a reactor with effective multiplication factor larger than 1.0. **supercriticality**

Portable instrument for the measurement of radiation fields and detection of possible contaminations. **survey meter**

Monitored radiation area outside controlled areas. According to the ICRP recommendations, individuals working in these areas might be exposed to radiation levels of more than 1 mSv per year. **surveyed area**

Nuclear reactor in which the core is immersed in a large open tank of water. The blue color of the water is caused by Cherenkov radiation of relativistic electrons from nuclear beta decay of fission products. **swimming-pool reactor**

A synchrotron accelerates particles on a circular orbit of constant radius. The strength of the guiding field is varied proportionally with the momentum during acceleration. **synchrotron**

Intense, laser-like, broad-band light source in the UV or X-ray range produced by electrons accelerated and deflected in synchrotrons. The radiation can even be intensified by suitable wigglers or undulators. **synchrotron radiation**

Circular electron accelerator, in which the electrons – deflected by special magnetic elements (wigglers and/or undulators) – generate intense synchrotron light in the UV or X-ray regime. **synchrotron radiation source**

See chart of nuclides. **table of isotopes**

A technetium-99m generator, also called 'technetium cow', is a device in which the metastable Tc 99m is 'milked' from the decay of molybdenum 99. **technetium generator**

Environmental factors, such as ionizing radiation or viruses, acting on a fetus, can cause congenital abnormality. **teratogen**

The process of radiation causing birth defects. **teratogenicity**

Fission in which the nucleus disintegrates into three fission fragments. The lightest fragment is usually an α particle or a tritium nucleus. **ternary fission**

Natural ionizing radiation from the Earth's crust. Typical radioisotopes are ^{40}K, ^{226}Ra, and ^{232}Th. The radiation exposure from terrestrial radiation is about 0.5 mSv/yr. **terrestrial radiation**

Gas consisting of 90% argon and 10% methane, frequently used as gas filling for proportional counters. Methane is used as quencher. **test gas**

Type of reactor in which fission neutrons are thermalized by moderators and breed transuranic elements. **thermal breeder**

thermal neutrons See neutrons, thermal.

thermoluminescence dosimeter In certain materials stable excited states are formed by ionizing radiation. Their number is proportional to the received dose. Heating the material causes the states to decay and give off light. The light yield is proportional to the absorbed dose. Reading the thermoluminescence detector erases the dose information.

Thomson scattering Elastic scattering of electrons off atomic electrons in the energy range $E_\gamma \ll m_e c^2$, where m_e is the electron mass.

Three-Mile-Island reactor In this reactor a severe accident happened in 1979 whose consequence was a partial core meltdown. Contamination of the environment was only avoided because of good reactor containment.

threshold dose Dose below which no immediate radiation injury is observed. To be on the safe side, one should assume that there is no threshold dose for stochastic radiation effects. In contrast, there appears to be a threshold dose for early radiation effects, the value of which is significantly higher than the dose from environmental radioactivity (which is $\approx 2\,\mathrm{mSv/yr}$). An analysis of a blood sample will only indicate increased radiation exposure if the dose is larger than 250 mSv.

time-of-flight counter Detector for particle identification based on the principle that particles with different masses but the same momentum will have different velocities.

tissue-equivalent material Characterization of a material whose absorption power is comparable to biological tissue.

tissue weighting factor Weighting factor assessing the different radiation sensitivities of tissues or organs. The ICRP-recommended tissue weighting factors are: gonads 0.20, red bone marrow 0.12, stomach 0.12, colon 0.12, lung 0.12, bladder 0.05, chest 0.05, esophagus 0.05, liver 0.05, thyroid gland 0.05, periosteum (bone surface) 0.01, skin 0.01, other organs or tissue 0.05.

tokamak Toroidal combustion chamber within magnetic coils, in which a hydrogen plasma is fused. A large transformer induces a plasma current; also neutral-particle injection or radio-frequency heating increases the temperature of the plasma until fusion conditions are achieved.

toxicity Some radioisotopes (e.g. ^{239}Pu, ^{240}Pu, ^{249}Cf) have very long biological half-lives, and consequently lead to high radiation doses after incorporations. Because of their high radiotoxicity, the exemption limits for these isotopes are rather low. Radiotoxic substances are usually also of high chemical toxicity.

tracer A radioactive tracer, or radioactive label, is a substance containing a radioisotope. Tracers are usually admixed with stable chemical compounds to track the movement of a substance through a biological system.

track-etch detector
See plastic detector.

transfer factor
Factor which describes the transfer of radioactive substances from one biosystem to another (e.g. soil → grass → cow → humans).

transmutation
Long-lived radioactive waste can be transformed into short-lived or even stable isotopes by proton or neutron bombardment. This technique has so far only been demonstrated to work on small samples.

transport index
Depending on the ambient dose at the accessible surface of a packaging system containing radioactive material (e.g. CASTOR container), the cargo is classified by a transport index, which describes the possible hazard. This international transport index is defined as the highest ambient dose at a distance of one meter from the accessible surface of the cargo (measured in mSv/h) multiplied by a factor of 100 (which gives the dose equivalent in mrem).

transuranic elements
Elements beyond uranium ($Z \geq 93$).

tritium
Radioactive isotope of hydrogen with two neutrons (^{3}H). The tritium activity of normal drinking water is around 0.1 Bq/l.

tritium light source
Light source in which β rays from the tritium-containing gas in a lamp cause fluorescence in the fluorescent material coating the inner surface of the lamp container.

triton
Nucleus of the tritium atom.

UMTS
Universal Mobile Telecommunications System; works in the frequency range around 2 GHz.

uncertainty principle
Heisenberg's uncertainty principle states that it is impossible to measure complementary physics quantities at the same time with absolute precision. Complementary quantities are particular pairs, such as momentum and position or energy and time, whose product is that of an angular momentum (called an action, measured in J s or W s^2).

undulator
Sequence of dipole magnets of alternating polarity which cause the electrons going through to generate synchrotron radiation. The magnet structure in undulators is arranged in such a way that coherent radiation is produced.

unrestricted area
Area to which access is not controlled for purposes of protection of individuals from exposure to radiation.

UNSCEAR
United Nations Scientific Committee on the Effects of Atomic Radiation.

unsealed radioactive sources
The handling of unsealed radioactive sources presents a potentially high risk, and is subject to stronger restrictions compared to the handling of sealed sources.

Van Allen belts Low-energy cosmic-ray solar particles are captured in certain belts in the Earth's magnetic field and stored there. The radiation levels in the electron and proton belts are rather high.

vitrification Technique to process and contain high-level radioactive waste. Liquid waste is melted with glass beads at high temperature to obtain a homogeneous vitrified product. The molten product is stored for final disposal in steel containers where it will solidify after cooling down.

washout Precipitation of radioactive material by rain from the atmosphere, e.g. after atmospheric tests of nuclear weapons.

waste, radioactive There are several sources of radioactive waste: nuclear facilities, science and engineering, and particularly nuclear medicine. One has to distinguish solid, liquid, and gaseous radioactive waste. Highly radioactive waste requires particular care. It must be disposed of for safe long-term storage.

***W* bosons** Charged carriers (W^+ and W^-) of the weak current (e.g. in nuclear β decay: $n \rightarrow p + W^-$, with subsequent decay of the W^- according to $W^- \rightarrow e^- + \bar{\nu}_e$).

weak interaction Interaction responsible for 'charged currents' in which quark flavors change, or for 'neutral currents' which are mediated by the exchange of a neutral Z boson; e.g., neutron decay is mediated by weak interactions where a u quark from the proton is transformed into a d quark under the emission of a virtual charged quantum of weak interactions, a W^-, which decays into an electron and an electron antineutrino ($n \rightarrow p + W^-$ with $W^- \rightarrow e^- + \bar{\nu}_e$).

weighting factor Measure of the effectiveness of a type of radiation to produce a biological effect. It depends on the linear energy transfer of ionizing radiation. See radiation weighting factor and tissue weighting factor.

well logging Technique in oil and gas exploration using neutron or γ activation, or X-ray fluorescence methods, to predict the commercial viability of wells.

whole-body counter Radiation system consisting of scintillation detectors to monitor the low-level γ activity from radioisotopes absorbed in the human body.

whole-body dose Average of the dose equivalent over head, body, arms, and legs as a consequence of an irradiation of the whole body on the assumption that the irradiation is homogeneous.

wiggler Arrangement of dipole magnets with alternating polarity which cause electrons being deflected there to create incoherent synchrotron radiation in the keV range.

window counter Counter with a thin entrance window (made, for example, of mica) which measures low-energy photons, electrons, or α particles.

wipe sample
Sample made in order to detect possible surface contaminations.

wipe test
Technique to detect contaminations on instruments, work places, or clothing.

workers, radiation-exposed
See radiation-exposed worker.

working level (WL)
The concentration of radon daughters in uranium mines is usually measured in working-level (WL) units. The working level measures the concentration of α particles in air. One 'Working Level' is approximately equivalent to $3700\,\mathrm{Bq/m^3}$ of ^{222}Rn in equilibrium with its decay products.

working-level month (WLM)
A unit of measure used to determine cumulative exposures to radon for workers in uranium mines. The exposure to radon daughters is expressed in units of Working-Level Months (WLM, 1 month corresponds to 170 working hours). 1 WLM is roughly 5 mSv.

X rays
Electromagnetic radiation with energies between 1 keV and a few hundred keV. X rays are created by transitions between inner shells of atoms and by bremsstrahlung. X rays are mainly used for diagnostic radiography and for crystallography. X rays are a form of ionizing radiation.

X-ray diagnostics
Medical diagnostics with X rays.

X-ray fluorescence
An excited atom can emit energies in transitions between different shells in the form of photons in the visible range or as X rays. Transitions between inner shells are usually in the X-ray regime. These photons are called characteristic X rays or X-ray fluorescence photons.

X-ray passport
Document which lists information on the X-ray examinations of a patient. It should contain the date and time of the examination, the exposure, the part of the body examined, and the name of the physician.

X-ray regulations
Organize the handling of devices which generate X rays. The limits given in the X-ray regulations follow those of radiation-protection regulations closely.

yearly dose
The annual dose for radiation workers is limited by the national radiation-protection regulations. For example, in Europe it is 20 mSv for category-A persons in controlled areas.

yellowcake
Product obtained through the milling and chemical processing of uranium ore forming a coarse powder. The material is a mixture of uranium oxides that can vary in color from yellow to orange to dark green. From yellowcake uranium hexafluoride (UF_6) is produced and in the next step nuclear-fuel elements are manufactured.

Yokota glass
Silver-activated phosphate glass, widely used in radiation dosimetry, e.g. for finger-ring dosimeters.

Yukawa potential Attractive potential between nucleons, responsible for nuclear binding.

zinc sulfide 'Historical' screen ('zinc blende') which emits scintillation light upon impact of charged nuclear particles or γ rays.

***Z* boson** Neutral carrier of the weak current (see also W bosons).

zircaloy Trade name of an alloy of zirconium used for the cladding of fuel rods in water-cooled and water-moderated reactors. Zircaloy has high mechanical strength, a low neutron-attachment cross section, and a high resistance to corrosion. It consists of a zirconium alloy with small amounts of tin, iron, and nickel.

A Table of Frequently Used Radioisotopes

Only decays with the largest branching fractions are listed. For β emitters the maximum energies of the continuous β-ray spectra are given. '$\rightarrow$' denotes the decay to the subsequent element in the table. EC stands for 'electron capture', a (= annus, Latin) for years, h for hours, d for days, min for minutes, s for seconds, and ms for milliseconds.

isotope $^{A}_{Z}$element	decay type	half-life	β resp. α energy (MeV)	γ energy (MeV)
$^{3}_{1}$H	β^-	12.3 a	0.0186	no γ
$^{7}_{4}$Be	EC, γ	53 d	–	0.48
$^{10}_{4}$Be	β^-	1.5×10^6 a	0.56	no γ
$^{14}_{6}$C	β^-	5730 a	0.156	no γ
$^{22}_{11}$Na	β^+, EC	2.6 a	0.54	1.28
$^{24}_{11}$Na	β^-, γ	15.0 h	1.39	1.37
$^{26}_{13}$Al	β^+, EC	7.17×10^5 a	1.16	1.84
$^{32}_{14}$Si	β^-	172 a	0.20	no γ
$^{32}_{15}$P	β^-	14.2 d	1.71	no γ
$^{37}_{18}$Ar	EC	35 d	–	no γ
$^{40}_{19}$K	β^-, EC	1.28×10^9 a	1.33	1.46
$^{51}_{24}$Cr	EC, γ	27.8 d	–	0.325
$^{54}_{25}$Mn	EC, γ	312 d	–	0.84
$^{55}_{26}$Fe	EC	2.73 a	–	0.006
$^{57}_{27}$Co	EC, γ	272 d	–	0.122
$^{60}_{27}$Co	β^-, γ	5.27 a	0.32	1.17 & 1.33
$^{66}_{31}$Ga	β^+, EC, γ	9.4 h	4.15	1.04
$^{68}_{31}$Ga	β^-, EC, γ	68 min	1.88	1.07
$^{85}_{36}$Kr	β^-, γ	10.8 a	0.67	0.52
$^{89}_{38}$Sr	β^-	51 d	1.49	no γ
$^{90}_{38}$Sr $\rightarrow$	β^-	28.7 a	0.55	no γ
$^{90}_{39}$Y	β^-	64 h	2.28	no γ
$^{99m}_{43}$Tc	γ	6 h	–	0.140

C. Grupen, *Introduction to Radiation Protection*,
Graduate Texts in Physics, DOI 10.1007/978-3-642-02586-0

isotope ${}^{A}_{Z}$element	decay type	half-life	β resp. α energy (MeV)	γ energy (MeV)
${}^{106}_{44}$Ru $\rightarrow$	β^-	1.0 a	0.04	no γ
${}^{106}_{45}$Rh	β^-, γ	30 s	3.54	0.51
${}^{112}_{47}$Ag	β^-, γ	3.13 h	3.90	0.62
${}^{109}_{48}$Cd $\rightarrow$	EC	1.27 a	–	no γ
${}^{109m}_{47}$Ag	γ	40 s	–	0.088
${}^{113}_{50}$Sn	EC, γ	115 d	–	0.392
${}^{132}_{52}$Te	β^-, γ	77 h	0.22	0.23
${}^{125}_{53}$I	EC, γ	60 d	–	0.035
${}^{129}_{53}$I	β^-, γ	1.6×10^7 a	0.15	0.038
${}^{131}_{53}$I	β^-, γ	8.05 d	0.61	0.36
${}^{133}_{54}$Xe	β^-, γ	5.24 d	0.35	0.08
${}^{134}_{55}$Cs	β^-, β^+, γ	2.06 a	0.65	0.61
${}^{137}_{55}$Cs $\rightarrow$	β^-	30 a	0.51 & 1.18	0.66
${}^{137m}_{56}$Ba	γ	2.6 min	–	0.66
${}^{133}_{56}$Ba	EC, γ	10.5 a	–	0.36
${}^{140}_{57}$La	β^-, γ	40.2 h	1.34	1.60
${}^{144}_{58}$Ce $\rightarrow$	β^-, γ	285 d	0.32	0.13
${}^{144}_{59}$Pr	β^-, γ	17.5 min	3.12	0.69
${}^{144}_{60}$Nd	α	2.3×10^{15} a	1.80	no γ
${}^{152}_{63}$Eu	EC, $\beta^{\mp}$, γ	13.5 a	0.68	0.122
${}^{192}_{77}$Ir	EC, β^-, γ	74 d	0.67	0.32
${}^{198}_{79}$Au	β^-, γ	2.7 d	0.96	0.41
${}^{204}_{81}$Tl	β^-, EC	3.78 a	0.76	no γ
${}^{207}_{83}$Bi	EC, γ	31.6 a	0.48	0.57
${}^{222}_{86}$Rn $\rightarrow$	α, γ	3.8 d	5.48	0.51
${}^{218}_{84}$Po $\rightarrow$	α, β^-	3.1 min	α: 6.00	no γ
${}^{214}_{82}$Pb $\rightarrow$	β^-, γ	26.8 min	0.73	0.35
${}^{214}_{83}$Bi	β^-,γ	19.9 min	1.51	0.61
${}^{226}_{88}$Ra	α, γ	1600 a	4.78	0.19
${}^{228}_{90}$Th	α, γ	1.9 a	5.42	0.24
${}^{234}_{92}$U	α, γ	2.5×10^5 a	4.77	0.05

isotope $^{A}_{Z}$element	decay type	half-life	β resp. α energy (MeV)	γ energy (MeV)
$^{235}_{92}$U	α, γ	7.1×10^8 a	4.40	0.19
$^{238}_{92}$U	α, γ	4.5×10^9 a	4.20	0.05
$^{239}_{94}$Pu	α, γ	24 110 a	5.15	0.05
$^{240}_{94}$Pu	α, γ	6564 a	5.16	0.05
$^{241}_{95}$Am	α, γ	432 a	5.49	0.06
$^{252}_{98}$Cf	α, γ	2.6 a	6.11	0.04
$^{252}_{100}$Fm	α, γ	25 h	7.05	0.096
$^{268}_{109}$Mt	α	70 ms	10.70	–

Explanatory note

The heavy α-ray-emitting radioisotopes can also decay by spontaneous fission. Half-lives for spontaneous fission are usually rather long. More detailed information about decay modes and level diagrams can be taken from nuclear data tables. Corresponding references are listed under 'Further Reading' in the section 'Tables of Isotopes and Nuclear Data Sheets'. The most recent information on the table of isotopes can be found in the Internet under

`http://atom.kaeri.re.kr/`

and

`http://isotopes.lbl.gov/education` .

"We will be rich!
This isotope decays into gold!"

B Examples of Exemption Limits for Absolute and Specific Activities

There are no universal international values for exemption limits for radioactive sources and radioactive material. Different countries have defined limits based on the guidelines as recommended by the International Commission on Radiological Protection. The table below gives some examples which have been adopted by the new German radiation-protection ordinance in 2001. The corresponding limits in other countries are quite similar, although there are also some important differences in some national regulations.

If several sources each with activity A_i and corresponding exemption limit $A_i^{\max}$ are handled in a laboratory, the following condition must be fulfilled:

$$\sum_{i=1}^{N} \frac{A_i}{A_i^{\max}} \leq 1 \ .$$

This prevents the acquisition of several sources each with an activity below the exemption limit thereby possibly circumventing the idea of the exemption limit.

radioisotope	**exemption limit**	
	activity in Bq	**specific activity in Bq/g**
$^{3}_{1}$H	10^9	10^6
$^{7}_{4}$Be	10^7	10^3
$^{14}_{6}$C	10^7	10^4
$^{24}_{11}$Na	10^5	10
$^{32}_{15}$P	10^5	10^3
$^{40}_{19}$K*	10^6	10^2
$^{54}_{25}$Mn	10^6	10
$^{55}_{26}$Fe	10^6	10^4
$^{57}_{27}$Co	10^6	10^2
$^{60}_{27}$Co	10^5	10

radioisotope	exemption limit	
	activity in Bq	specific activity in Bq/g
$^{82}_{35}$Br	10^6	10
$^{89}_{38}$Sr	10^6	10^3
$^{90}_{38}$Sr†	10^4	10^2
$^{99m}_{43}$Tc	10^7	10^2
$^{106}_{44}$Ru†	10^5	10^2
$^{110m}_{47}$Ag	10^6	10
$^{109}_{48}$Cd†	10^6	10^4
$^{125}_{53}$I	10^6	10^3
$^{129}_{53}$I	10^5	10^2
$^{131}_{53}$I	10^6	10^2
$^{134}_{55}$Cs	10^4	10
$^{137}_{55}$Cs†	10^4	10
$^{133}_{56}$Ba	10^6	10^2
$^{152}_{63}$Eu	10^6	10
$^{197}_{80}$Hg	10^7	10^2
$^{204}_{81}$Tl	10^4	10^4
$^{214}_{82}$Pb	10^6	10^2
$^{207}_{83}$Bi	10^6	10
$^{210}_{84}$Po	10^4	10
$^{220}_{86}$Rn†	10^7	10^4
$^{222}_{86}$Rn†	10^8	10
$^{226}_{88}$Ra†	10^4	10
$^{227}_{89}$Ac†	10^3	0.1
$^{232}_{90}$Th†	10^4	10
$^{233}_{92}$U	10^4	10
$^{235}_{92}$U†	10^4	10
$^{238}_{92}$U†	10^4	10
$^{239}_{94}$Pu	10^4	1
$^{240}_{94}$Pu	10^3	1

radioisotope	exemption limit	
	activity in Bq	specific activity in Bq/g
$^{241}_{95}$Am	10^4	1
$^{244}_{96}$Cm	10^4	10
$^{252}_{98}$Cf	10^4	10

* as naturally occurring isotope unlimited

† in equilibrium with its daughter nuclei; the radiation exposure due to these daughter isotopes is taken account of in the exemption limits

C Maximum Permitted Activity Concentrations Discharged from Radiation Areas

There are no universal international values for the limits of radioactive material that may be released from radiation areas. Different countries have defined limits based on the guidelines as recommended by the International Commission on Radiological Protection. These limits generally refer to a maximum annual dose of 0.3 mSv that people from the general public may receive from such discharges. The table below gives some examples which have been adopted by the new German radiation protection ordinance in 2001. The corresponding limits in other countries are quite similar, but do vary in some national regulations.

radioisotope	**maximum permitted activity concentration**	
	in air in Bq/m^3	**in water in Bq/m^3**
$^{3}_{1}$H	10^2	10^7
$^{7}_{4}$Be	6×10^2	5×10^6
$^{14}_{6}$C	6	6×10^5
$^{24}_{11}$Na	90	3×10^5
$^{32}_{15}$P	1	3×10^4
$^{42}_{19}$K	2×10^2	2×10^5
$^{54}_{25}$Mn	20	2×10^5
$^{55}_{26}$Fe	20	10^5
$^{57}_{27}$Co	30	3×10^5
$^{60}_{27}$Co	1	2×10^4
$^{82}_{35}$Br	50	10^5
$^{89}_{38}$Sr	4	3×10^4
$^{90}_{38}$Sr	0.1	4×10^3

radioisotope	maximum permitted activity concentration	
	in air in Bq/m^3	in water in Bq/m^3
$^{99m}_{43}$Tc	2×10^3	4×10^6
$^{106}_{44}$Ru	0.6	10^4
$^{110m}_{47}$Ag	1	4×10^4
$^{109}_{48}$Cd	4	4×10^4
$^{125}_{53}$I	0.5	2×10^4
$^{129}_{53}$I	0.03	4×10^3
$^{131}_{53}$I	0.5	5×10^3
$^{134}_{55}$Cs	2	2×10^4
$^{137}_{55}$Cs	0.9	3×10^4
$^{133}_{56}$Ba	4	4×10^4
$^{152}_{63}$Eu	0.9	5×10^4
$^{197}_{80}$Hg	10^2	4×10^5
$^{204}_{81}$Tl	10	7×10^4
$^{214}_{82}$Pb	2	3×10^5
$^{207}_{83}$Bi	1	9×10^4
$^{210}_{84}$Po	0.008	30
$^{226}_{88}$Ra	0.004	2×10^2
$^{227}_{89}$Ac	7×10^{-5}	30
$^{232}_{90}$Th	3×10^{-4}	2×10^2
$^{233}_{92}$U	0.004	2×10^3
$^{235}_{92}$U	0.004	3×10^3
$^{238}_{92}$U	0.005	3×10^3
$^{239}_{94}$Pu	3×10^{-4}	2×10^2
$^{240}_{94}$Pu	3×10^{-4}	2×10^2
$^{241}_{95}$Am	4×10^{-4}	2×10^2
$^{244}_{96}$Cm	6×10^{-4}	3×10^2
$^{252}_{98}$Cf	0.002	2×10^2
any unknown isotope mixture	10^{-5}	10

These limits describe maximum activity concentrations in air released from radiation areas with the danger of inhalation, and maximum permitted activity concentrations, which are allowed to be discharged as sewage water.

Correspondingly, the condition

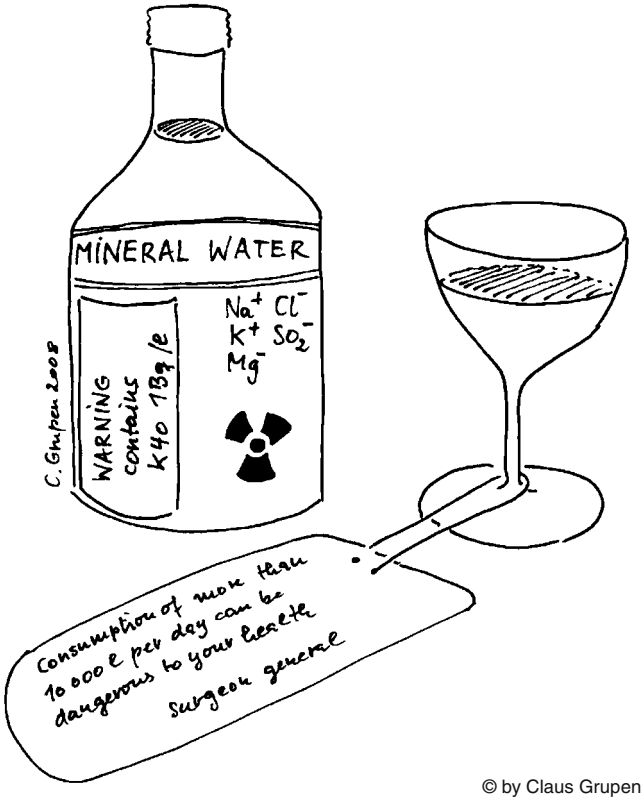
$$\sum_{i=1}^{N} \frac{\bar{C}_{i,\mathrm{a}}}{C_i} \leq 1$$

must be respected, where

C_i is the maximum permitted activity concentration

and

$\bar{C}_{i,\mathrm{a}}$ the actual released average annual activity concentration.



Examples of Clearance Levels

There are no universal international values for clearance levels for material containing residual radioactivity. After approved clearance the material is no longer considered as radioactive. Different countries have defined limits based on the guidelines as recommended by the International Commission on Radiological Protection. Clearance can only be approved if the residual activity causes insignificant exposure to the public ($\leq 10\,\mu Sv/yr$). The table below gives some examples which have been adopted by the new German radiation-protection ordinance in 2001. The corresponding limits in other countries are quite similar.

	clearance of		
radioisotope	**solid material, liquids (Bq/g)**	**construction waste, excavation residues (Bq/g)**	**ground area (Bq/g)**
^{3}H	1000	60	3
^{32}P	20	20	0.02
^{60}Co	0.1	0.09	0.03
^{90}Sr*	2	2	0.002
^{137}Cs*	0.5	0.4	0.06
^{226}Ra*	0.03	0.03	†
^{232}Th	0.03	0.03	†
^{235}U*	0.5	0.3	†
^{238}U*	0.6	0.4	†
^{239}Pu	0.04	0.08	0.04
^{240}Pu	0.04	0.08	0.04
^{241}Am	0.05	0.05	0.06

* in equilibrium with daughter isotopes; the radiation exposure due to these daughter isotopes is taken care of in the clearance levels

† naturally occurring radioisotopes in the ground with activities around 0.01 Bq/g

D Examples of Limits for Surface Contaminations

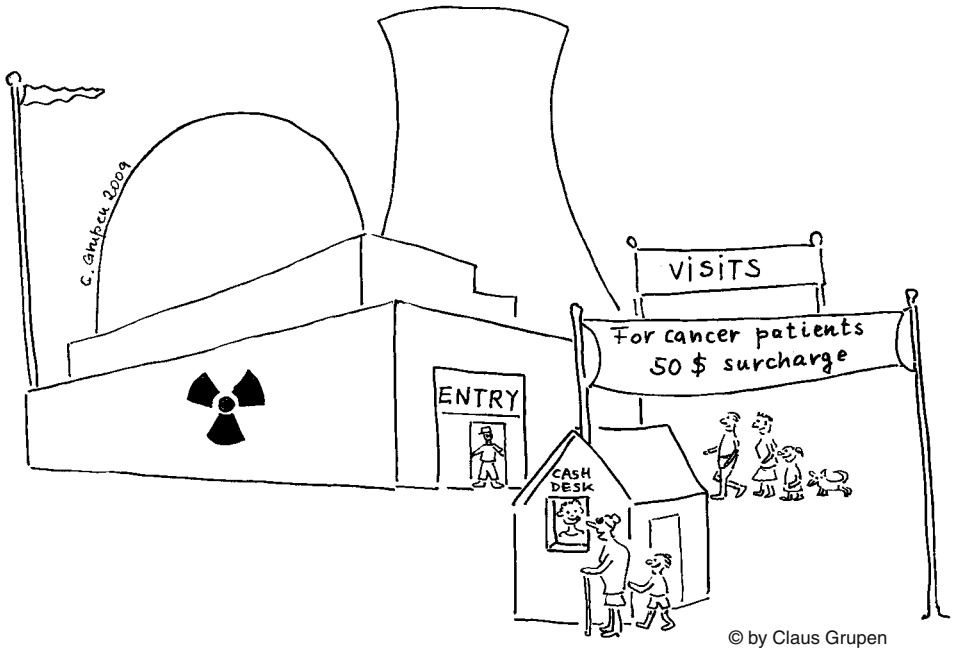
There are no universal international values for limits on surface contaminations in working areas. Because of the higher biological effectiveness the limits for α particles are more stringent compared to those of β- and γ-ray emitters, usually by a factor of 10. Different countries have defined limits based on the guidelines as recommended by the International Commission on Radiological Protection. The table below gives some examples which have been adopted by the new German radiation-protection ordinance in 2001. The corresponding limits in other countries are quite similar.

radioisotope	**surface contamination in Bq/cm^2**
$^{3}_{1}$H, $^{7}_{4}$Be, $^{14}_{6}$C	100
$^{18}_{9}$F, $^{24}_{11}$Na, $^{38}_{17}$Cl	1
$^{54}_{25}$Mn, $^{60}_{27}$Co, $^{90}_{38}$Sr	1
$^{64}_{29}$Cu, $^{76}_{33}$As, $^{75}_{34}$Se	10
$^{99m}_{43}$Tc, $^{105}_{45}$Rh, $^{106}_{44}$Ru	10
$^{111}_{47}$Ag, $^{109}_{48}$Cd, $^{99}_{43}$Tc	100
$^{125}_{53}$I, $^{131}_{53}$I, $^{129}_{55}$Cs	10
$^{134}_{55}$Cs, $^{137}_{55}$Cs, $^{140}_{56}$Ba	1
$^{152}_{63}$Eu, $^{154}_{63}$Eu, $^{190}_{77}$Ir	1
$^{204}_{81}$Tl, $^{197}_{78}$Pt, $^{210}_{83}$Bi	100
$^{226}_{88}$Ra, $^{227}_{89}$Ac, $^{233}_{92}$U	1
$^{239}_{94}$Pu, $^{240}_{94}$Pu, $^{252}_{98}$Cf	0.1
$^{248}_{96}$Cm	0.01
β emitter or EC emitter[1] with $E_e^{\max} < 0.2\,\mathrm{MeV}$	100
β or γ emitter in general	1
α emitter or radioisotopes from spontaneous fission	0.1

In case of surface contaminations by different isotopes the following condition must be fulfilled:

$$\sum_{i=1}^{N} \frac{A_i}{A_i^{\max}} \leq 1 \ ,$$

where A_i are the observed surface contaminations and $A_i^{\max}$ the corresponding limits as given in the table.



[1] EC = electron capture

E Definition of Radiation Areas

The definition of radiation areas varies somewhat in different countries, see Chap. 6 on 'International Safety Standards for Radiation Protection'. In the following table the radiation areas according to the ICRP recommendations, adopted by many countries, are given.

<table>
<tr><th colspan="2">controlled area</th><th>surveyed area</th></tr>
<tr><td rowspan="3">exclusion area
> 3 mSv/h</td><td>6–20 mSv/yr</td><td>1–6 mSv/yr</td></tr>
<tr><td colspan="2">radiation-exposed workers (2000 h/yr)</td></tr>
<tr><td colspan="2">cat. A 6–20 mSv/yr
cat. B 1–6 mSv/yr</td></tr>
<tr><td colspan="3">neighborhood outside radiation areas
< 1 mSv/yr permanent residence</td></tr>
<tr><td colspan="3">limit for the general public
for discharges from nuclear facilities[1]
≤ 0.3 mSv/yr</td></tr>
</table>

[1] This limit relates to maximum permitted releases of activity concentrations from radiation facilities (nuclear power plants, recycling facilities) via air and water, which are limited to 0.3 mSv/yr for the general public.

F Radiation Weighting Factors w_R

The following radiation weighting factors w_R are almost generally accepted in all countries, see also Chap. 6.[1] In the early days of radiation protection the biological effect of radiation was taken care of by the so-called quality factors q (see also Chap. 2).

type of radiation and energy range	**radiation weighting factor w_R**
photons, all energies	1
electrons and muons, all energies	1
neutrons < 10 keV	5
10 keV–100 keV	10
> 100 keV–2 MeV	20
> 2 MeV–20 MeV	10
> 20 MeV	5
protons, except recoil protons, energy > 2 MeV	5
α particles, fission fragments, heavy nuclei	20

[1] The radiation weighting factors as adopted in the United States, which are somewhat different, are given in Table 6.1 on page 94.

G Tissue Weighting Factors w_T

The following tissue weighting factors w_T are almost generally accepted in all countries, see also Chaps. 2 and 6.[1]

organs or tissue	tissue weighting factor w_T
gonads	0.20
red bone marrow	0.12
large intestine	0.12
lung	0.12
stomach	0.12
bladder	0.05
chest	0.05
liver	0.05
esophagus	0.05
thyroid gland	0.05
skin	0.01
periosteum (bone surface)	0.01
other organs or tissue	0.05

[1] The tissue weighting factors as adopted in the United States, which are somewhat different, are given in Table 6.2 on page 94.

H Physical Constants

Constants, which are exact, are given with their precise values, if possible. They are characterized with an $*$. For experimental values only the significant decimals are given, i.e., the measurement error is less than the last decimal place.

quantity	symbol	value	unit
velocity of light*	c	299 792 458	m/s
Planck constant	h	$6.626\,07 \times 10^{-34}$	J s
electron charge magnitude	e	$1.602\,177 \times 10^{-19}$	C
electron mass	m_e	$9.109\,38 \times 10^{-31}$	kg
proton mass	m_p	$1.672\,62 \times 10^{-27}$	kg
α-particle mass	m_α	$6.644\,661\,8 \times 10^{-27}$	kg
unified atomic mass unit	m_u	$1.660\,54 \times 10^{-27}$	kg
electron–proton mass ratio	m_e/m_p	$5.446\,170\,21 \times 10^{-4}$	
permittivity of free space*	$\varepsilon_0 = 1/(\mu_0\, c^2)$	$8.854\,187\ldots \times 10^{-12}$	F/m
permeability of free space*	μ_0	$4\,\pi \times 10^{-7}$	$\mathrm{N/A^2}$
fine-structure constant	$\alpha = e^2/(4\,\pi\,\varepsilon_0\,\hbar\,c)$	1/137.035 999	
classical electron radius	$r_e = e^2/(4\,\pi\,\varepsilon_0\, m_e\, c^2)$	$2.817\,940 \times 10^{-15}$	m
Compton wavelength	$\lambda_\mathrm{C} = h/(m_e c)$	$2.426\,310\,2 \cdot 10^{-12}$	m
gravitational constant	γ	6.674×10^{-11}	$\mathrm{m^3/(kg\,s^2)}$
standard gravitational acceleration*	g	9.806 65	$\mathrm{m/s^2}$
Avogadro constant	N_A	$6.022\,14 \times 10^{23}$	$\mathrm{mol^{-1}}$
Boltzmann constant	k	$1.380\,65 \times 10^{-23}$	J/K
molar gas constant	$R\ (= N_\mathrm{A}\, k)$	8.3144	J/(K mol)
molar volume[1]	V_mole	22.414×10^{-3}	$\mathrm{m^3/mol}$
Rydberg energy	$E_\mathrm{Ry} = m_e c^2 \alpha^2/2$	13.6057	eV
Stefan–Boltzmann constant	$\sigma = \pi^2 k^4/(60\,\hbar^3 c^2)$	5.6704×10^{-8}	$\mathrm{W\,m^{-2}\,K^{-4}}$
Bohr radius	$a_0 = 4\pi\varepsilon_0\hbar^2/(m_e c^2)$	$0.529\,177\,21 \times 10^{-10}$	m
Faraday constant	$F = eN_\mathrm{A}$	96 485.309	C/mol
electron charge-to-mass ratio	e/m_e	$1.758\,820 \times 10^{11}$	C/kg

[1] at standard temperature and pressure ($T = 273.15\,\mathrm{K}$, $p = 101\,325\,\mathrm{Pa}$)

I Useful Conversions

quantity	conversion
force	$1\,\mathrm{N} = 1\,\mathrm{kg\,m/s^2}$
work, energy	$1\,\mathrm{eV} = 1.602\,177 \times 10^{-19}\,\mathrm{J}$
	$1\,\mathrm{cal} = 4.186\,\mathrm{J}$
	$1\,\mathrm{erg} = 10^{-7}\,\mathrm{J}$
	$1\,\mathrm{kWh} = 3.6 \times 10^{6}\,\mathrm{J}$
energy dose	$1\,\mathrm{Gy} = 100\,\mathrm{rad}$
	$1\,\mathrm{rad} = 10\,\mathrm{mGy}$
dose equivalent	$1\,\mathrm{Sv} = 100\,\mathrm{rem}$
	$1\,\mathrm{rem} = 10\,\mathrm{mSv}$
ion dose	$1\,\mathrm{R} = 258\,\mu\mathrm{C/kg}$
	$\widehat{=}\ 8.77 \times 10^{-3}\,\mathrm{Gy}$ (in air)
ion-dose rate	$1\,\mathrm{R/h} = 7.17 \times 10^{-8}\,\mathrm{A/kg}$
activity	$1\,\mathrm{Ci} = 3.7 \times 10^{10}\,\mathrm{Bq}$
	$1\,\mathrm{Bq} = 27.03\,\mathrm{pCi}$
pressure	$1\,\mathrm{bar} = 10^{5}\,\mathrm{Pa}$
	$1\,\mathrm{atm} = 1.013\,25 \times 10^{5}\,\mathrm{Pa}$
	$1\,\mathrm{Torr} = 1\,\mathrm{mm\ Hg}$
	$= 1.333\,224 \times 10^{2}\,\mathrm{Pa}$
	$1\,\mathrm{kp/m^2} = 9.806\,65\,\mathrm{Pa}$
charge	$1\,\mathrm{C} = 2.997\,924\,58 \times 10^{9}\,\mathrm{esu}$[1]
length	$1\,\mathrm{m} = 10^{10}\,\text{Å}$
temperature	$\theta\ [^\circ\mathrm{C}] = T\ [\mathrm{K}] - 273.15$
	$T\ [^\circ\text{Fahrenheit}] = 1.80\,\theta\ [^\circ\mathrm{C}] + 32$
	$= 1.80\,T\ [\mathrm{K}] - 459.67$
time	$1\,\mathrm{d} = 86\,400\,\mathrm{s}$
	$1\,\mathrm{yr} = 3.1536 \times 10^{7}\,\mathrm{s}$

[1] esu – electrostatic unit

J List of Abbreviations

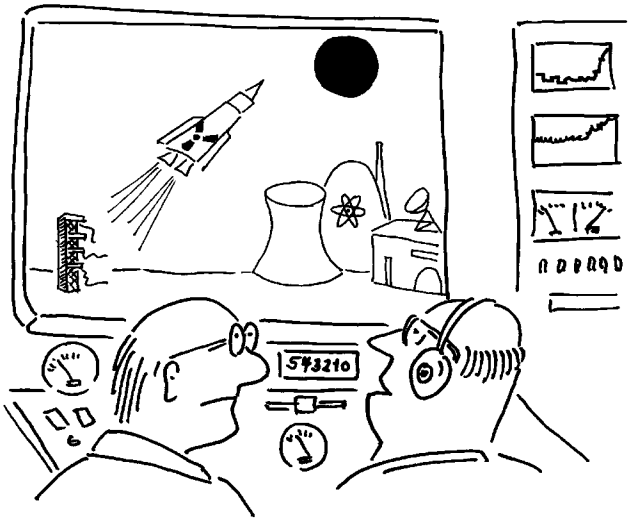
Å	–	angstrom (unit of length); $1\,\text{Å} = 10^{-10}\,\text{m}$
a	–	year (from the Latin word 'annus')
A	–	ampere
ACS	–	American Chemical Society
ADR	–	Accord européen relatif au transport international des marchandises dangereuses par la route (European agreement about the transport of dangerous goods via roads)
AERB	–	Atomic Energy Regulatory Board of India
AIDS	–	Acquired Immune Deficiency Syndrome
ALARA	–	as low as reasonably achievable
arctan	–	arc tangent (Latin: arcus tangens): inverse function of tangent (on pocket calculators usually denoted by $\tan^{-1}$)
ALI	–	Annual Limit on Intake
ANSTO	–	Australian Nuclear Science and Technology Organisation
ARPANS	–	Australian Radiation Protection and Nuclear Safety
atm	–	atmosphere (unit of pressure)
bar	–	unit of pressure, from the Greek $\beta\alpha\rho o\varsigma$, 'weight'
barn	–	unit of the (total) cross section ($= 10^{-24}\,\text{cm}^2$)
BF_3	–	boron trifluoride
BMU	–	federal ministry for environment in Germany (Bundesministerium für Umwelt)
Bq	–	becquerel
C	–	coulomb (unit of the electric charge)
cal	–	calory (unit of energy)
CASTOR	–	cask for storage and transport of radioactive material
CEDE	–	Committed Effective Dose Equivalent
CERN	–	Conseil Européenne pour la Recherche Nucléaire (European Center for Particle Physics in Geneva)
Ci	–	curie
CW lasers	–	Continuous-Wave lasers
d	–	day (from the Latin word 'dies')
DARI	–	Dose Annuelle due aux Radiations Internes (annual dose due to internal radiation from the body)
DF	–	decontamination factor
DIN	–	German institute for engineering standards (Deutsches Institut für Normung)
DIS dosimeter	–	Direct Ion Storage dosimeter

DNA	–	deoxyribonucleic acid
DTPA	–	diethylenetriamine pentaacetate
e	–	Eulerian number (e = 2.718 281 . . .)
EC	–	electron capture (mostly from the K shell)
EDTA	–	ethylenediamine tetraacetate
erg	–	unit of energy (1 g cm^2/s^2); from the Greek $\epsilon\rho\gamma o\nu$, 'work'
ERR	–	Excess Relative Risk
esu	–	unit of charge: electrostatic unit
EU	–	European Union
EURATOM	–	European Atomic Union
exp	–	short for the exponential function
eV	–	electron volt
F	–	farad (unit of capacitance)
FAO	–	Food and Agricultural Organization of the United Nations
FWHM	–	Full Width at Half Maximum
GBq	–	gigabecquerel
GeV	–	giga electron volt
GGVS	–	German ordinance for the transport of dangerous goods (Gefahrgut Verordnung Straße)
GM counter	–	Geiger–Müller counter
GSF	–	German research center for environment and health (Forschungszentrum für Umwelt und Gesundheit)
GSI	–	Gesellschaft für Schwerionenforschung, Darmstadt, Germany
Gy	–	gray
h	–	hour (from the Latin word 'hora')
hPa	–	hectopascal
HPGe detector	–	High Purity Germanium detector
HTR	–	high-temperature reactor
Hz	–	hertz (1/s)
IAD	–	inevitable annual dose
IAEA	–	International Atomic Energy Agency
IAEO	–	International Atomic Energy Organization
ICAO	–	International Civil Aviation Organization (Technical Instructions for Safe Transport of Dangerous Goods by Air)
ICNIRP	–	International Commission on Non-Ionizing Radiation Protection
ICRP	–	International Commission on Radiological Protection
ICRU	–	International Commission on Radiation Units and Measurements
ILO	–	International Labor Organization
IMDG	–	International Maritime Dangerous Goods code

ITER	–	International Thermonuclear Experimental Reactor
IUPAC	–	International Union for Pure and Applied Chemistry
IUPAP	–	International Union for Pure and Applied Physics
J	–	joule (unit of energy; 1 J = 10^7 erg)
JAZ	–	annual intake (from the German 'Jahresaktivitätszufuhr')
JET	–	Joint European Torus
K	–	kelvin (absolute temperature)
kBq	–	kilobecquerel
kerma	–	kinetic energy released per unit mass (also: kinetic energy released in matter (or material))
keV	–	kilo electron volt
kHz	–	kilohertz (or kilocycle)
kJ	–	kilojoule
kp	–	kilopond
kT	–	kiloton (explosive)
kV	–	kilovolt
LASER	–	Light Amplification by Stimulated Emission of Radiation
LD	–	lethal dose
LEP	–	Large Electron–Positron collider at CERN
LET	–	Linear Energy Transfer
LINAC	–	linear accelerator
ln	–	logarithmus naturalis (natural logarithm)
LNT	–	Linear No-Threshold hypothesis
mA	–	milliampere
MBq	–	megabecquerel
µC	–	microcoulomb
mCi	–	millicurie
µCi	–	microcurie
meV	–	milli electron volt
MeV	–	mega electron volt
mGy	–	milligray
µGy	–	microgray
mK	–	millikelvin
µK	–	microkelvin
mole	–	amount of material which contains 6.022×10^{23} molecules/atoms (= Avogadro number)
MOSFET	–	Metal Oxide Field Effect Transistor
MOX	–	Mixture of Oxides

mrem	–	millirem
MRT	–	Microbeam Radiation Therapy
mSv	–	millisievert
µSv	–	microsievert
mV	–	millivolt
MW	–	megawatt
N	–	newton (unit of force)
NASA	–	National Aeronautics and Space Administration
NEA	–	Nuclear Energy Agency
NIR	–	Non-Ionizing Radiation
NPL	–	National Physical Laboratory
nSv	–	nanosievert
OECD	–	Organization for Economic Cooperation and Development
Ω	–	ohm
Pa	–	pascal (unit of pressure)
PBD	–	2-(4-tert.-butylene-phenyl)- 5-(4-biphenyl-1,3,4-oxadiazole)
pCi	–	picocurie
PET	–	Positron-Emission Tomography
pF	–	picofarad (10^{-12} F)
PIPS detector	–	Passive Implanted Planar Silicon detector
PM	–	photomultiplier
PMMA	–	polymethyl methacrylate
ppm	–	parts per million (10^{-6})
PTB	–	German national physical laboratory for weights and measures (Physikalisch–Technische Bundesanstalt in Braunschweig, equivalent to the British NPL)
R	–	roentgen
rad	–	radiation absorbed dose
rad	–	radian (unit of angle, the full radian is 2π)
Radar	–	Radio Detecting and Ranging
rem	–	roentgen equivalent man
RBE	–	relative biological effectiveness
RID	–	règlement international concernant le transport des marchandises dangereuses provision about the transport of dangerous goods
RNA	–	ribonucleic acid
RTG	–	Radioisotope Thermoelectric Generator
SAR	–	specific absorption rate

steradian	–	unit of solid angle; the full solid angle corresponds to the surface of the unit sphere: $4\,\pi$
StrlSchV	–	Strahlenschutzverordnung (German radiation-protection ordinance)
Sv	–	sievert
TeV	–	tera electron volt
TLD	–	thermoluminescence dosimeter
TNT	–	trinitrotoluol (explosive)
Torr	–	torricelli (unit of pressure, mm column of mercury)
UMTS	–	Universal Mobile Telecommunications System
UN	–	United Nations
UNSCEAR	–	United Nations Scientific Committee on the Effects of Atomic Radiation
UV	–	ultraviolet
UVA	–	ultraviolet type A radiation, wavelength 400–315 nm
UVB	–	ultraviolet type B radiation, wavelength 315–280 nm
UVC	–	ultraviolet type C radiation, wavelength 280–100 nm
V	–	volt
VDI	–	Verein Deutscher Ingenieure (association of German engineers)
WHO	–	World Health Organization
W	–	watt (unit of power),
W s		watt second (unit of energy)



"The perfect final deposit: A Black Hole!"

K List of Elements*

1 H hydrogen (Greek: $\upsilon\delta\omega\rho$, hydor, water + $\gamma\epsilon\iota\nu o\mu\alpha\iota$, geinomai, to engender; Latin: hydrogenium);
D = $^{2}_{1}$H deuterium (Greek: $\delta\epsilon\upsilon\tau\epsilon\rho o\varsigma$, deuteros, second) and T = $^{3}_{1}$H tritium (Greek: $\tau\rho\iota\tau o\varsigma$ tritos, third) are isotopes of hydrogen

2 He helium (Greek: $\eta\lambda\iota o\varsigma$, helios, sun)

3 Li lithium (Greek: $\lambda\iota\theta o\varsigma$, lithos, stone, rock)

4 Be beryllium (Greek: $\beta\eta\rho\upsilon\lambda\lambda o\varsigma$, beryllos, beryl)

5 B boron (Latin: boracium; Arabic: borax)

6 C carbon (Latin: carbo, coal; French: charbon, charcoal)

7 N nitrogen (Greek: $\nu\iota\tau\rho o\nu$, nitron + $\gamma\epsilon\iota\nu o\mu\alpha\iota$, geinomai, to engender, soda forming; Latin: nitrogenium)

8 O oxygen (Greek: $o\xi\upsilon\varsigma$, oxys, acid + $\gamma\epsilon\iota\nu o\mu\alpha\iota$, geinomai, to engender, acid forming; Latin: oxygenium)

9 F fluorine (Latin: fluere, to flow, to stream)

10 Ne neon (Greek: $\nu\epsilon o\varsigma$, neos, new, young)

11 Na sodium (Latin: sodanum; Hebrew: neter, soda; German: Natrium; from the Arabic word 'natrun' = soda)

12 Mg magnesium (Greek: $M\alpha\gamma\nu\eta\sigma\iota\alpha$, Magnesia (district in the Greek town Thessaly))

13 Al aluminum (Latin: alumen, a bitter salt)

14 Si silicon (Latin: silex, flint)

15 P phosphorus (Greek: $\phi\omega\sigma\phi o\rho o\varsigma$, phosphoros, light bearing, luminous)

16 S sulphur (Latin: sulfur)

17 Cl chlorine (Greek: $\chi\lambda\omega\rho o\varsigma$, chloros, light green, green-yellow)

18 Ar argon (Greek: $\alpha\rho\gamma o\nu$, argon, inactive, idle)

19 K potassium (German: Kalium from the Arabic word al-qali = ash or English: potash)

20 Ca calcium (Latin: calx, limestone)

21 Sc scandium (Latin: from Scandinavia)

22 Ti titanium (Greek: $\tau\iota\tau\alpha\nu o\varsigma$, Titans, children of the Earth)

23 V vanadium (Vanadis, Scandinavian goddess of beauty)

24 Cr chromium, (Greek: $\chi\rho\tilde{\omega}\mu\alpha$, chroma, color)

25 Mn manganese, (Greek: $M\alpha\gamma\nu\eta\sigma\iota\alpha$, Magnesia (district in the Greek town Thessaly); Latin: magnes, magnet)

26 Fe iron (Latin: ferrum)

27 Co cobalt (German: Kobold, goblin, evil spirit)

28 Ni nickel (German: Kupfernickel = devil's copper)

29 Cu copper (Greek: $\kappa\upsilon\pi\rho\iota o\varsigma$, kuprios; Latin: cuprum; metal from the island of Cyprus)

30 Zn zinc (German: Zink, sharp point)

31 Ga gallium (Latin: Gallia, France)

32 Ge germanium (Latin: Germania, Germany)

33 As arsenic (Arabic: al-zarnikh, gold-colored)

34 Se selenium (Greek: $\sigma\epsilon\lambda\eta\nu\eta$, selene, moon)

35 Br bromine (Greek: $\beta\rho o\mu o\varsigma$, bromos, stench)

36 Kr krypton (Greek: $\kappa\rho\upsilon\pi\tau o\varsigma$, kryptos, hidden)

37 Rb rubidium (Latin: rubidus, deep red)

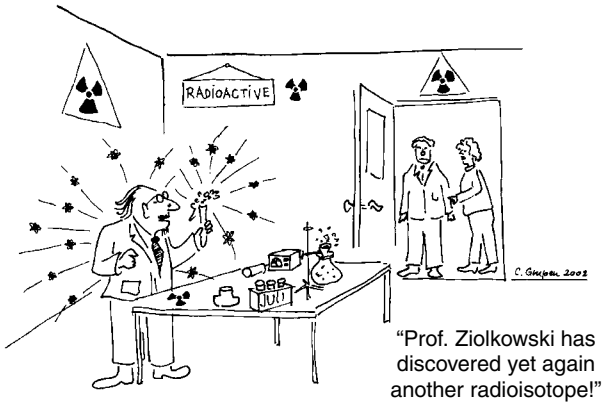
38 Sr strontium (Strontian, village in Scotland)

39 Y yttrium (after the Swedish village Ytterby)

* see also `www.periodensystem.info/periodensystem.htm`
resp. `www.webelements.com/`
or `http://elements.vanderkrogt.net/elem/`

40 Zr zirconium (Persian: zargûn, gold color)
41 Nb niobium ($Νιοβη$, Niobe, daughter of Tantalus)
42 Mo molybdenum (Greek: $μολυβδος$, molybdos, lead ore)
43 Tc technetium (Greek: $τεχνητος$, technetos, artificial)
44 Ru ruthenium (Latin: Ruthenia = Ukraine, sometimes Russia is meant)
45 Rh rhodium (Greek: $ροδον$, rodon, rose)
46 Pd palladium (Greek: named after Pallas Athene, the Greek goddess of wisdom) $Παλλας\ Αθηνη$
47 Ag silver (Latin: argentum)
48 Cd cadmium (named after 'Kadmos', the founder of the Egyptian city of Thebes).
49 In indium (named after the indigo blue spectral color)
50 Sn tin (Latin: stannum or Indo-European: stag, dripping)
51 Sb antimonium (Latin: stibium or Greek: $στιβι$, stibi, cosmetic powder)
52 Te tellurium (Latin: tellus, earth, ground)
53 I iodine (Greek: $ιοειδης$, ioeides, violet color)
54 Xe xenon (Greek: $ξενος$, xenos, strange)
55 Cs cesium (Latin: caesius = bluish gray)
56 Ba barium (Greek: $βαρυς$, barys, heavy)
57 La lanthanum (Greek: $λανθανω$, lanthano, to lie hidden)
58 Ce cerium (Ceres, asteroid discovered in 1801)
59 Pr praseodymium (Greek: $πρασιος$ + $διδυμος$, prasios + didymos, green and twins)
60 Nd neodymium (Greek: $νεος$ + $διδυμος$, neos + didymos, new and twins)
61 Pm promethium (Greek: $Προμηθευς$, named after Prometheus)
62 Sm samarium (samarskite, mineral named after V.E. Samarskij-Byhovec)
63 Eu europium (Latin: Europa, Europe)
64 Gd gadolinium (gadolinite, mineral named after Johan Gadolin)
65 Tb terbium (named after the Swedish village Ytterby)
66 Dy dysprosium (Greek: $δυσπροσιτος$, dysprositos, hard to obtain)
67 Ho holmium (Latin: Holmia = Stockholm)
68 Er erbium (named after the Swedish village Ytterby)
69 Tm thulium (Latin: Thule in Scandinavia)
70 Yb ytterbium (named after the Swedish village Ytterby)
71 Lu lutetium (after the Roman name of Paris: Lutetia Parisorum)
72 Hf hafnium (Latin: Hafnia = København, Copenhagen)
73 Ta tantalum (Greek: $Ταντα λος$, Tantalos, figure in Greek mythology)
74 W tungsten (Swedish: Tung Sten, heavy stone; Wolfram: mineral wolframite, from 'Wolf Rahm' (German for wolf's foam))
75 Re rhenium (Latin: Rhenus, Rhine)
76 Os osmium (Greek: $οσμη$, osme, stench)
77 Ir iridium (Greek: $Ιρις$, Greek goddess of the rainbow)
78 Pt platinum (Spanish: platina (del Pinto) = small silver (beads) of the river Pinto)
79 Au gold (Latin: aurum)
80 Hg mercury (Greek: $υδραργυρος$, hydrargyros, liquid silver; Latin: hydrargyrum)
81 Tl thallium (Greek: $θαλλος$, thallos, green shot)
82 Pb lead (Latin: plumbum)
83 Bi bismuth (Latin: bisemutum; German: Weisse Masse, white substance)
84 Po polonium (Latin: Polonia = Polska, Poland)
85 At astatine (Greek: $αστατος$, astatos, unstable)
86 Rn radon (Latin: nitens, shining; named after the element radium, changed to radon to match the endings of most other noble gases)
87 Fr francium (Latin: named after France)
88 Ra radium (Latin: radius, ray)
89 Ac actinium (Greek: $ακτις$, aktis, ray)

90 Th thorium (Thor, Scandinavian god of war)
91 Pa protactinium (Greek: $\pi\rho\omega\tau o\varsigma$ + actinium, first element after actinium in the uranium–actinium decay series)
92 U uranium (named after the planet Uranus)
93 Np neptunium (named after the planet Neptun)
94 Pu plutonium (named after the dwarf planet Pluto ($\Pi\lambda o\upsilon\tau\omega\nu$, Plouton), the Greek god of the underworld)
95 Am americium (Latin: America)
96 Cm curium (named after Marie Curie)
97 Bk berkelium (Berkeley, town in California)
98 Cf californium (California, state of the USA)
99 Es einsteinium (named after Albert Einstein)
100 Fm fermium (named after Enrico Fermi)
101 Md mendelevium (named after Dmitri I. Mendeleyev)
102 No nobelium (named after Alfred Nobel)
103 Lr lawrencium (named after Ernest O. Lawrence)
104 Rf rutherfordium (named after Ernest Rutherford)
105 Db dubnium (named after Dubna, a town in the Moscow region)
106 Sg seaborgium (named after Glenn T. Seaborg)
107 Bh bohrium (named after Niels Bohr)
108 Hs hassium (named after the German state Hassia, Hessen)
109 Mt meitnerium (named after Lise Meitner)
110 Ds darmstadtium (named after Darmstadt, a town in Germany)
111 Rg roentgenium (named after Wilhelm Conrad Röntgen)
112 Cn copernicium (named after Nicolaus Copernicus)
113 †
114 †
115 †
116 †
118 †



"Prof. Ziolkowski has discovered yet again another radioisotope!"

† $Z = 113, 114, 115, 116, 118$: Lawrence Livermore–Dubna Colaboration, Russia, and Berkeley, USA

L Decay Chains

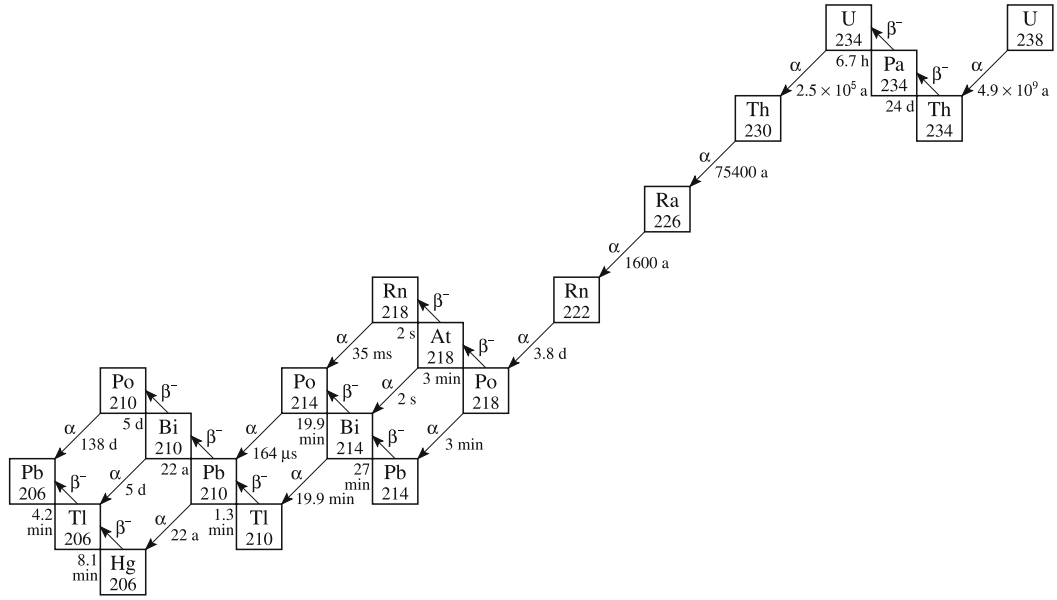


Figure L.1
Uranium (^{238}U) decay chain
(a = annus, year)

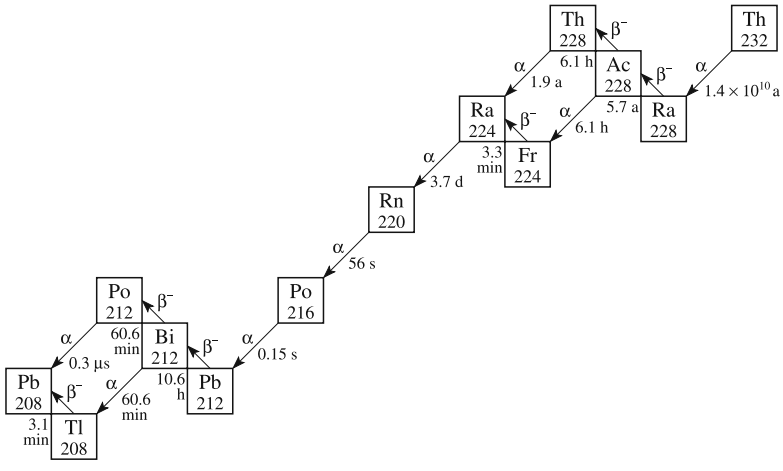


Figure L.2
Thorium (^{232}Th) decay chain
(a = annus, year)

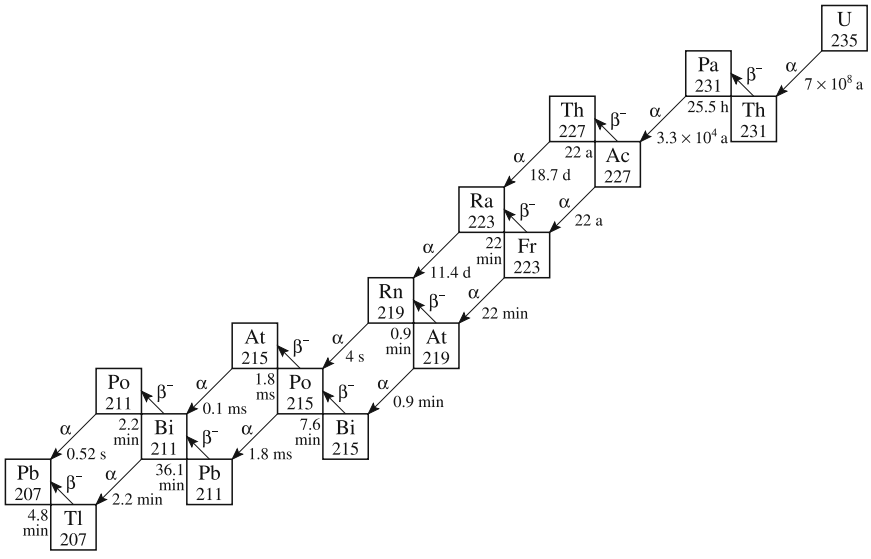


Figure L.3
Actinium (^{235}U) decay chain
(a = annus, year)

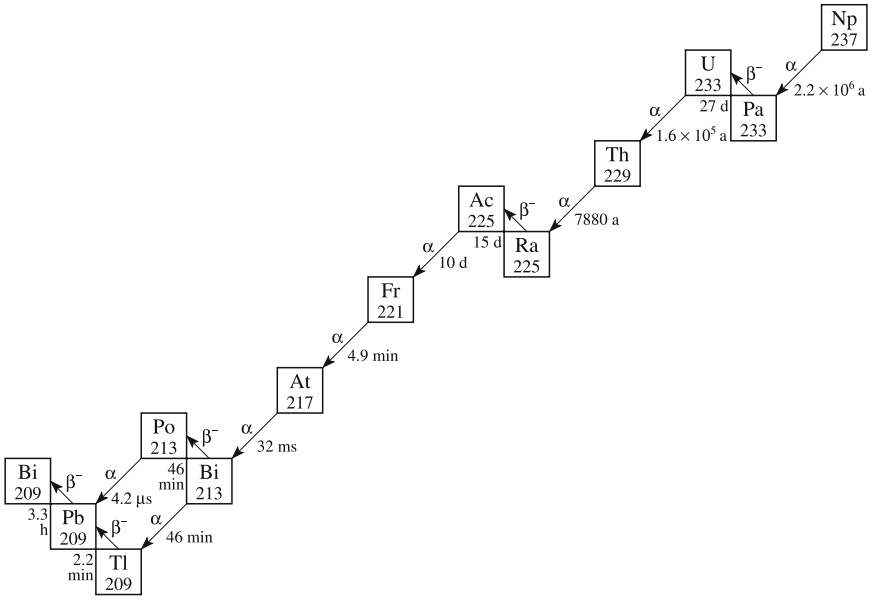


Figure L.4
Neptunium (^{237}Np) decay chain
(a = annus, year)

M List of Isotopes Frequently Used in Nuclear Medicine and Radiology

isotope	half-life	decay	main energy	application
protons	stable		≈ 200 MeV	particle therapy
^{3}H	12.3 yrs	β^-, no γ	0.02 MeV	total body water content determination
^{11}B	stable			melanoma and brain tumor treatment
^{11}C	20.4 min	β^+, no γ	1.0 MeV	Positron-Emission Tomography; PET scans
^{12}C	stable		≈ 300 MeV per nucleon	particle therapy
^{14}C	5730 yrs	β^-, no γ	0.2 MeV	e.g. pancreatic studies
^{13}N	10 min	β^+, no γ	1.2 MeV	Positron-Emission Tomography; PET scans
^{15}O	2 min	β^+, no γ	1.7 MeV	Positron-Emission Tomography; PET scans
^{18}F	110 min	β^+, no γ	0.6 MeV	Positron-Emission Tomography; PET scans
^{22}Na	2.6 yrs	β^+ γ	0.5 MeV ... 1275 keV	electrolyte studies
^{24}Na	15 h	β^- γ	1.4 MeV ... 2754 keV ...	studies of electrolytes within the body
^{32}P	14.3 d	β^-, no γ	1.7 MeV	treatment against excess of red blood cells
^{42}K	12.4 h	β^- γ	3.5 MeV 1525 keV ...	for measurement of coronary blood flow
^{47}Ca	4.5 d	β^- γ	0.7 MeV... 1297 keV ...	bone metabolism
^{51}Cr	27.7 d	γ EC	320 keV	labeling of red blood cells
^{59}Fe	44.5 d	β^- γ	0.5 MeV ... 1099 keV ...	metabolism in the spleen
^{57}Co	272 d	γ EC	122 keV...	marker to estimate organ size

isotope	half-life	decay	main energy	application
^{58}Co	71 d	β^+ γ EC	0.5 MeV ... 811 keV	gastrointestinal absorption
^{60m}Co	10.5 min	γ	59 keV	external beam radiotherapy
^{60}Co	5.3 yrs	β^- γ γ	0.3 MeV ... 1173 keV 1332 keV	tumor treatment
^{62}Cu	9.7 min	β^+ γ	2.9 MeV ... 1173 keV ...	positron-emitting radionuclide for PET
^{64}Cu	12.7 h	β^- β^+ γ EC	0.6 MeV 0.7 MeV 1346 keV	study of genetic of diseases
^{67}Cu	61.9 h	β^- γ	0.4 MeV ... 185 keV ...	radioimmunotherapy
^{64}Ga	2.6 min	β^+ γ	2.9 MeV ... 992 keV ...	treatment of pulmonary diseases
^{67}Ga	78.3 h	γ EC, no β^+	93 keV ...	tumor imaging
^{68}Ga	67.6 min	β^+ γ	1.9 MeV ... 1077 keV ...	study thrombosis and atherosclerosis detection of pancreatic cancer
^{68}Ge	271 d	no β^+, no γ, EC		PET imaging
^{72}As	26 h	β^+ γ	2.5 MeV ... 834 keV ...	planar imaging, SPECT, or PET
^{75}Se	120 d	γ EC	265 keV ...	radiotracer used in brain studies scintigraphy scanning study of the production of digestive enzymes
^{81m}Kr from ^{81}Rb	13 s	γ EC	190 keV	pulmonary ventilation
^{82}Rb from ^{82}Sr	6.3 h	β^+ γ	0.8 MeV ... 776 keV ...	PET agent in myocardial perfusion imaging
^{89}Sr	50.5 d	β^- γ	1.5 MeV ... 909 keV	reducing the pain due to prostate and bone cancer
^{90}Y	64.1 h	β^- γ	2.3 MeV ... 2186 keV ...	cancer brachytherapy

isotope	half-life	decay	main energy	application
^{99}Mo	66 h	β^- γ	1.2 MeV ... 740 keV ...	parent of ^{99m}Tc
^{99m}Tc	6 h	γ	141 keV ...	skeleton, heart muscle, brain, thyroid, lungs, liver, spleen, kidney, gall bladder, bone marrow, salivary, and lacrimal glands
^{103}Ru	39.4 d	β^- γ	0.2 MeV ... 497 keV ...	myocardial blood flow
^{103}Pd	17 d	γ EC	357 keV ...	brachytherapy for early prostate cancer
^{109}Cd	463 d	no γ, EC		cancer detection, pediatric imaging
^{111}In	2.8 d	γ EC, no β^+	245 keV ...	brain studies
^{117m}Sn	13.6 d	γ	159 keV ...	bone cancer pain relief
^{122}I	3.6 min	β^+ γ	3.1 MeV ... 564 keV ...	brain blood flow studies
^{123}I	13.2 h	γ EC, no β^+	159 keV ...	diagnosis of the thyroid function
^{125}I	59.4 d	γ EC	35 keV	cancer brachytherapy (prostate and brain) filtration rate of kidneys
^{131}I	8.0 d	β^- γ	0.6 MeV ... 364 keV ...	treatment of thyroid cancer with beta therapy
^{132}I	2.3 h	β^- γ	2.1 MeV ... 668 keV ...	marking of red blood cells
^{130}Cs	29.2 min	β^+ β^- γ EC	2.0 MeV ... 0.4 MeV 536 keV	myocardial localizing agent
^{127}Xe	36.4 d	γ EC	203 keV ...	neuroimaging for brain disorders
^{133}Xe	5.3 d	β^- γ	0.3 MeV ... 81 keV ...	lung ventilation studies
^{137}Cs	30.2 yrs	β^- γ	0.5 MeV ... 662 keV ...	brachytherapy
^{141}Ce	32.5 d	β^- γ	0.4 MeV ... 145 keV	gastrointestinal tract diagnosis

isotope	half-life	decay	main energy	application
^{153}Sm	46.3 h	β^-	0.7 MeV ...	prostate and breast cancer
		γ	103 keV ...	relieving pain of secondary cancers
^{155}Eu	4.8 yrs	β^-	0.17 MeV ...	osteoporosis detection
		γ	87 keV ...	
^{165}Dy	2.4 h	β^-	1.3 MeV ...	treatment of arthritis
		γ	95 keV ...	
^{166}Ho	26.8 h	β^-	1.9 MeV ...	treatment of liver tumors
		γ	81 keV ...	
^{169}Er	9.4 d	β^-	0.3 MeV ...	for relieving arthritis
		γ	110 keV ...	
^{170}Tm	129 d	β^-	1.0 MeV ...	portable blood irradiations for leukemia
		γ	84 keV ...	
^{169}Yb	32 d	γ	63 keV ...	cerebrospinal fluid studies in the brain
		EC		
^{177}Lu	6.7 d	β^-	0.5 MeV ...	β radiation for small tumors
		γ	208 keV ...	γ rays for imaging
^{178}Ta	9.3 min	β^+	0.9 MeV	viewing of heart and blood vessels
		γ	93 keV ...	
		EC		
^{182}Ta	115 d	β^-	0.5 MeV ...	bladder cancer treatment
		γ	68 keV ...	
^{186}Re	3.7 d	β^-	1.1 MeV ...	for pain relief in bone cancer
		γ	137 keV ...	for imaging
		EC		
^{188}Re	17 h	β^-	2.1 MeV ...	β irradiation of coronary arteries
		γ	155 keV ...	
^{191m}Ir	5 s	γ	129 keV ...	cardiovascular angiography
^{192}Ir	74 d	β^-	0.7 MeV ...	cancer brachytherapy
		γ	317 keV ...	source supplied
		EC		in wire form
^{198}Au	2.7 d	β^-	1.0 MeV ...	brachytherapy and liver treatment
		γ	412 keV ...	
^{201}Tl	73.1 h	γ	167 keV ...	diagnosis of coronary artery disease
		EC		
^{213}Bi	45.6 min	α	5.87 MeV ...	
		β^-	1.4 MeV ...	Targeted Alpha Therapy (TAT)
		γ	440 keV ...	

isotope	half-life	decay	main energy	application
^{226}Ra	1600 yrs	α γ	4.78 MeV . . . 186 keV . . .	brachytherapy
^{238}Pu	87.7 yrs	α γ sf	5.50 MeV . . . 43 keV . . .	pacemaker (no ^{236}Pu contaminants)
^{241}Am	432 yrs	α γ sf	5.49 MeV . . . 60 keV . . .	osteoporosis detection, heart imaging
^{252}Cf	2.6 yrs	α γ sf	6.12 MeV . . . 43 keV . . .	brain cancer treatment

Abbreviations

PET – Positron-Emission Tomography
SPECT – Single Photon Emission Computed Tomography
TAT – Targeted Alpha Therapy
EC – electron capture
sf – spontaneous fission

all γ energies are given in keV
for β decays the endpoint energies (i.e. the maximum energies) are given
for α decays the discrete energies are given

References:

Radioisotopes in Medicine: www.world-nuclear.org/info/inf55.htm,
www.expresspharmaonline.com/20050331/radiopharmaceuticals01.shtml,
www.radiochemistry.org/nuclearmedicine/frames/medical_radioisotopes/index.html

N Critical Organs for Various Radioisotopes

isotope	physical half-life	effective half-life	emitter	critical organ
^{3}H	12.3 yrs	10 d	β^-	whole body
^{7}Be	53.3 d	53.3 d	γ, EC	whole body, bones
^{10}Be	1.6×10^6 yrs	4 yrs	β^-	whole body
^{14}C	5730 yrs	40 d	β^-	whole body
^{16}N	7.1 s	7.1 s	β^-, γ	lung
^{18}F	110 min	110 min	β^+	skeleton
^{22}Na	2.6 yrs	11 d	β^+, γ	whole body
^{24}Na	15 h	14 h	β^-, γ	gastrointestinal tract
^{32}Si	172 yrs	100 d	β^-	whole body
^{32}P	14.3 d	14.1 d	β^-	bones
^{33}P	25.3 d	25.3 d	β^-	bones
^{35}S	87.5 d	44 d	β^-	whole body
^{36}Cl	3×10^5 yrs	30 d	β^-	whole body
^{39}Ar	269 yrs	5 min	β^-	lung
^{40}K	1.28×10^9 yrs	30 d	β^+, β^-, γ	whole body
^{45}Ca	163 d	163 d	β^-, γ	bones
^{47}Ca	4.5 d	4.5 d	β^-, γ	bones
^{51}Cr	27.7 d	22.8 d	γ, EC	lung, gastrointestinal tract
^{54}Mn	312 d	88.5 d 23 d	γ, EC	lung liver
^{55}Fe	2.7 yrs	1.1 yrs	EC	spleen
^{59}Fe	44.5 d	41.9 d	β^-, γ	spleen
^{60}Co	5.3 yrs	117 d	β^-, γ	lung

isotope	physical half-life	effective half-life	emitter	critical organ
^{63}Ni	100 yrs	variable	β^-	whole body
^{64}Cu	12.7 h	12 h	β^+, β^-, γ, EC	whole body
^{65}Zn	245 d	194 d 81 d	β^+, γ, EC	whole body lung
^{75}Se	120 d	61 d 10 d	γ, EC	lung kidney
^{82}Br	35.3 h	30.5 h	β^-, γ	whole body
^{81m}Kr	13.1 s	13 s	γ, EC	lung
^{85}Kr	10.7 yrs	5 min	β^-, γ	whole body
^{86}Rb	18.7 d	13 d	β^-, γ, EC	whole body, pancreas, liver
^{87}Rb	4.8×10^{10} yrs	44 d	β^-, γ, EC	whole body, pancreas, liver
^{85}Sr	65 d	65 d	γ, EC	bones
^{89}Sr	50.5 d	50.5 d	β^-, γ	bones
^{90}Sr	28.6 yrs	18 yrs	β^-	bones
^{90}Y	64.1 h	30 h	β^-, γ	gastrointestinal tract
^{91}Y	58.5 d	58 h	β^-, γ	bones, liver
^{95}Zr	64.0 d	64 d	β^-, γ	bones
^{99}Mo	66.0 h	65 h	β^-, γ	bones, liver
^{99m}Tc	6 h	4 h	γ	thyroid, gastrointestinal tract
^{103}Ru	39.4 d	35 d	β^-, γ	lung, whole body
^{105}Ru	4.4 d	4 d	β^-, γ	lung, whole body
^{106}Ru	373.6 d	35 d	β^-	lung, whole body
^{110m}Ag	250 d	50 d	β^-, γ	liver
^{109}Cd	463 d	463 d	EC	kidney
^{111}In	2.8 d	2.8 d	γ, EC	bone marrow, liver
^{113m}In	99.5 min	96.6 min	γ	kidney, gastrointestinal tract
^{125}Sb	2.8 yrs	5 d	β^-, γ	bones, liver
^{129m}Te	33.6 d	20 d	β^-, γ	bones, kidney
^{132}Te	76.3 h	24 h	β^-, γ	bones, kidney
^{123}I	13.2 h	13 h	γ, EC	thyroid
^{125}I	59.4 d	41.8 d	γ, EC	thyroid

isotope	physical half-life	effective half-life	emitter	critical organ
^{129}I	1.6×10^7 yrs	80 d	β^-, γ	thyroid
^{131}I	8.0 d	7.6 d	β^-, γ	thyroid
^{132}I	2.3 h	2 h	β^-, γ	thyroid
^{133}I	20.8 h	20 h	β^-, γ	thyroid
^{134}I	52 min	52 min	β^-, γ	thyroid
^{135}I	6.6 h	6 h	β^-, γ	thyroid
^{133}Xe	5.3 d	5 min	β^-, γ	whole body
^{134}Cs	2.1 yrs	120 d	β^+, β^-, γ	muscles, whole body
^{136}Cs	13.2 d	13 d	β^-, γ	muscles, whole body
^{137}Cs	30.2 yrs	110 d	β^-, γ	muscles, whole body
^{140}Ba	12.8 d	10.7 d	β^-, γ	gastrointestinal tract
^{138} La	1.1×10^{11} yrs	10 yrs	β^-, γ, EC	liver, bones
^{141}Ce	32.5 d	32 d	β^-, γ	bones, liver
^{144}Ce	284.8 d	280 d	β^-, γ	bones, liver
^{147}Pm	2.6 yrs	2.4 yrs	β^-, γ	bones, liver
^{147}Sm	1.1×10^{11} yrs	10 yrs	α	liver, bones
^{176}Lu	3.8×10^{10} yrs	10 yrs	β^-, γ	bones
^{186}Re	89.3 h	48 h	β^-, γ, EC	muscle tissue
^{187}Re	5×10^{10} yrs	2 d	β^-	muscle tissue
^{198}Au	2.7 d	1 d	β^-, γ	kidney, gastrointestinal tract
^{203}Hg	46.6 d	11 d	β^-, γ	kidney
^{201}Tl	73.1 h	72 h	γ, EC	whole body
^{202}Tl	12.2 d	10 d	γ, EC	whole body
^{208}Tl	3.1 min	3 min	β^-, γ	whole body
^{210}Pb	22.3 yrs	1.2 yrs 6.8 yrs	β^-, γ	kidney bones
^{212}Pb	10.6 h	10 h	β^-, γ	bones, liver
^{212}Bi	60.6 min	60 min	α, β^-, γ	kidney
^{214}Bi	19.9 min	19 min	α, β^-, γ	kidney
^{210}Po	138.4 d	31.7 d 66.7 d	α, γ	kidney lung

isotope	physical half-life	effective half-life	emitter	critical organ
^{220}Rn	55.6 s	55 s	α, γ	lung
^{222}Rn	3.8 d	5 min	α, γ	lung
^{224}Ra	3.7 d	3.7 d	α, γ	bones, bone marrow, lung
^{226}Ra	1600 yrs	41 yrs	α, γ	bones, bone marrow, lung
^{228}Ra	5.8 yrs	5.7 yrs	β^-, γ	bones, bone marrow, lung
^{227}Ac	21.8 yrs	21 yrs	α, β^-, γ	bones, liver
^{228}Ac	6.1 h	6 h	α, β^-, γ	bones, liver
^{228}Th	1.9 yrs	1.9 yrs	α, γ	lung, periosteum (bone surface)
^{230}Th	7.5×10^4 yrs	25 yrs	α, γ	lung, periosteum (bone surface)
^{232}Th	1.4×10^{10} yrs	25 yrs	α, γ	lung, bones
^{234}Th	24.1 d	24 d	β^-, γ	lung, periosteum (bone surface)
^{231}Pa	3.3×10^4 yrs	10 yrs	α, γ	bones
^{233}U	1.6×10^5 yrs	variable, $\leq$ 14 yrs	α, γ	bones, lung, kidney
^{234}U	2.5×10^5 yrs	variable, $\leq$ 14 yrs	α, γ, sf	bones, lung, kidney
^{235}U	7×10^8 yrs	variable, $\leq$ 14 yrs	α, γ, sf	bones, lung, kidney
^{238}U	4.5×10^9 yrs	variable, $\leq$ 14 yrs	α, γ, sf	bones, lung, kidney
^{237}Np	2.1×10^6 yrs	variable	α, γ, sf	bones, liver
^{238}Pu	87.7 yrs	46.2 yrs	α, γ, sf	periosteum (bone surface) liver, lung, blood
^{239}Pu	24110 yrs	100 yrs	α, γ, sf	periosteum (bone surface) liver, lung, blood
^{240}Pu	6563 yrs	100 yrs	α, γ, sf	periosteum (bone surface) liver, lung, blood
^{242}Pu	3.8×10^5 yrs	100 yrs	α, γ, sf	periosteum (bone surface) liver, lung, blood
^{241}Am	432 yrs	84 yrs	α, γ, sf	bones
^{242}Cm	163 d	162 d	α, γ, sf	bones, liver, lung
^{243}Cm	29.1 yrs	15 yrs	α, γ, sf	bones, liver, lung
^{244}Cm	18.1 yrs	15 yrs	α, γ, sf	bones, liver, lung
^{249}Bk	320 d	316 d	α, β^-, γ, sf	bones
^{252}Cf	2.6 yrs	2.5 yrs	α, γ, sf	bones
^{253}Es	20.5 d	20.5 d	α, γ, sf	bones

Abbreviations

sf – spontaneous fission
EC – electron capture

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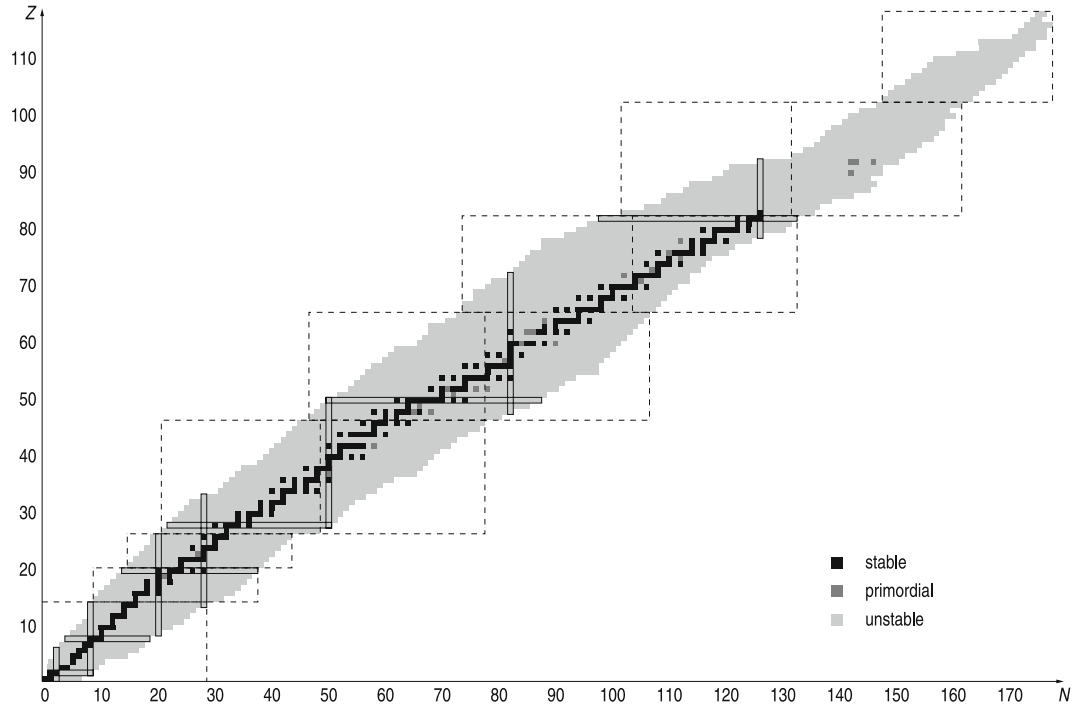
It has to be mentioned that the values for the effective half-life differ in various publications. Also, the effective half-life varies for different organs and tissues. Therefore the quoted figures just give a rough idea for the effective half-life.

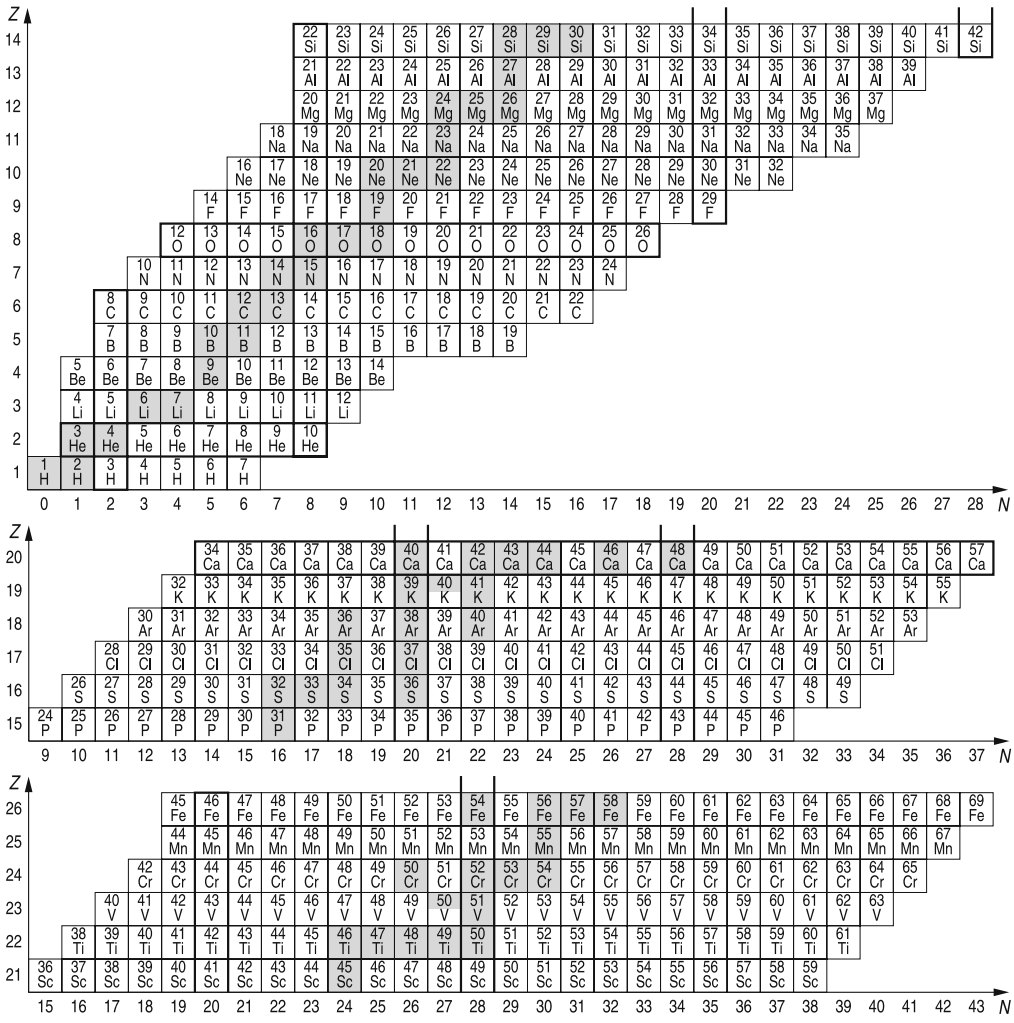
O Simplified Table of Isotopes and Periodic Table of Elements

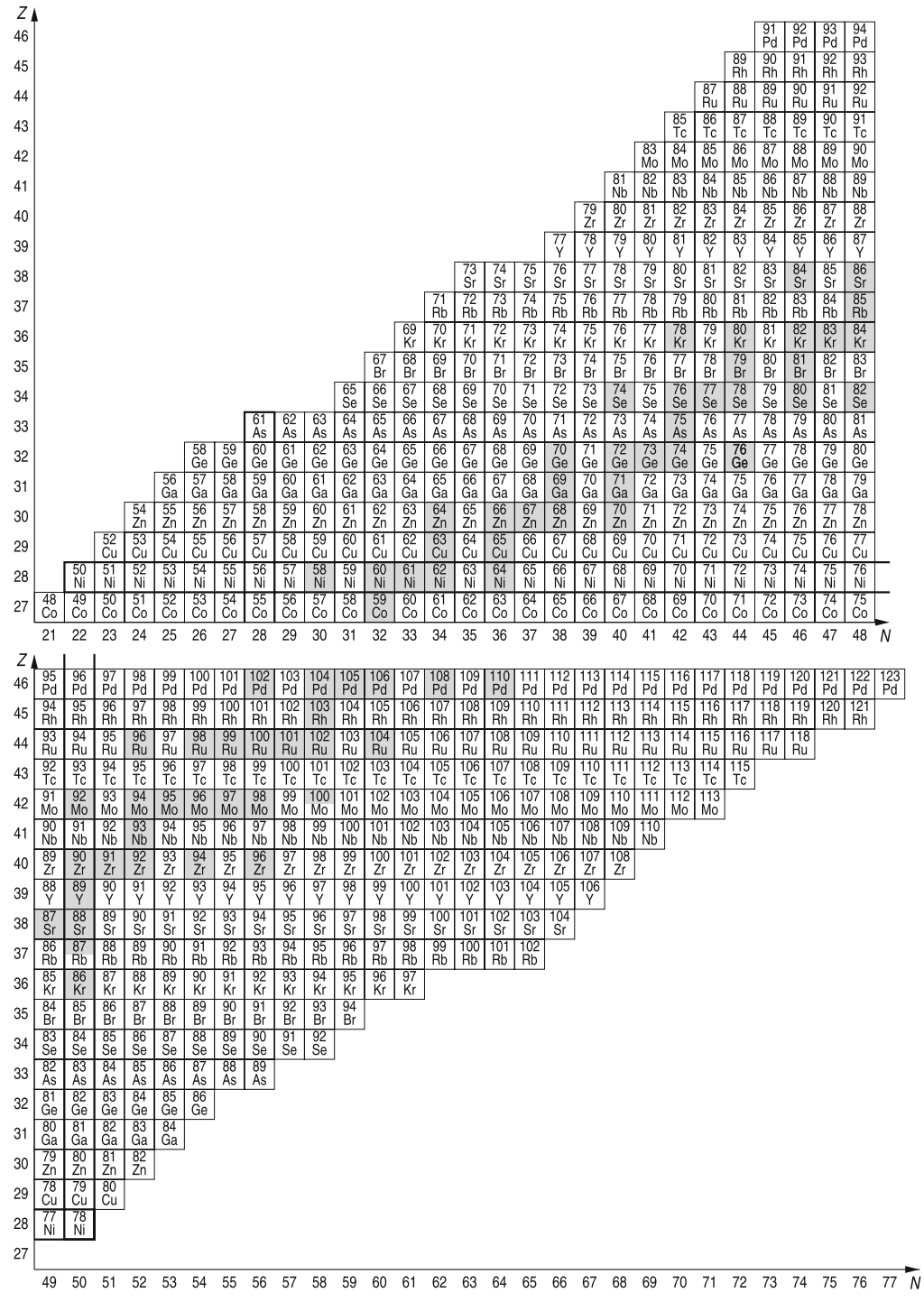
The isotopes (fixed number of protons Z and variable number of neutrons) of various elements are arranged horizontally. Isotones (fixed number of neutrons N) are put vertically.

In the overview table below, stable, primordial, and unstable nuclides are displayed with different gray scales, and the cut-out tables are marked by dash-dotted frames; the latter are shown in the order from lighter to heavier isotopes, i.e. from the lower left to the upper right. In the cut-out tables the stable nuclides are highlighted by a light gray background and the primordial ones by such a background in the upper half of their small box. Magic numbers are marked by frames of bold solid lines.



An isotope is said to be stable, if its half-life is larger than 10^{10} yrs, which roughly corresponds to the age of the universe. The mass number is conserved in β decays. Such nuclear decays therefore describe transitions in the diagonal (isobars) $A = Z + N =$ const (β^-: one isotope to the upper left; β^+: one isotope to the lower right). α decays change the mass number by 4 units and the nuclear-charge number by 2 units. In the diagram these transitions are obtained by $\Delta N = \Delta Z = -2$. Decays by spontaneous fission only occur for elements with $Z \geq 90$. The decay by spontaneous fission is often in competition to α decay.

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52 Cu 53 Cu 54 Cu 55 Cu 56 Cu 57 Cu 58 Cu 59 Cu 60 Cu 61 Cu 62 Cu 63 Cu 64 Cu 65 Cu 66 Cu 67 Cu 68 Cu 69 Cu 70 Cu 71 Cu 72 Cu 73 Cu 74 Cu 75 Cu 76 Cu 77 Cu
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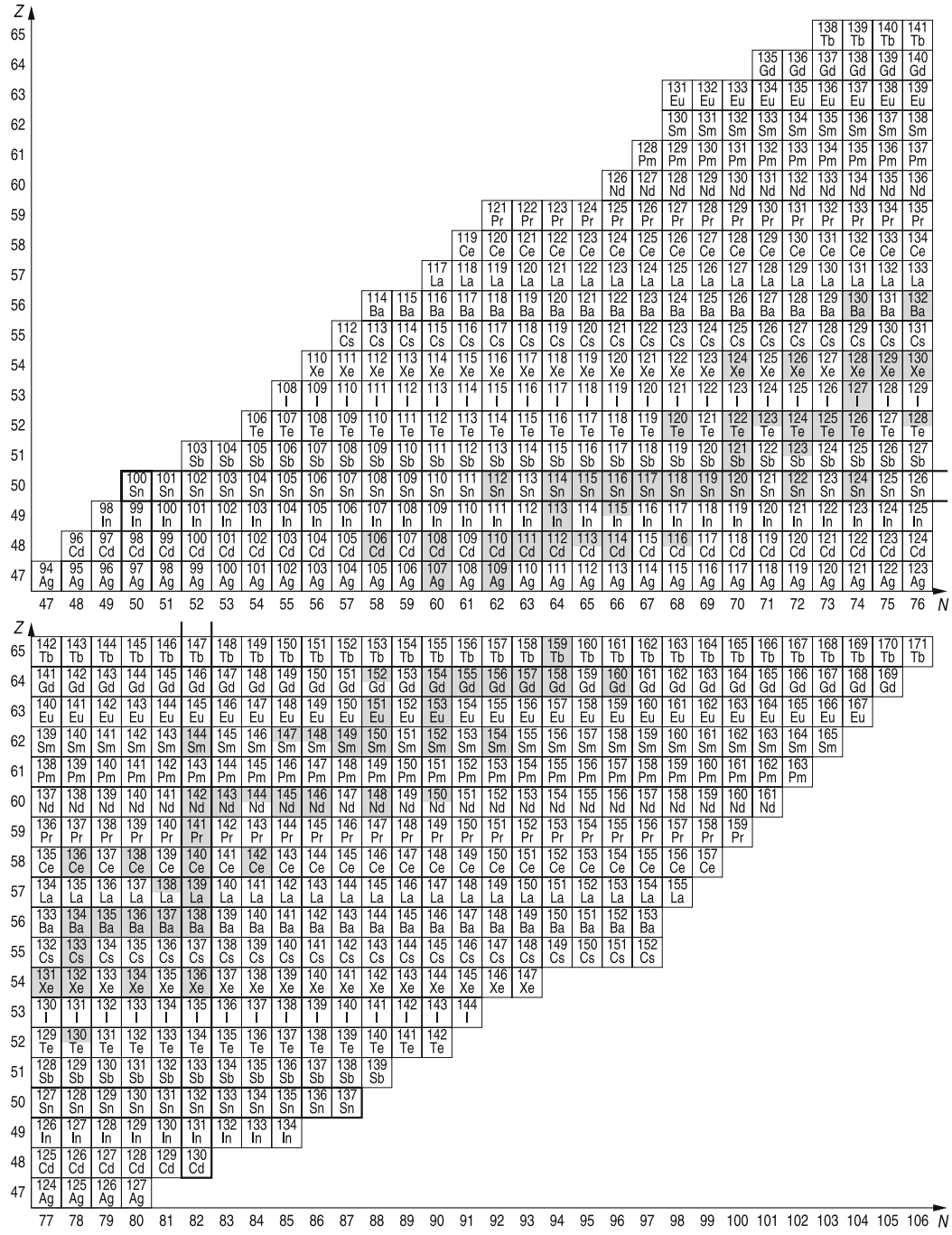
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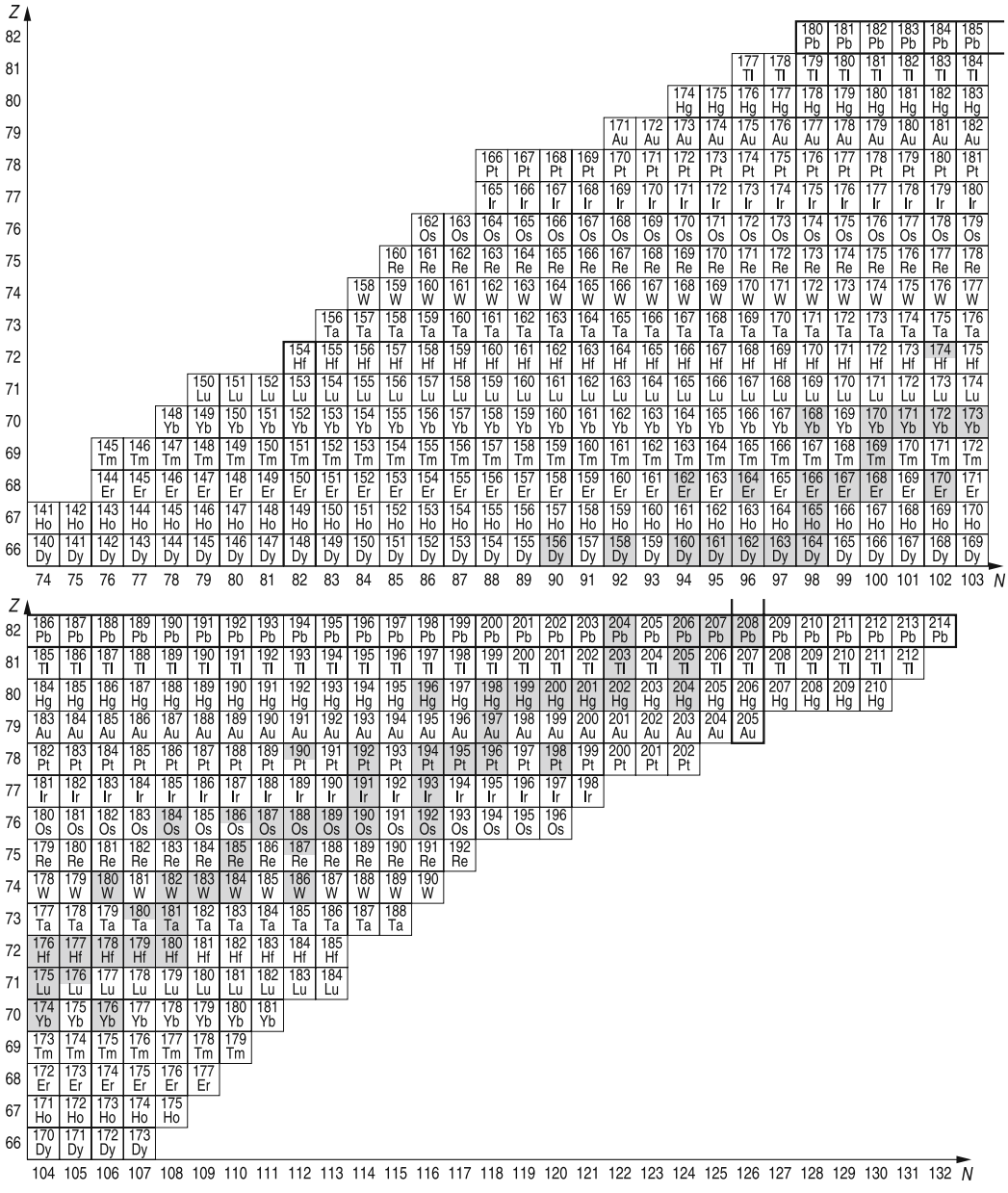
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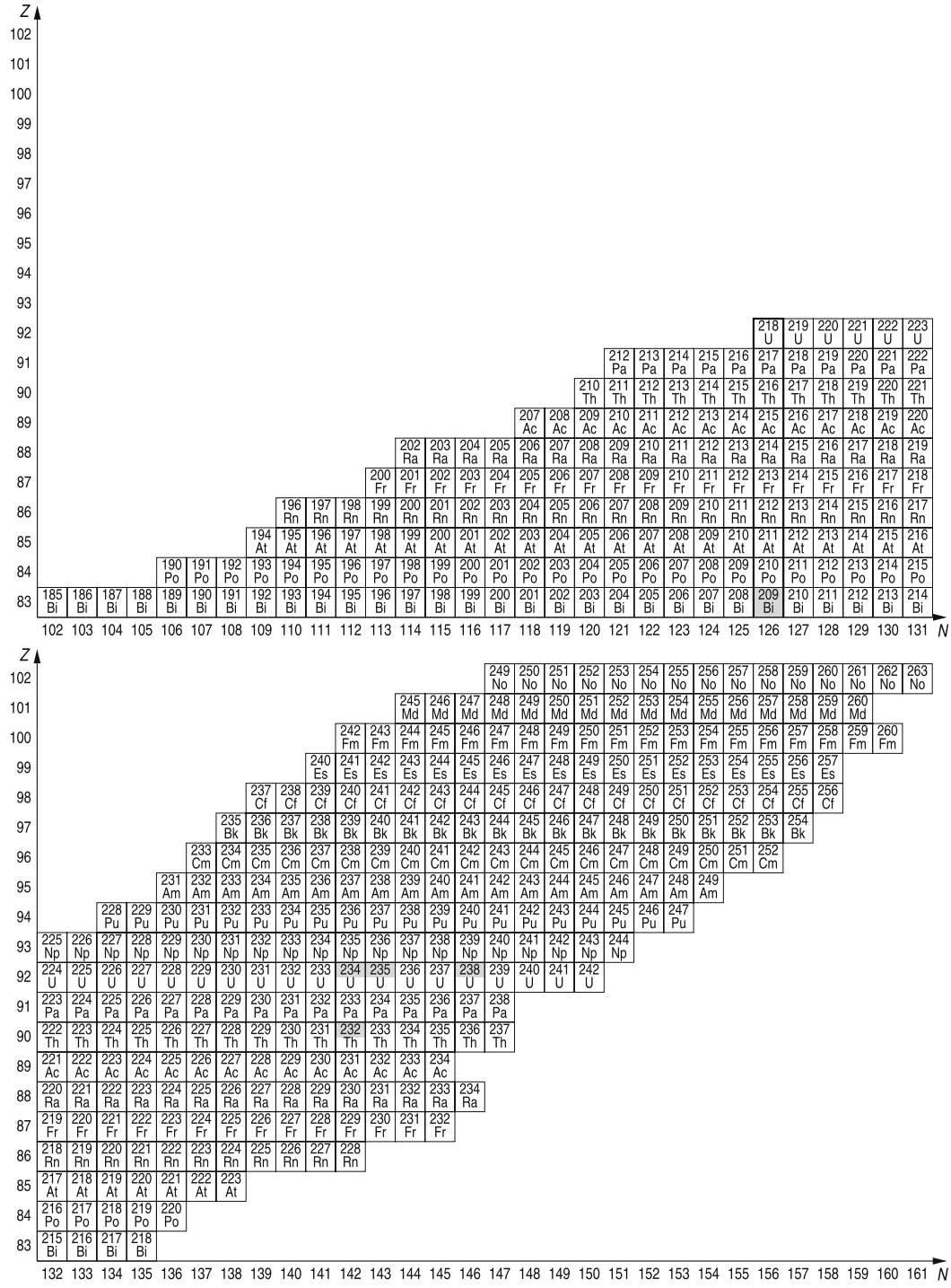
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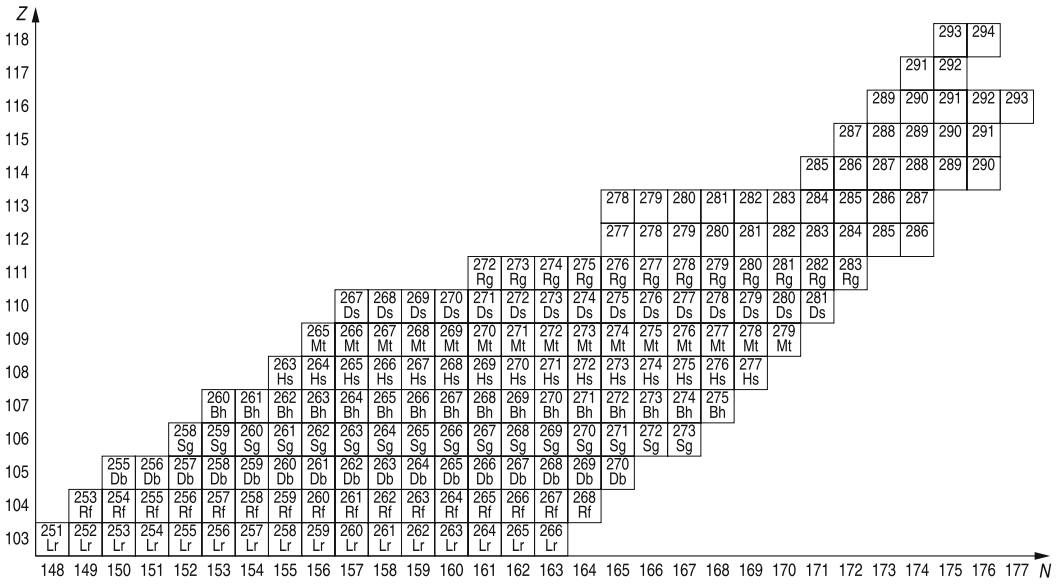
233 Cm 234 Cm 235 Cm 236 Cm 237 Cm 238 Cm 239 Cm 240 Cm 241 Cm 242 Cm 243 Cm 244 Cm 245 Cm 246 Cm 247 Cm 248 Cm 249 Cm 250 Cm 251 Cm 252 Cm
231 Am 232 Am 233 Am 234 Am 235 Am 236 Am 237 Am 238 Am 239 Am 240 Am 241 Am 242 Am 243 Am 244 Am 245 Am 246 Am 247 Am 248 Am 249 Am
228 Pu 229 Pu 230 Pu 231 Pu 232 Pu 233 Pu 234 Pu 235 Pu 236 Pu 237 Pu 238 Pu 239 Pu 240 Pu 241 Pu 242 Pu 243 Pu 244 Pu 245 Pu 246 Pu 247 Pu
225 Np 226 Np 227 Np 228 Np 229 Np 230 Np 231 Np 232 Np 233 Np 234 Np 235 Np 236 Np 237 Np 238 Np 239 Np 240 Np 241 Np 242 Np 243 Np 244 Np
224 U 225 U 226 U 227 U 228 U 229 U 230 U 231 U 232 U 233 U 234 U 235 U 236 U 237 U 238 U 239 U 240 U 241 U 242 U
223 Pa 224 Pa 225 Pa 226 Pa 227 Pa 228 Pa 229 Pa 230 Pa 231 Pa 232 Pa 233 Pa 234 Pa 235 Pa 236 Pa 237 Pa 238 Pa
222 Th 223 Th 224 Th 225 Th 226 Th 227 Th 228 Th 229 Th 230 Th 231 Th 232 Th 233 Th 234 Th 235 Th 236 Th 237 Th
221 Ac 222 Ac 223 Ac 224 Ac 225 Ac 226 Ac 227 Ac 228 Ac 229 Ac 230 Ac 231 Ac 232 Ac 233 Ac 234 Ac
220 Ra 221 Ra 222 Ra 223 Ra 224 Ra 225 Ra 226 Ra 227 Ra 228 Ra 229 Ra 230 Ra 231 Ra 232 Ra 233 Ra 234 Ra
219 Fr 220 Fr 221 Fr 222 Fr 223 Fr 224 Fr 225 Fr 226 Fr 227 Fr 228 Fr 229 Fr 230 Fr 231 Fr 232 Fr
218 Rn 219 Rn 220 Rn 221 Rn 222 Rn 223 Rn 224 Rn 225 Rn 226 Rn 227 Rn 228 Rn
217 At 218 At 219 At 220 At 221 At 222 At 223 At
216 Po 217 Po 218 Po 219 Po 220 Po
215 Bi 216 Bi 217 Bi 218 Bi
132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 161



A complete overview of known isotopes is given in "Karlsruher Nuklidkarte" from 2006 (G. Pfennig, H. Klewe-Nebenius, W. Seelmann-Eggebert, Forschungszentrum Karlsruhe 2006). Up-to-date information one finds also under e.g. `www.nucleonica.net`.

Periodic Table of Elements

Group																	
Ia	IIa	IIIb	IVb	Vb	VIb	VIIb	VIIIb	VIIIb	VIIIb	Ib	IIb	IIIa	IVa	Va	VIa	VIIa	VIIIa
1 **H** Hydrogen 1.01																	2 **He** Helium 4.00
3 **Li** Lithium 6.94	4 **Be** Beryllium 9.01											5 **B** Boron 10.81	6 **C** Carbon 12.01	7 **N** Nitrogen 14.01	8 **O** Oxygen 16.00	9 **F** Fluorine 19.00	10 **Ne** Neon 20.18
11 **Na** Sodium 22.99	12 **Mg** Magnesium 24.31											13 **Al** Aluminum 26.98	14 **Si** Silicon 28.09	15 **P** Phosphorus 30.97	16 **S** Sulfur 32.07	17 **Cl** Chlorine 35.45	18 **Ar** Argon 39.95
19 **K** Potassium 39.10	20 **Ca** Calcium 40.08	21 **Sc** Scandium 44.96	22 **Ti** Titanium 47.87	23 **V** Vanadium 50.94	24 **Cr** Chromium 52.00	25 **Mn** Manganese 54.94	26 **Fe** Iron 55.85	27 **Co** Cobalt 58.93	28 **Ni** Nickel 58.69	29 **Cu** Copper 63.55	30 **Zn** Zinc 65.39	31 **Ga** Gallium 69.72	32 **Ge** Germanium 72.64	33 **As** Arsenic 74.92	34 **Se** Selenium 78.96	35 **Br** Bromine 79.90	36 **Kr** Krypton 83.80
37 **Rb** Rubidium 85.47	38 **Sr** Strontium 87.62	39 **Y** Yttrium 88.91	40 **Zr** Zirconium 91.22	41 **Nb** Niobium 92.91	42 **Mo** Molybdenum 95.94	43 **Tc** Technetium 97.91	44 **Ru** Ruthenium 101.07	45 **Rh** Rhodium 102.91	46 **Pd** Palladium 106.42	47 **Ag** Silver 107.87	48 **Cd** Cadmium 112.41	49 **In** Indium 114.82	50 **Sn** Tin 118.71	51 **Sb** Antimony 121.76	52 **Te** Tellurium 127.60	53 **I** Iodine 126.90	54 **Xe** Xenon 131.29
55 **Cs** Cesium 132.91	56 **Ba** Barium 137.33	57-71 Lanthanides	72 **Hf** Hafnium 178.49	73 **Ta** Tantalum 180.95	74 **W** Tungsten 183.84	75 **Re** Rhenium 186.21	76 **Os** Osmium 190.23	77 **Ir** Iridium 192.22	78 **Pt** Platinum 195.08	79 **Au** Gold 196.97	80 **Hg** Mercury 200.59	81 **Tl** Thallium 204.38	82 **Pb** Lead 207.20	83 **Bi** Bismuth 208.98	84 **Po** Polonium 208.98	85 **At** Astatine 209.99	86 **Rn** Radon 222.02
87 **Fr** Francium 223.02	88 **Ra** Radium 226.03	89-103 Actinides	104 **Rf** Rutherfordium 261.11	105 **Db** Dubnium 262.11	106 **Sg** Seaborgium 263.12	107 **Bh** Bohrium 262.12	108 **Hs** Hassium 277.15	109 **Mt** Meitnerium 268.14	110 **Ds** Darmstadtium 271.15	111 **Rg** Roentgenium 272.15							

Lanthanide series	57 **La** Lanthanum 138.91	58 **Ce** Cerium 140.12	59 **Pr** Praseodymium 140.91	60 **Nd** Neodymium 144.24	61 **Pm** Promethium 144.91	62 **Sm** Samarium 150.36	63 **Eu** Europium 151.96	64 **Gd** Gadolinium 157.25	65 **Tb** Terbium 158.93	66 **Dy** Dysprosium 162.50	67 **Ho** Holmium 164.93	68 **Er** Erbium 167.26	69 **Tm** Thulium 168.93	70 **Yb** Ytterbium 173.04	71 **Lu** Lutetium 174.97
Actinide series	89 **Ac** Actinium 227.03	90 **Th** Thorium 232.04	91 **Pa** Protactinium 231.04	92 **U** Uranium 238.03	93 **Np** Neptunium 237.05	94 **Pu** Plutonium 244.06	95 **Am** Americium 243.06	96 **Cm** Curium 247.07	97 **Bk** Berkelium 247.07	98 **Cf** Californium 251.08	99 **Es** Einsteinium 252.08	100 **Fm** Fermium 257.09	101 **Md** Mendelevium 258.10	102 **No** Nobelium 259.10	103 **Lr** Lawrencium 262.11

For each element the atomic number (top left) and atomic mass (bottom) is given. The atomic mass is weighted by the isotopic abundance in the Earth's crust.

P Decay-Level Schemes

In the following simplified decay-level schemes for some frequently used isotopes in the field of radiation protection are given. For the continuous electron spectra the maximum energies are given. EC stands for electron capture and 'a' for annum (year).

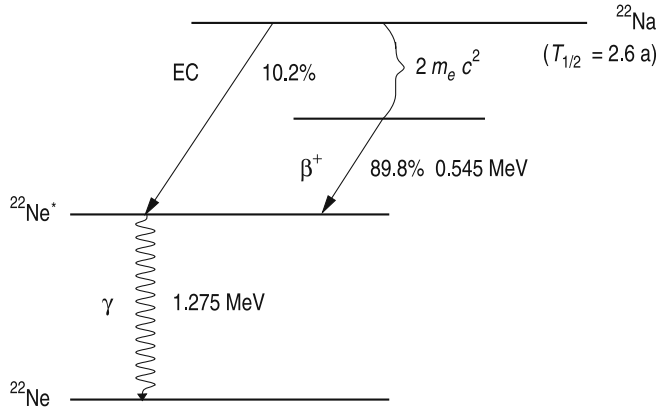
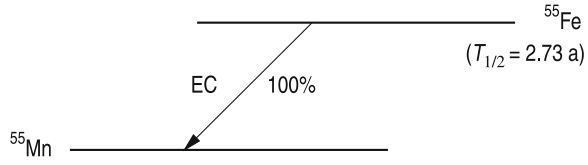


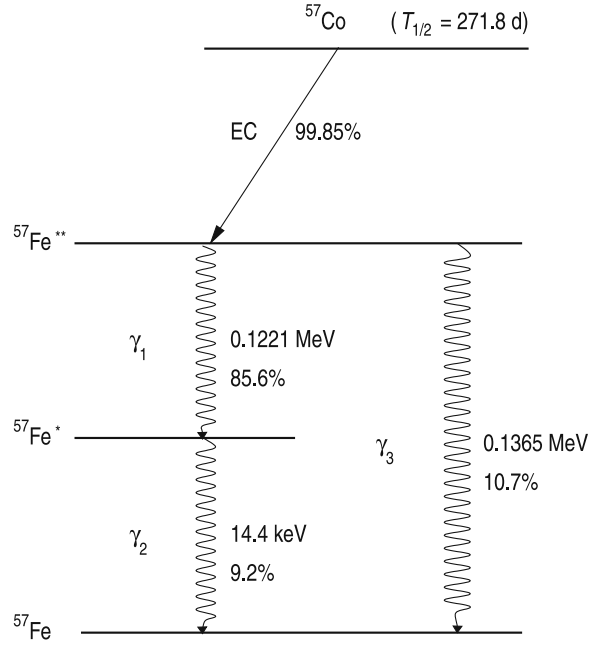
Figure P.1
Decay-level scheme of ^{22}Na



Characteristic X rays of ^{55}Mn:

$K_\alpha = 5.9\,\text{keV}$
$K_\beta = 6.5\,\text{keV}$

Figure P.2
Decay-level scheme of ^{55}Fe



Conversion electrons:

$K(\gamma_1) = 0.115\,\text{MeV}$ $L(\gamma_1) = 0.121\,\text{MeV}$
$K(\gamma_2) = 0.0073\,\text{MeV}$ $L(\gamma_2) = 0.0136\,\text{MeV}$
$K(\gamma_3) = 0.1294\,\text{MeV}$ $L(\gamma_3) = 0.1341\,\text{MeV}$

Figure P.3
Decay-level scheme of ^{57}Co

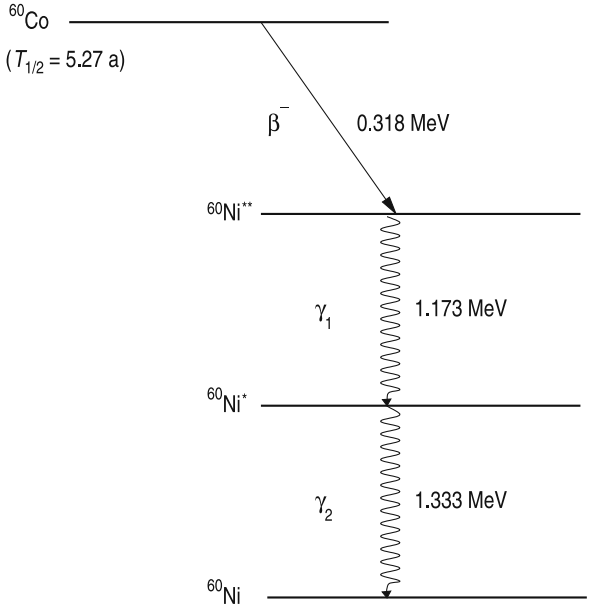


Figure P.4
Decay-level scheme of ^{60}Co

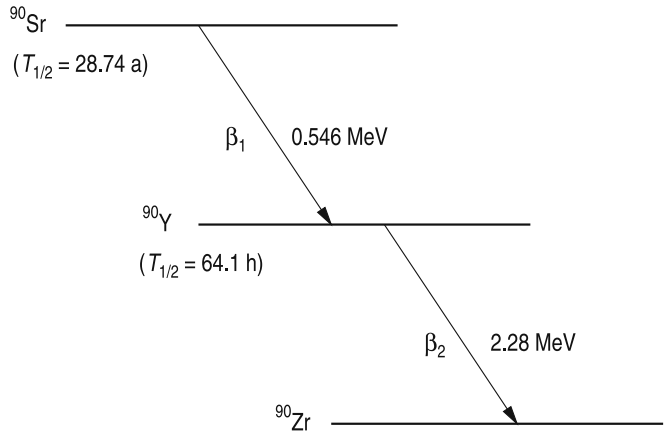


Figure P.5
Decay-level scheme of ^{90}Sr

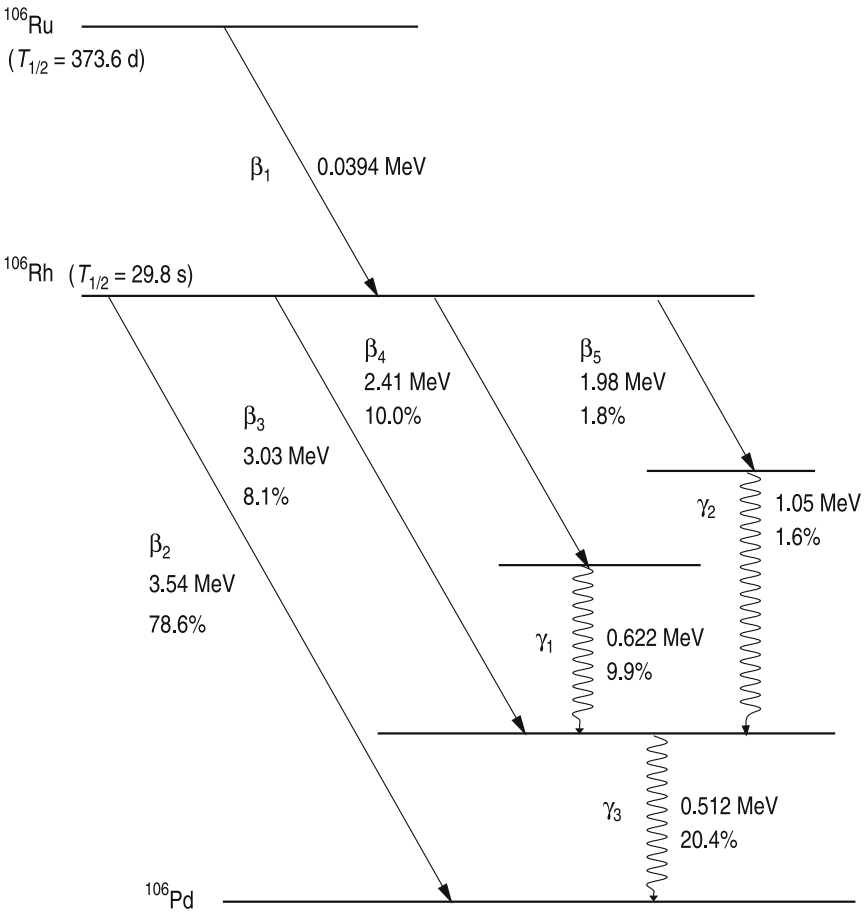
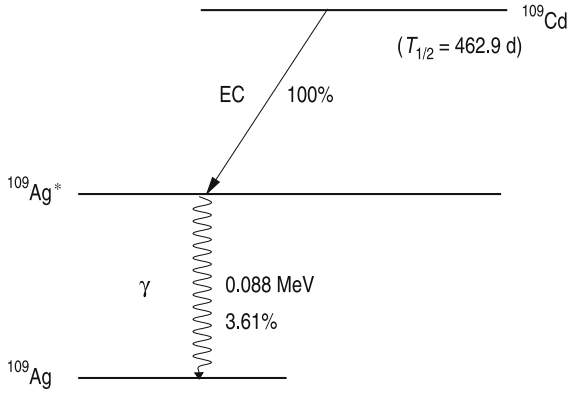


Figure P.6
Decay-level scheme of ^{106}Ru

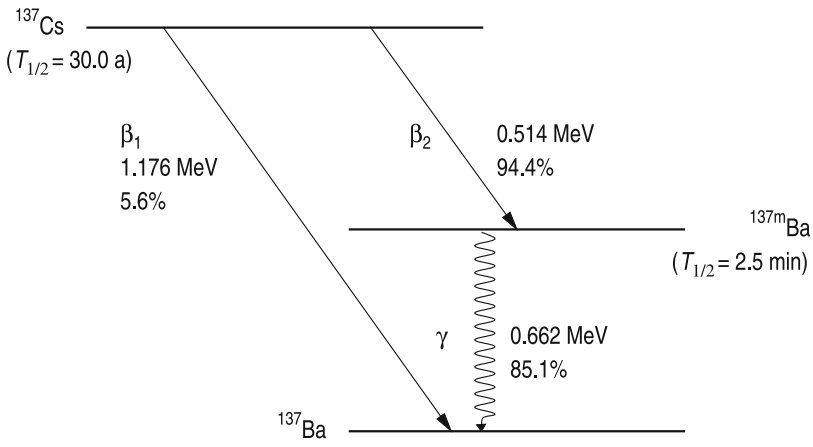


Conversion electrons:

$K(\gamma) = 0.0625\,\text{MeV}$
$L(\gamma) = 0.0842\,\text{MeV}$
$M(\gamma) = 0.0873\,\text{MeV}$

K_α X rays: 0.022 MeV
K_β X rays: 0.025 MeV

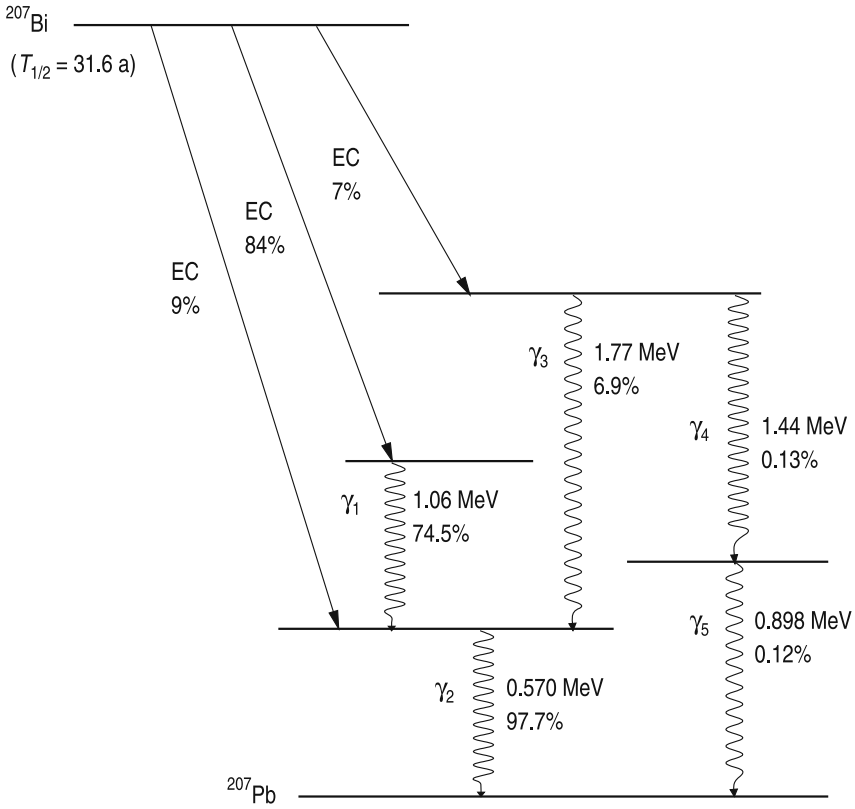
Figure P.7
Decay-level scheme of ^{109}Cd



Conversion electrons:

$K(\gamma) = 0.624\,\text{MeV}$
$L(\gamma) = 0.656\,\text{MeV}$

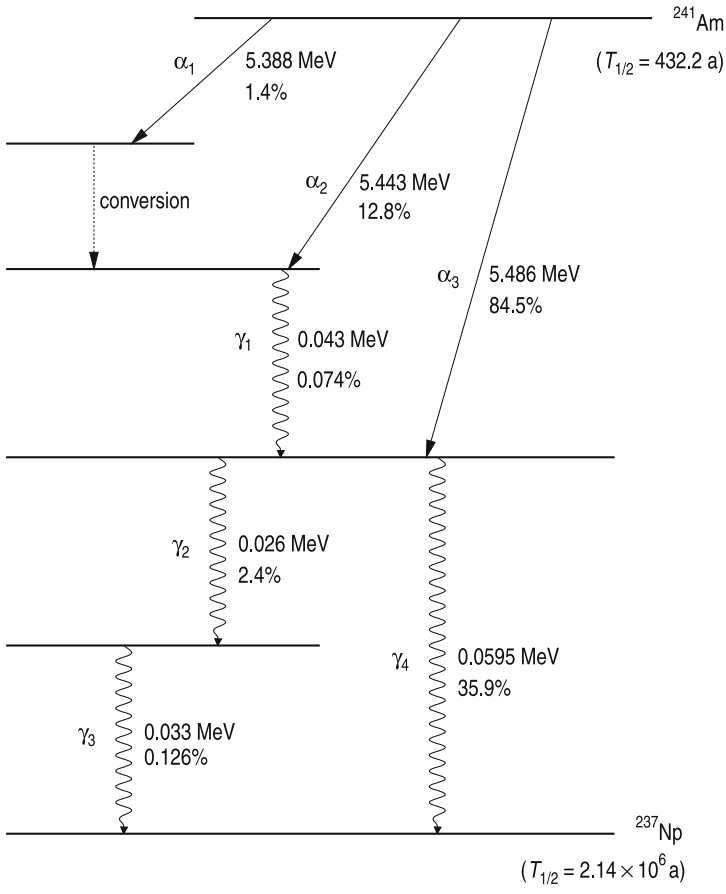
Figure P.8
Decay-level scheme of ^{137}Cs



Conversion electrons:

$K(\gamma_1) = 0.976\,\text{MeV}$ $L(\gamma_1) = 1.048\,\text{MeV}$
$K(\gamma_2) = 0.482\,\text{MeV}$ $L(\gamma_2) = 0.554\,\text{MeV}$
$K(\gamma_3) = 1.682\,\text{MeV}$ $L(\gamma_3) = 1.754\,\text{MeV}$
$K(\gamma_4) = 1.352\,\text{MeV}$ $L(\gamma_4) = 1.424\,\text{MeV}$
$K(\gamma_5) = 0.810\,\text{MeV}$ $L(\gamma_5) = 0.882\,\text{MeV}$

Figure P.9
Decay-level scheme of ^{207}Bi



Conversion electrons:

$K(\gamma_i)$ kinematically impossible
$L(\gamma_1) = 0.0210\,\text{MeV}$
$L(\gamma_2) = 0.0039\,\text{MeV}$
$L(\gamma_3) = 0.0108\,\text{MeV}$
$L(\gamma_4) = 0.0371\,\text{MeV}$

Figure P.10
Decay-level scheme of ^{241}Am

Q Introduction into the Basics of Mathematics

"The physicist in preparing for his work needs three things: mathematics, mathematics, and mathematics."

Wilhelm Conrad Röntgen

Correlations and laws in natural science can most elegantly be represented by diagrams and elementary mathematical functions. The description of physics relations in mere words – like the simple law on the forces between two massive bodies – as it was standard three centuries ago (e.g. in Newton's Philosophiae Naturalis Principia Mathematica, 1687), is hard to understand and lacks the precision of mathematical notation. On the other hand, basic mathematical relations are not easily accessible to everyone, and it requires some experience and basic knowledge of getting used to them.

Nature, however, is governed by some natural laws and functions which cannot easily be described in words. Instead they are best represented by simple mathematical formulae. In the following, therefore, some basic concepts are explained, which are relevant for many aspects associated with radiation protection and radioactivity and which allow a precise representation of correlations and laws for data and facts.

Q.1 Derivatives and Integrals

The temporal and spatial change of a quantity is called its derivative. This feature will be explained for the example of a path–time diagram. Figure Q.1 shows the uniform motion of some object as a function of space x and time t.

The constant slope of this line – expressed by the ratio $\Delta x/\Delta t$ – is the constant velocity v. If the velocity is not constant, the current value of the velocity depends on the size of the finite time and space intervals Δt and Δx. Such a non-linear path–time relation is plotted in Fig. Q.2.

difference quotient

The ratio $\Delta x/\Delta t$ for very small values of intervals leads to the concept of the instantaneous velocity at the time t_1. If the exact value of the velocity at the time t_1 is required, one has to select infinitesimally small space and time intervals. To characterize such infinitesimal intervals Leibniz proposed the notation $\mathrm{d}x/\mathrm{d}t$. The quantity $\mathrm{d}x/\mathrm{d}t$ therefore describes the slope of the path–time relation at the

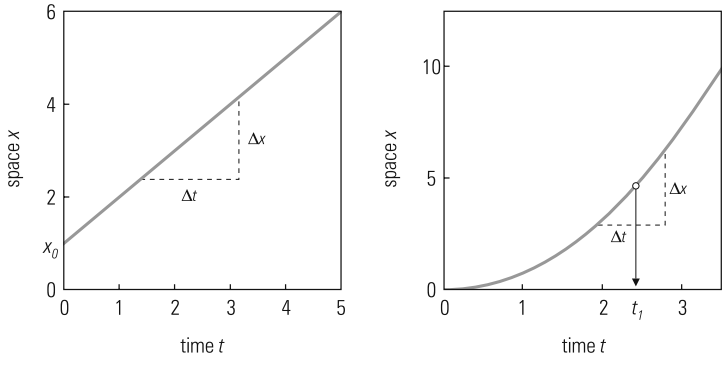


Figure Q.1
Relation between space and time for a uniform motion

Figure Q.2
Example of a non-linear relation between space and time

particular time t_1, which is the instantaneous velocity at the time t_1. Newton, who independently of Leibniz discovered this 'calculus', introduced as notation for the time derivative a dot over the spatial symbol: $\dot{x}$. Therfore we have the equivalence

notation convention

$$\frac{\mathrm{d}x}{\mathrm{d}t} \equiv \dot{x} \ . \tag{Q.1}$$

Leibniz' way to characterize the time derivative by $\mathrm{d}x/\mathrm{d}t$ has advanced the development of calculus (differential and integral calculus) substantially in continental Europe, while Newton's notation using dots on top of quantities – which was kept in England due to Newton's authority – hindered and delayed the advancement of calculus significantly. This was due to the fact that Leibniz' notation could be inverted without problems (see integration below), while this turned out to be difficult with the dot over the symbol.

Presently both notations are used only for time derivatives of physical quantities. Of course, both notations are equivalent. Figure Q.2 clearly shows that for a non-linear path–time relation the velocity $v = \mathrm{d}x/\mathrm{d}t$ changes with time. The object (e.g. a car starting at a traffic light when it turned green) accelerates from $t = 0$, where the acceleration is the change of velocity per time:

time derivative

acceleration

$$\text{acceleration } a = \frac{\mathrm{d}v}{\mathrm{d}t} = \dot{v} \ . \tag{Q.2}$$

Starting from considerations of the difference quotient, one can derive simple rules for the way how to differentiate special functions. For a polynomial

$$x(t) = a + b\,t + c\,t^2 \tag{Q.3}$$

one gets

$$\frac{\mathrm{d}x(t)}{\mathrm{d}t} = b + 2\,c\,t \ , \tag{Q.4}$$

as can be easily seen from Figs. Q.1 and Q.2 (the slope of a constant a is zero, the slope of a linear function $b\,t$ is equal to b, and the slope of a parabola $c\,t^2$ is obtained to be $2\,c\,t$).[1]

In general, a power-law relation is differentiated as

$$\frac{\mathrm{d}}{\mathrm{d}t}\,t^n = n\,t^{n-1}\ . \tag{Q.5}$$

In this rule t must not necessarily be the time, but it can be any variable.

The inverse of differentiation is the integration. Let us consider the particular velocity–time relation $v(t) = a\,t$, which is the straight line with slope a as shown in Fig. Q.3.

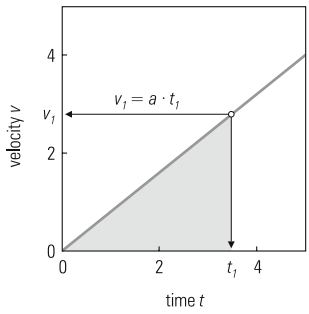


Figure Q.3
Example of a linear velocity–time relation

The integral over the velocity–time relation in the limits from $t = 0$ to $t = t_1$ is the area under the curve $v(t) = a\,t$ in these limits, i.e. the shaded area. This can be worked out, in this example, from the area of the rectangular triangle with the base along the time axis t_1 and the height $v_1 = a\,t_1$ divided by 2,

$$\frac{t_1\,a\,t_1}{2} = \frac{1}{2}\,a\,t_1^2\ . \tag{Q.6}$$

integration = determination of an area

For this operation one uses as shorthand the integral over the function $v = a\,t$ in the limits from $t = 0$ to $t = t_1$:[2]

$$\int_0^{t_1} a\,t\,\mathrm{d}t = \frac{1}{2}\,a\,t^2\Big|_0^{t_1} = \frac{1}{2}\,a\,t_1^2\ . \tag{Q.7}$$

power-law integration

The general rule for integrating a polynomial reads:

$$\int_0^{t_1} t^n\,\mathrm{d}t = \frac{t^{n+1}}{n+1}\Big|_0^{t_1} = \frac{t_1^{n+1}}{n+1}\ . \tag{Q.8}$$

In case of an integration without giving limits the result of the integral is naturally only determined up to a constant, which can only be fixed by the integration limits (boundary conditions):

$$\int t^n\,\mathrm{d}t = \frac{t^{n+1}}{n+1} + \mathrm{const}\ . \tag{Q.9}$$

---

1 $\frac{c\,(t+\frac{\Delta t}{2})^2 - c\,(t-\frac{\Delta t}{2})^2}{\Delta t} = \frac{c\,(t^2 + t\,\Delta t + \frac{\Delta t^2}{4}) - c\,(t^2 - t\,\Delta t + \frac{\Delta t^2}{4})}{\Delta t} = \frac{2\,c\,t\,\Delta t}{\Delta t} = 2\,c\,t$

2 In general, the integral over a linear function between two arbitrary limits t_1 and t_2 is worked out to be:

$$\int_{t_1}^{t_2} a\,t\,\mathrm{d}t = \frac{1}{2}\,a\,t^2\Big|_{t_1}^{t_2} = \frac{1}{2}\,a\,t_2^2 - \frac{1}{2}\,a\,t_1^2 = \frac{1}{2}\,a\,\left(t_2^2 - t_1^2\right)\ .$$

Formally, the consistency of this prescription can be verified by differentiating the result of the integration on the right-hand side. The differentiation of a constant (in this case the integration constant) gives zero (a constant has no slope), and thus the initial function t^n is again retrieved.

Q.2 Exponential Function

radioactive decay

In radioactive decay the number of decayed nuclei ΔN is proportional to the number of existing nuclei N and the observation time Δt. Obviously the number of nuclei decreases by decay. This results in a minus sign as in the following relation:

$$\Delta N \sim -N\,\Delta t \quad . \tag{Q.10}$$

Since the decay rate changes in time, a differential notation is appropriate,

$$\mathrm{d}N \sim -N\,\mathrm{d}t \quad . \tag{Q.11}$$

The introduction of a constant of proportionality leads to the identity

$$\mathrm{d}N = -\lambda\,N\,\mathrm{d}t \quad , \tag{Q.12}$$

where λ is the decay constant. Such a relation – one of the most basic differential equations – is solved by the so-called exponential function[3]

$$N = N_0\,\mathrm{e}^{-\lambda t} \quad . \tag{Q.13}$$

The number e, first introduced by Leonhard Euler, has the numerical value of $\mathrm{e} = 2.718\,28\ldots$.

N_0 denotes the number of originally existing nuclei, i.e. at $t = 0$. An example for the exponential function is plotted in Fig. Q.4. The exponential function describes a large number of natural processes, for example, the attenuation of γ rays in matter or the variation of the atmospheric pressure with altitude. For technical reasons the function $\mathrm{e}^{-\lambda t}$ is occasionally also printed as $\exp(-\lambda t)$.

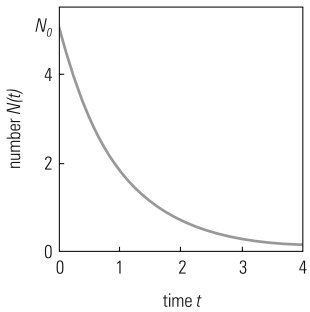


Figure Q.4
Example for the exponential variation of a quantity (e.g. decay rate) with time

properties of the exponential function

The exponential function has a very remarkable property: the slope of the function e^t, i.e. its derivative, is also an exponential, that means, it reproduces exactly itself,

$$\frac{\mathrm{d}}{\mathrm{d}t}\,\mathrm{e}^t = \mathrm{e}^t \quad . \tag{Q.14}$$

[3] $\frac{\mathrm{d}N}{N} = -\lambda\,\mathrm{d}t \Rightarrow \int \frac{\mathrm{d}N}{N} = -\int \lambda\,\mathrm{d}t \Rightarrow \ln N = -\lambda t + \text{const}$ (see also Eq. (Q.25)). $\mathrm{e}^{\ln N} = N = \mathrm{e}^{-\lambda t + \text{const}} = \mathrm{e}^{-\lambda t}\mathrm{e}^{\text{const}}$; boundary condition $N(t=0) = \mathrm{e}^{\text{const}} = N_0 \Rightarrow N = N_0\,\mathrm{e}^{-\lambda t}$.

It is the only function with this astonishing feature. If there is a parameter α as factor in the exponent, one has

$$\frac{\mathrm{d}}{\mathrm{d}t}\,\mathrm{e}^{\alpha t} = \alpha\,\mathrm{e}^{\alpha t}\ . \tag{Q.15}$$

In the same way the integration of the function e^t retrieves the exponential function,

$$\int \mathrm{e}^t\,\mathrm{d}t = \mathrm{e}^t + \text{const}\ , \tag{Q.16}$$

rules for exponentials

and correspondingly

$$\int \mathrm{e}^{\alpha t}\,\mathrm{d}t = \frac{1}{\alpha}\,\mathrm{e}^{\alpha t} + \text{const}\ . \tag{Q.17}$$

The known rules for powers also apply to exponentials, e.g.

$$\mathrm{e}^{\alpha}\,\mathrm{e}^{\beta} = \mathrm{e}^{\alpha+\beta}\ . \tag{Q.18}$$

Q.3 Natural Logarithm

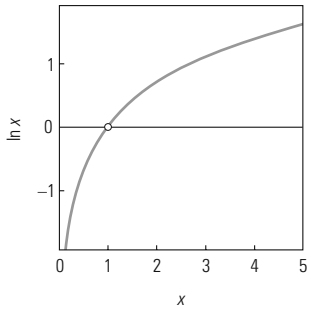


Figure Q.5
Graphical representation of a logarithmic variation of a quantity x

It is desirable that the human senses can perceive a large dynamic range of impressions. Therefore nature, or the evolution of life, has arranged that the sensual perception is proportional to the logarithm of the stimulus (Weber–Fechner law). The logarithm is a weakly rising monotonic function (Fig. Q.5).

The logarithm is the inverse function to the exponential. Equation

$$\mathrm{e}^{y} = x \tag{Q.19}$$

is exactly fulfilled, if

$$y = \ln x\ . \tag{Q.20}$$

rules for logarithms

The logarithm was also the basis for slide rules, which have by now been overcome by pocket calculators. Slide rules were based on the property that the logarithm reduces multiplication to addition and powers to multiplication,[4]

[4] If one is willing to memorize a few numbers, one can easily approximate in one's head all logarithms. For the natural logarithm one should memorize $\ln 2 = 0.6931$ and $\ln 10 = 2.30$. Thus, e.g. $\ln 8000 = \ln 8 + \ln 1000 = 3\ln 2 + 3\ln 10 \approx 2.1 + 6.9 = 9.0$. Analogously, one can proceed with the common logarithm (to the base 10), if one is ready to remember just one value, namely $\lg 2 = 0.3010$; see also Footnote 6.

$$\ln(x\ y) = \ln x + \ln y \ , \tag{Q.21}$$

$$\ln \frac{x}{y} = \ln x - \ln y \ , \tag{Q.22}$$

$$\ln x^n = n\ \ln x \ . \tag{Q.23}$$

A plot of the logarithmic function (Fig. Q.5) shows that its slope is large for small x and low for large x. The derivative of the logarithm is obtained to be[5]

integration and differential of the natural logarithm

$$\frac{\mathrm{d}}{\mathrm{d}x}\ \ln x = \frac{1}{x} \quad \text{(see also } \ln x \text{ from Fig. Q.5).} \tag{Q.24}$$

Since the integration is the inverse operation to differentiation, one has

$$\int \frac{1}{x}\,\mathrm{d}x = \ln x + \text{const} \ . \tag{Q.25}$$

With these rules also the radioactive decay law can now be understood: From

$$N = N_0\ \mathrm{e}^{-\lambda t} \tag{Q.26}$$

one obtains by differentiating

$$\frac{\mathrm{d}N}{\mathrm{d}t} = -\lambda\ N_0\ \mathrm{e}^{-\lambda t} = -\lambda\ N \quad , \tag{Q.27}$$

which can be rewritten as

$$\mathrm{d}N = -\lambda\ N\ \mathrm{d}t \tag{Q.28}$$

(compare (Q.12)).

One can easily recognize that the handling of differentials follows the standard and normal rules of calculation.

So far only the natural logarithm (to the base e) has been introduced. It is, however, possible to define logarithms also for other bases (e.g for the base 10: common, Briggs, or decadic logarithm).[6]

The fact that the logarithm linearizes powers can be used to simplify graphical representations. The exponential which characterizes radioactive decay, can be linearized by subdividing the axis that describes the number of nuclei that have not decayed in a logarithmic fashion: Because of

simplifying diagrams by using appropriate scales

[5] $\mathrm{e}^y = x\ ;\ y = \ln x\ ;\ \frac{\mathrm{d}\ln x}{\mathrm{d}x} = \frac{\mathrm{d}y}{\mathrm{d}x} = \frac{1}{\frac{\mathrm{d}x}{\mathrm{d}y}} = \frac{1}{\frac{\mathrm{d}\mathrm{e}^y}{\mathrm{d}y}} = \frac{1}{\mathrm{e}^y} = \frac{1}{x}$

[6] The natural (or Napierian) logarithm is usually abbreviated as $\ln x$ ('logarithmus naturalis'); in mathematics it is frequently written as $\log x$, even though this notation is not unique. The common, Briggs, or decadic logarithm to the base 10 is mostly denoted by $\lg x$. Since the natural logarithm has been introduced as the inverse function to the exponential, one has $\ln \mathrm{e} = 1$; analogously $\lg 10 = 1$.

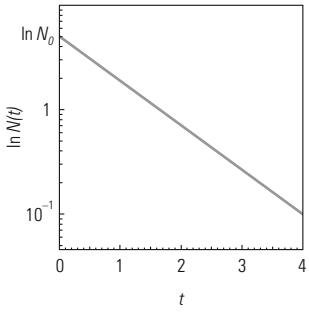


Figure Q.6
Linearization of an exponential in a semilogarithmic plot

$$N = N_0 \, \mathrm{e}^{-\lambda t} \tag{Q.29}$$

and

$$\ln N = \ln N_0 - \lambda t \tag{Q.30}$$

one obtains a straight line with a slope of $-\lambda$ and an intersect $\ln N_0$ (Fig. Q.6).

In an analogous way powers – plotted on double logarithmic paper (log–log paper) – result is straight lines. The power law

$$y = x^n \tag{Q.31}$$

leads to

$$\ln y = n \, \ln x \ , \tag{Q.32}$$

which is a straight line with slope n if both axes are subdivided logarithmically, i.e. if $\ln y$ is plotted against $\ln x$.

"Don't worry, it takes an infinite amount of time to sink completely."

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www.anl.gov/
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Germany
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Canadian Centre for Occupational Health and Safety
135 Hunter Street East
Hamilton ON
Canada L8N 1M5
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Thermo Fisher Scientific Inc.
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Waltham, MA 02454
USA

www.thermo-esm.com

Freiwillige Feuerwehr Eßfeld e.V.
D-97232 Eßfeld
Germany

www.ffwessfeld.de/

GRAETZ Strahlungsmesstechnik GmbH
Westiger Strasse 172
58762 Altena
Germany
www.graetz.com/

GSF – Forschungszentrum für Umwelt und Gesundheit GmbH
GSF National Research Center for Environment and Health in the Helmholtz Association
Ingolstädter Landstrasse 1
85764 Neuherberg
Germany
www.gsf.de/

Harshaw TLD
see Thermo Scientific
www.thermo.com/com/

ICx Radiation GmbH (former: target systemelectronic GmbH)
Kölner Strasse 99
42651 Solingen
Germany

100 Midland Road
Oak Ridge, Tennessee 37830
USA
www.icx-radiation.de/

Headquarters ICx Technologies
2100 Crystal Drive
Arlington, VA 22202, USA

JL Goslar, Kerntechnik und Strahlenschutz
Im Schleeke 108
D-38640 Goslar
Germany
www.jlgoslar.de

Lawrence Livermore National Laboratory
7000 East Avenue
Livermore, CA 94551
USA
www.llnl.gov/

L. Meitner and K. Freitag
Zeitschrift für Physik, Vol. 37, page 481 (1926)
also in K.W.F. Kohlrausch 'Radioaktivität', page 478;
Akademische Verlagsgesellschaft, Leipzig 1928
www.aka-verlag.com/

mab Strahlenmesstechnik
Neuer Höltigbaum 30
D-22143 Hamburg
Germany
www.pmabode.de

Materialprüfungsamt Nordrhein-Westfalen
Marsbruchstrasse 186
D-44287 Dortmund
Germany
www.mpanrw.de/start.html

Mini Instruments
Perspective Instruments Ltd
Pinewood
61 Folly Lane, Shaw
Wiltshire SN12 8HB
England
www.perspectiveinstruments.co.uk/

Oxford Technologies Ltd
7 Nuffield Way
Abingdon
Oxon, UK
OX14 1RJ
www.oxfordtechnologies.co.uk

PTW–Freiburg
Physikalisch–Technische Werkstätten Dr. Pychlau GmbH
Lörracher Strasse 7
79115 Freiburg
Germany
www.ptw.de

QSA Global GmbH
Gieselweg 1
38110 Braunschweig
Germnay

QSA Global Inc.
40 North Avenue
Burlington, MA 01803
USA

Sales offices also in France and Honk Kong
www.qsa-global.de
www.isotrak.de

RadiologyInfo™

www.radiologyinfo.org
nmap@acr.org
mamm-accred@acr.org

Radon Lab
Forskningsveien 3 B
0373 Oslo
Norway

www.radonlab.net/tracketch.htm

RADOS Technology GmbH
Ruhrstrasse 49
D-22761 Hamburg
Germany

World Headquarters
Bishop Ranch 8
3000 Executive Parkway Suite 220
San Ramon, CA 94583
USA

www.rados.com www.mirion.com/index.php?p=dosimetry_division

Many international representatives (21) to be found under:
www.mirion.com/index.php?p=locations#noram

S.E.A. GmbH
(Strahlenschutz- Entwicklungs- und Ausrüstungs-Gesellschaft)
Ortsdamm 139
48249 Dülmen
Germany

www.sea-duelmen.de

Siemens Healthcare
Wittelsbacherplatz 2
80333 München
Germany

Representatives in 35 countries
www.medical.siemens.com/

Strahlenzentrum of the Justus-Liebig University Giessen
Leihgesterner Weg 217
35392 Giessen
Germany
www.strz.uni-giessen.de/

Synchrotron Radiation Angiography (St. Fiedler)
Canadian Light Source Inc.
University of Saskatchewan
101 Perimeter Road
Saskatoon, SK.
Canada, S7N 0X4
www.lightsource.ca/
www.lightsource.ca/bioimaging/Saskatoon_2004_sf.pdf

Terra Universal, Inc.
800 S. Raymond Avenue,
Fullerton, CA 92831
USA
www.terrauniversal.com
Many international representatives (21) to be found under:
www.terrauniversal.com/international/localreps.shtml

Thermo Eberline ESM
Frauenauracher Strasse 96
91056 Erlangen
Germany
www.esm-online.de/

Thermo Fisher Scientific Inc.
81 Wyman Street
Waltham, MA 02454
USA
www.thermo.com/
Many international representatives (209) to be found under:
www.thermo.com/com/cda/article/general/1,,882,00.html

US Department of Energy
Office of Civilian Radioactive Waste Management
Yucca Mountain Project
1551 Hillshire Drive
Las Vegas, NV 89134
USA
www.ocrwm.doe.gov/contact/index.shtml
www.ocrwm.doe.gov/factsheets/doeymp0010.shtml

VacuTec Meßtechnik GmbH
Dornblüthstrasse 14
D-01277 Dresden
Germany
www.e-meditec.de/firm05/vacutec_messtechnik_4508.htm

Wikipedia
http://en.wikipedia.org/wiki/Radioisotope_thermoelectric_generator
http://commons.wikimedia.org/wiki/Image:Coolidge_xray_tube.jpg
http://en.wikipedia.org/wiki/Radium_Girls

This list has been checked early in 2009. Many companies occasionally change their name and can no longer be found easily. The 'Supplier Name Change' list helps to locate the companies with their new names. This list can be found under
www.purchasing.upenn.edu/buyinfo/suppliers/name_changes.php.

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* Pages in italics refer to the glossary.