TOPICAL REVIEW

The lifetime of the free neutron

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Abstract. We review the results and techniques of experiments on the lifetime of the free neutron. The present mean value is 887.4 (1.7) s at the 1 σ confidence level. We further discuss the relevance of these results for other fields like weak interaction theory, neutrino physics, astrophysics and cosmology.

1. Introduction

It took many years from the discovery of the neutron by Chadwick [1] in 1932 and the conjecture of its instability by Chadwick and Goldhaber [2] in 1935 until its radioactive decay was observed by Snell and Miller [3] in 1948. The dominant decay mode of the neutron is:

$$\mathbf{n} \to \mathbf{p} + \mathbf{e}^- + \bar{\nu}_e + 782 \text{ keV}. \tag{1}$$

The energy release is mainly shared between the electron and the antineutrino. The maximum proton recoil is only 0.755 keV. Very weak decay branches include the emission of a γ quantum of sizable energy and decay into a hydrogen atom [4]. They will not be considered here in detail. Decay branches involving pions or positrons would be much more favoured by phase space, but they are strongly hindered and not detectable due to the well established law of baryon number conservation. Sensitive experiments also exist in the search for the possible oscillation of neutrons into antineutrons, which would violate the baryon number by two units. The present limit for a free space $n\bar{n}$ oscillation time is 5×10^7 s [5].

The free neutron decay is the fundamental reaction for semileptonic decays in the first generation of elementary particles. In the quark picture it corresponds to the transformation of a d quark into a u quark under (virtual) emission of a W-boson (figure 1).

The decay probability of the free neutron is rather small, partly due to the three particle decay and to the small mass difference of 1233 keV between the neutron and the proton; partly due to the small strength of the weak interaction mediating the decay. This leads to a neutron life time τ_n as long as 15 min, τ_n being defined via the ordinary decay law

$$N_{\rm n}(t) = N_{\rm n}(t=0) \,{\rm e}^{-t/\tau_{\rm n}}$$
 (2)

where $N_n(t)$ denotes the number of neutrons surviving at time t.

The late development of experiments on the neutron decay was mainly caused by the fact that free neutrons could be produced in sufficiently large numbers only when research reactors became available. Since then about a dozen experiments have aimed for a precise determination of the neutron decay constant.

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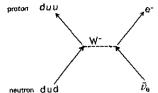


Figure 1. Neutron decay in the quark picture.

With improved precision of the experiments it became evident that the system of the freely decaying neutron conveys a variety of important kinds of information on the weak interaction of quarks in nucleons. In the present article we will concentrate only on the experiments related to the lifetime of the neutron, though many other complementary data are available nowadays on the various correlation coefficients between the neutron decay particles. The full set of precise data gives us a fundamental insight into the standard model of weak interaction and sensitive limits for possible deviations from its basic assumptions. These points will be dealt with more explicitly in the last section of the article, where we also show the importance of the neutron lifetime for cosmology and neutrino physics.

Table 1 gives a summary of neutron lifetime experiments. It demonstrates the recent progress in precision which was achieved owing to better neutron sources and new techniques. Several review articles and conferences were devoted in the past to this subject. (See for instance [28–30].)

There are basically two types of methods for neutron lifetime determinations.

Table 1. History of neutron lifetime measurements. For the mean value only data published after 1970 and only the last results from each research group were used (marked by *).

$\tau_{n}(s)$	Year	Method	Reference
(>21 min)	1948	proton counter	[3]
(13-36 min)	1950	proton counter	[6]
(14-43 min)	1950	e-p coincidence	[7]
1108 ± 216	1951	e-p coincidence	[8]
1013 ± 26	1959	proton counter	[9]
1099 ± 164	1959	cloud chamber	[10]
*918 ± 14	1972	e-spectrometer	[11, 12]
877 ± 8	1978	proton counter	[13]
907 ± 70	1978	VCN magnetic storage	[14]
875 ± 95	1980	UCN storage, aluminium	[15]
937 ± 18	1980	proton trap	[16]
903 ± 13	1986	UCN storage	[17]
850 ± 60	1986	UCN storage, Fomblin	[18]
$*876 \pm 21$	1988	e-spectrometer, pulsed beam	[19]
*891 ± 9	1988	proton counter	[20]
*900 ± 11	1988	UCN storage, D ₂ O ice	[21]
*877 ± 10	1989	VCN magnetic storage	[22]
*878 ± 31	1989	TPC, pulsed beam	[23]
$*887.6 \pm 3.0$	1989	UCN storage, Fomblin	[24]
$*893.6 \pm 5.3$	1990	variable size p trap	[25]
*888.4 ± 2.9	1990	UCN gravitational trap	[26]
*883.2 ± 2.9	1990	UCN storage, Fomblin, variable temperature	[27]

The first type is based on the counting of the decay products emerging from a neutron beam. In the second type the neutrons are stored in a volume and their number is counted as a function of the storage time.

2. Neutron lifetime measurements with neutron beams

2.1. Principle

The measurement of the neutron lifetime τ_n by neutron beam methods is based on the differential form of the decay law and on the detection of one or several decay product(s) N_d :

$$\frac{\mathrm{d}N_{\mathrm{d}}}{\mathrm{d}t} = -N_{\mathrm{n}}/\tau_{\mathrm{n}}.\tag{3}$$

Equation (3) is a good approximation since the neutron lifetime is in general much longer than the time of flight of the neutron (typically <1 ms) through the detection area of the decay products.

The real experimental situation has to take into account more details of the beam and the detectors leading in general to the determination of τ_n via the equation

$$\tau_{\rm n} = \int \varepsilon_{\rm d} \rho_{\rm n} \, {\rm d}V_{\rm d}/n_{\rm d}. \tag{4}$$

Here ε_d denotes the detection efficiency for decay products emerging from the decay volume V_d with neutron density ρ_n . The quantity n_d is the count rate in the decay product detector. The neutron density ρ_n is related to the neutron flux ϕ_n by

$$\phi_{n} = \rho_{n} \int n_{v} v_{n} \, \mathrm{d}v_{n} \tag{5}$$

where n_v denote the distribution of the neutron velocity v_n normalized to $\int n_v dv_n = 1$.

Thus neutron beam methods for τ_n are confronted with the problem of measuring the decay product rate and the number of neutrons N_n in a well defined volume V_d both on an absolute scale. For the special case of a chopped neutron beam the volume is just the size of a neutron packet.

In general only a small fraction of the neutrons decay on their path through the decay volume. For a cold neutron beam with a typical neutron velocity of $800 \,\mathrm{m\,s^{-1}}$ this fraction is about $10^{-6} \,\mathrm{m^{-1}}$ of flight pass. Therefore, the neutron beam flux, integrated over the beam cross section, can equally well be measured up or down stream of the decay product detector.

In the following section the concepts of neutron density measurements are described and the different methods are compared. In addition the general difficulties arising from the detection of the decay products, electron and/or proton, are outlined. How the problems were solved experimentally will be discussed in more detail in section 3 where the results of the various neutron lifetime beam experiments are presented.

2.2. Determination of the number of neutrons in a given beam section

Very intense neutron beams are available at high flux reactors, with neutron capture fluxes up to 2×10^{10} for direct beams and 10^{10} neutrons/cm² s at the exit of neutron guides for cold neutrons (values for the High Flux Reactor, Grenoble). These values correspond to neutron densities of about 10^5 and 5×10^4 neutrons/cm³, respectively. Some of this beam intensity is lost in the experiments since usually a highly collimated beam is required.

The experimental problems resulting from the determination of the number of neutrons, $\rho_n V_n$, are different according to whether a continuous or a chopped neutron beam is used. In the former case the neutron density in the decay volume has to be determined. In the latter case the absolute number of neutrons per neutron packet must be known.

2.2.1. Neutron density measurement in a continuous beam. The neutron flux in a beam can be determined by the neutron induced nuclear reaction rate in a thin target layer through which the beam passes. This reaction rate dN_r/dt is given by

$$dN_r/dt = \int \phi_n (1 - e^{-m\sigma_r}) dA = \int \rho_n \int n_\nu v_n (1 - e^{-m\sigma_r}) dv_n dA$$
 (6)

where m denotes the area density of nuclei in the target with reaction cross section σ_r . Equation (6) assumes no subsequent absorption of the scattered neutrons in the target. The integral covers the beam cross section A which is used for the neutron decay measurement.

The neutron reaction cross section far from a neutron resonance obeys the $1/v_n$ law:

$$\sigma_{r}(v_{n}) = \sigma_{0}v_{0}/v_{n}. \tag{7}$$

For a thin target $(m\sigma_r \ll 1)$ equations (6) and (7) lead to

$$\frac{\mathrm{d}N_{\mathrm{r}}}{\mathrm{d}t} = \sigma_0 v_0 \int \rho_{\mathrm{n}} m \, \mathrm{d}A. \tag{8}$$

For the simple case of a uniform mass distribution over the sample and a detection efficiency ε_d which is uniform over the beam section, equation (4) results in

$$\tau_{n} = \frac{\varepsilon_{d}}{\varepsilon_{r}} \cdot \frac{n_{r}}{n_{d}} \sigma_{0} v_{0} m \tag{9}$$

where ε_r and n_r denote the detection efficiency and rate of the reaction products, respectively.

The absolute measurement of the reaction rates in the target depends on the type of reaction used. Basically two different methods were applied.

(i) On-line counting of the reaction products. Commonly the reaction 3 He(n, p)t or 10 B(n, α) 7 Li are used for this purpose. The corresponding neutron capture cross sections at the standard neutron velocity $v_0 = 2200$ m are well known as 5333(7) b and 3837(9) b [31, 32]. respectively. The 1/v law was thoroughly tested in these reactions. For the absolute measurement of the reaction products proportional gas counters filled with 3 He or BF₄ were used with well known gas densities. Also thin foils of boron were placed in the neutron beam as targets and the emitted alpha particles were measured with solid state detectors. The latter method has been

developed recently to a greater refinement at NIST, Washington [33] in view of a τ_n measurement.

(ii) Neutron activation and off-line determination of the number of long lived (τ_a) radioactive nuclei produced. In this method the time integrated neutron flux is determined (τ_a) irradiation time t_{ir} :

$$\int_0^{t_{\rm ir}} \phi_{\rm n} \, \mathrm{d}t = \mathrm{e}^{t_{\rm w}/\tau_{\rm a}} \frac{n_{\rm a} \tau_{\rm a}}{\varepsilon_{\rm a}} (1 - \mathrm{e}^{-m\sigma_{\rm r}})^{-1} \tag{10}$$

where τ_a is the lifetime of the (long-lived) radioactive nucleus, t_{ω} the waiting time after the irradiation, n_a and ε_a the count rate and efficiency for the off-line detection system of the radioactivity. Frequently gold or cobalt foils were used for this purpose. The corresponding cross sections at $v_0 = 2200$ m are known with good precision as 98.65(9) b and 37.45(45) b, respectively [31, 32, 34]. The beta decay half lives of these isotopes are 2.6935 d and 5.272 y, respectively. The 1/v law is not exactly valid for the capture cross section of these nuclei, but the rather small corrections are known and can be easily applied by measuring roughly the neutron velocity distribution in the beam.

The ultimate limit in these neutron density measurements is given by the present knowledge of the corresponding capture cross sections, i.e. about 0.3%. However, at this level of precision the absolute measurement of the number of reaction products is also a very difficult problem.

2.2.2. Number of neutrons in a chopped beam. For a chopped beam the number of neutrons per neutron packet has to be determined in an absolute scale. This can be achieved by capturing all neutrons in a beam stop. The rate of neutron capture reactions is then equal to the real neutron beam flux. In the evaluation the scattering of neutrons without following capture must be taken into account. With gold or cobalt as beam stop the neutron number $N_{\rm int}$ integrated over i packets can be determined off-line by the measurement of the beta activity of the radioactive isotope produced by the neutron capture reaction. The number of neutrons per packet is given by (see equation (10) with $m\sigma_r \gg 1$):

$$\frac{N_{\rm int}}{i} = e^{t_{\rm w}/\tau_{\rm a}} \frac{n_{\rm a}}{\varepsilon_{\rm a}} \tau_{\rm a}. \tag{11}$$

Since all neutrons are captured in this method the relevant neutron capture cross section and the neutron velocity distribution in the beam must not be known, except for the generally small correction for neutron scattering. The precision in this method is only limited by the determination of the absolute beta activity produced.

A combination of methods 2.2.1 and 2.2.2 may be applied in special cases.

2.3. Measurement of the decay products: general remarks

2.3.1. Measurement of decay electrons. As mentioned before the continuous beta spectrum of the free neutron has an end-point energy of 782 keV. The absolute number of these beta particles, emitted from a well defined decay volume, has to be determined. The low energy part of the spectrum is very difficult to detect and in general a lower energy threshold has to be introduced. Assuming the theoretical shape of the neutron beta spectrum, the measured part of the spectrum has then to be extrapolated to zero energy. A high stability and a well known response function

for the electron detectors are necessary for this procedure. On the other hand the spectral information provides a consistency check on whether the response function and the background are well determined. Further difficulties arise in the precise determination of the decay volume seen by the beta detector and in the solid angle of detection.

Finally electron counting is faced with a serious background problem. The decay rate is low compared with the neutron flux, and neutrons create background by capture reactions. Thus both the detection of the continuous beta spectrum down to low energies and the generally high background cause the major difficulties in neutron lifetime measurements based on decay electrons.

- 2.3.2. Detection of the decay protons. The proton recoil energy in the neutron beta decay ranges up to 0.75 keV. For an efficient detection the protons are accelerated to at least 10 keV. The detectors for protons such as surface barrier detectors, low pressure proportional counters, scintillation counters or open photomultipliers are quite delicate to handle. In general the entire proton spectrum is recorded with no valuable information on the proton energy distribution. Only small corrections are needed, due to the not quite 100% efficiency for proton detectors. The decay volume may be confined by electrostatic potential walls or/and by magnetic fields of high strength (proton trap). In other methods the decay volume is viewed under a well defined solid angle. Possible losses in collecting the protons may be due to neutral hydrogen formation by the collision of the protons with the rest gas or by the magnetic mirror effect in extracting protons from strong magnetic fields. On the other hand background events may be created by ions in the decay volume, which are accelerated towards the detectors in the same way as the decay protons. Ultra high vacuum conditions are necessary to limit this background. In general proton detectors do not show a high sensitivity for beta and gamma particles.
- 2.3.3. Coincidence method. The detection of both decay electrons and protons in coincidence reduces the background significantly. But the standard absolute rate determination of radioactivity by comparing single and coincidence rates is not easily applicable since the effective decay volume may be different for the two particles, the electron-proton angular distribution is not isotropic and the background rather high in the single spectra.

3. Review of beam experiments determining the neutron lifetime

The first measurement was published in 1948 by Snell and Miller [3]. They detected decay protons. From this obervation they estimated the neutron lifetime as >21 min. Subsequent experiments [6, 7] gave large still uncertainties. The first precise experiment was then performed by Robson in 1951 [8]. He carried out a neutron lifetime experiment with detection of electrons and protons in coincidence. The method is still of interest and will be briefly reviewed below. The result by the Moscow group [9] was revised later on (see section 3.3.1). In a cloud chamber experiment D'Angelo [10] observed individual tracks of decay electrons and achieved with $\tau_n = 1099(164)$ s a similar value and precision as Robson.

Selected neutron beam experiments will be described in detail in the following and grouped by the type of decay particles detected.

3.1. The experiments by Robson: detection of both the decay protons and electrons in coincidence [8]

The experiment of Robson [8] was carried out at the Chalk River reactor in a neutron beam of about 3 cm diameter and a thermal neutron flux of $\phi_n = 2 \times 10^9$ neutrons/cm² s. The set-up for the neutron lifetime experiment is shown in figure 2.

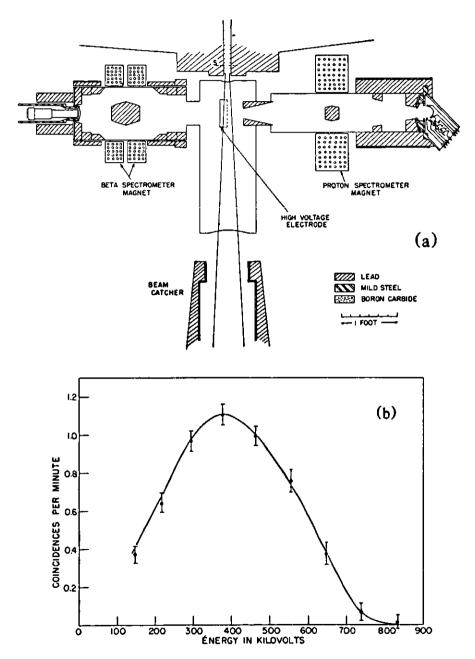


Figure 2. The neutron lifetime experiment by Robson [8]. The electron spectrum measured in coincidence with the proton detector is shown in figure 2(b).

The decay protons created within an electrostatic potential well (positively charged half cylinder) were accelerated to $10 \,\mathrm{keV}$ and focused by a magnetic field on an open photomultiplier. In coincidence with the proton counter the electron spectrum was scanned point by point using a magnetic spectrometer of 9% momentum resolution.

By this method Robson was able to measure for the first time the continuous beta spectrum in the free neutron decay (figure 2(b)). He achieved favourable background conditions in the coincidence data, despite the high gamma and fast neutron background at the experimental site. With improved modern equipment, a low background and an intense neutron beam it should be possible now to use a similar coincidence method and measure the beta spectrum with high accuracy. From the shape of this fundamental beta decay system small terms such as radiative corrections or weak magnetism terms could be extracted.

The volume viewed by the proton detector was $8.8\,\mathrm{cm}^3$. It was calculated from the electrostatic potential contours in the beam and also estimated from the observed coincidence rate. The proton single counting rate was finally used as a measure for the neutron decay rate. The precision in τ_n in the Robson experiment was mainly limited by the knowledge of the effective decay volume and by the efficiencies of the detector systems. The gold foil activation method provided the neutron density in the decay volume. Robson obtained a value of $\tau_n = 1108(216)\,\mathrm{s}$.

3.2. Neutron lifetime experiments detecting the decay electrons

3.2.1 The experiment of Christensen et al [12]. A major step towards a precise determination of τ_n was achieved by the experiment at Risø. The experimental set-up is shown in figure 3. The decay electrons were detected by scintillators placed

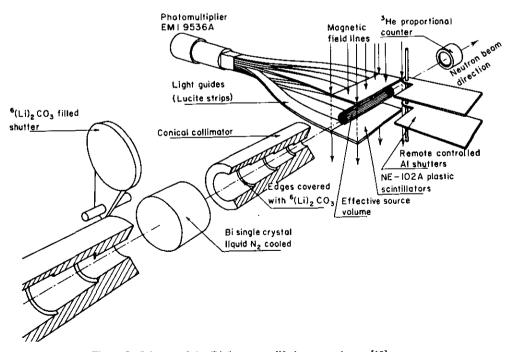


Figure 3. Scheme of the Risö neutron lifetime experiment [12].

along the beam. A magnetic field was applied perpendicular to the beam and the scintillators. Decay electrons were confined by this field in one dimension and thus guided towards the scintillators. The magnetic field and the size of the scintillators defined the length of the beam seen by the detectors (about 10 cm). The electrons deposited the entire energy in the detectors since even backscattered electrons remained confined between the two scintillator planes. Since the electrons spiral in the magnetic field, the decay volume is not sharply defined at the borders and had to be calculated.

In common with all decay electron measurements the background determination was a major problem. Finally only data above 204 keV electron energy were used for the evaluation of τ_n , the background being too high at lower energies. The measured spectrum was extrapolated on the basis of the theoretical shape of the spectrum and the measured detector response function. The neutron density was measured by gold and sodium activation analysis with a precision of 0.4%. A value of 500 neutrons/cm of beam length was found. Above the electron energy threshold of 204 keV, 3.5 counts/s from the neutron decay were detected, representing 68% of the whole spectrum. The room background was 5 counts/s above the threshold.

The final value for the neutron lifetime was $918 \pm 14 \,\mathrm{s}$. It superseded an earlier evaluation of the experiment [11] where a 3% loss of decay electrons by magnetic mirror effects was omitted. The uncertainty was governed by the determination of the neutron beam correlated background caused by neutron capture reactions in surrounding materials, and by the detection efficiency of the decay electrons.

3.2.2. Experiment with the PERKEO spectrometer [19]. Following a very precise measurement of the beta asymmetry in the decay of polarized neutrons [35] the spectrometer PERKEO [36] was used for a neutron lifetime experiment (Heidelberg-ILL-Argonne collaboration). The experiments were carried out with a cold neutron beam at the ILL High Flux Reactor in Grenoble. The neutron flux at the exit of the corresponding neutron guide H14-PN7 was 10⁹ neutrons/cm² s (real flux) with an intensity maximum at 4.5 Å. The experimental arrangement is shown in figure 4. A 20 cm long collimator arrangement made of ⁶LiF bars produced a spot of

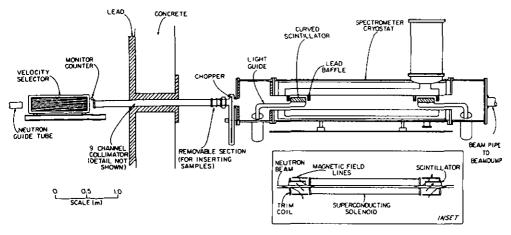


Figure 4. The electron spectrometer PERKEO in the configuration for a chopped beam neutron lifetime experiment [19].

about 20 mm diameter in the centre of the 3 m distant spectrometer. In the neutron flight path, between the collimator and the detector, were placed a velocity selector of the helical slit type and a ⁶LiF coated chopper. Neutron packets of 150 cm length were thus formed. The velocity selector (resolution $dv/v \approx 15\%$) limited the dispersion of the neutron packets during their flight through the spectrometer. The number of neutrons was about 4000 per packet with a repetition rate of 50 s⁻¹.

A chopped neutron beam was used for several reasons. Firstly, the background could be measured simultaneously and realistically during the time interval where the neutron packet moved outside of the detector (figure 5). Secondly, the decay electrons from the neutron packet could be measured over the full 4π solid angle while the neutron packet moved during a time interval Δt inside the spectrometer. Finally, the beam stop activation provides a precise method to measure the number of neutrons, which have passed through the spectrometer. As in the Christensen experiment the decay electrons were guided towards the detectors (plastic scintillators) by magnetic fields. For this a magnetic field of strength 1.6 T, parallel to the beam axis, was produced by a superconducting solenoid. At both ends the magnetic field was bent out of the beam to allow for the placing of the detectors. With this long solenoid a large decay volume could be viewed with comparatively small detector size and hence reduced background. For measuring the number of neutrons per packet the activation analysis of a beam absorber of gold or cobalt was used. Thus with an accumulated number of neutrons $N_{\rm abs}$ absorbed the beam stop yields a decay rate r_a of the produced radioisotope (see equation (11)). The rate r_a was then determined off-line by a detector of efficiency ε_a , showing a counting rate n_a after a waiting time t_w :

$$r_{\rm a} = \frac{n_{\rm a}}{\varepsilon_{\rm a}} = \frac{N_{\rm abs}}{\tau_{\rm a}} e^{-t_{\rm w}/\tau_{\rm a}}.$$
 (12)

Here τ_a is the lifetime of the radioactive nucleus. This formula holds for an exposure time short compared with τ_a and for the observation of a 100% β branch of the nucleus concerned. On the other hand, N_n neutrons have passed the spectrometer and a cumulated number N_{β} of decay electrons were observed with efficiency ε_{β} during the time interval Δt . Thus, the neutron beta decay rate r_{β} is given by

$$r_{\beta} = \frac{n_{\beta}}{\varepsilon_{\beta}} = N_{\beta}/\Delta t = N_{\rm n}/\tau_{\rm n}. \tag{13}$$

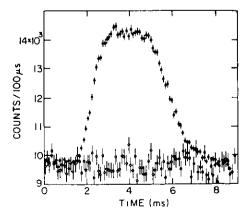


Figure 5. Electron signal with a chopped neutron beam at PERKEO. The detector counting rate plotted against time synchronized at the beam chopper is shown. In the range around 4 ms the entire neutron packet is contained in the spectrometer solenoid. Full points, chopper operating; open points, background level with chopper turned off [19].

For $N_{abs} = N_n$, i.e. no significant neutron backscattering in the beam stop (estimated to be less than 0.1%) no losses of neutrons between decay volume and beam stop and complete absorption in the beamstop, equations (12) and (13) lead to

$$\tau_{\rm n} = \tau_{\rm a} \frac{r_{\rm a}}{r_{\beta}} = \tau_{\rm a} \frac{n_{\rm a}}{n_{\beta}} \frac{\varepsilon_{\beta}}{\varepsilon_{\rm a}} e^{t_{\rm w}/\tau_{\rm a}}.$$
 (14)

The measurement is seen to be reduced to that of a ratio of two activities, r_a and r_β , each of which has to be measured on an absolute scale. Figure 5 shows the counting rate in one detector as a function of the time of flight of the neutron beam, i.e. position of the neutron packet in its flight through the system. The background subtraction turned out to be not perfect at lower energies. Hence a lower energy cut of 364 keV (the energy of an internal conversion electron line in the decay of ¹¹³Sn calibration source) was necessary with all the unavoidable calibration procedures. This energy cut introduced the main contribution to the systematic error, which stemmed from the gain stability of the scintillation detectors.

For the neutron beam measurement, i.e. the off-line determination of the activity of the beam stop, a precision of 0.4% is quoted. The final result was

$$\tau_{\rm n} = 876 \pm 10 ({\rm stat.}) \pm 19 ({\rm syst.}) {\rm s.}$$

Although a number of systematic uncertainties were overcome in this measurement compared to Christensen (in particular the difficulties with the decay volume determination) the rather high background and the only partial measurement of the spectrum bring limitations to a high precision in this method. Since the systematic error in this measurement was governed by the gain stability in the scintillation counters (quoted error 17 s), a substantial improvement in accuracy seems to be possible.

3.2.3. Measurement with a He-filled time projection chamber [23]. A different approach to a neutron lifetime determination was undertaken at the ILL by an ILL-ISN-LAPP collaboration. Again the cold neutron beam H14-PN7 was used. The experimental set-up is illustrated in figure 6. Neutron packets were formed by a chopper and a subsequent graphite monochromator. In this way a pulsed neutron beam of low gamma background was made available, at the expense of relatively

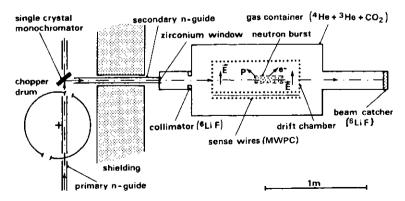


Figure 6. Experimental set-up for the neutron lifetime experiment using a He-filled TPC [23].

low intensity (2000 neutrons per packet of 20 cm length and 4 cm² cross section). The repetition rate was 60 packets/s.

The neutron packets passed along the central axis of a 70 cm long drift chamber which was tilled with a gas mixture of 880 mbar ⁴He and 70 mbar CO₂ serving as quenching gas. This type of counter gas has been chosen because of its low neutron capture and neutron scattering cross section [37]. The nucleus ⁴He has zero capture cross section and also a low scattering cross section of about 1 b/atom for 800 m s⁻¹ neutrons. The corresponding values for CO₂ are also low ($\sigma_{cap} = 1$ and 2 mb, $\sigma_{scatt} = 4$ and 5 b for C and O, respectively).

The ionization tracks from the decay electrons drifted in the applied electrical field towards the multiwire proportional counter section with a drift velocity of $1 \text{ cm } \mu \text{s}^{-1}$. The wires fired and the differences in drift times between parts of the ionization track section determined for each event the projection and the inclination of the electron track, respectively. The detector recorded the entire electron spectrum (energy threshold <1 keV) but provided no information on the spectral distribution. For a time interval of about 0.4 ms the neutron packet moved inside of the drift volume and thus the decay electrons were detected in a 4π geometry [38].

The background was relatively high due to neutrons scattered by the counter gas and being captured outside the drift chamber. A significant background reduction was already achieved by coating the detector chamber with ⁶LiF. The background could finally be determined from the time structure of the event rate and by comparing different sections in the drift volume (figure 7). The neutron number in the packet was simultaneously determined in the same detector. For this purpose a well defined amount of ³He was admixed to the counter gas. The neutrons undergo ³He(n, p)t reactions, which create short ionization tracks of high ionization density in the counter gas. Thus the events are well discriminated from the low specific ionization of neutron decay electron events. The neutron lifetime is finally determined by the ratio of measured events of each type.

$$\tau_{\rm n}^{-1} = \frac{\Delta N_{\rm e}}{(\Delta N_{\rm p} - \Delta N_{\rm p0})} \Delta \rho \sigma_0 \nu_0. \tag{15}$$

The event number ΔN was collected in a common time interval, where the neutron packet moves inside the drift chamber. For the (n, p) events the differences ΔN_p and ΔN_{p0} , with and without an additional ³He density $\Delta \rho$ in the counter gas, were used.

The event structure is shown in figure 7. The main problem in this method is again the high background in the electron counting which remains even after the track localization. In the Z-direction only the relative drift time, i.e. the declination of a track, is defined. Thus discrimination of the background from outside the chamber is limited. In a consecutive experiment with the TPC on the β asymmetry coefficient A these problems were overcome by measuring the TPC events in coincidence with plastic scintillators [39]. Furthermore, the signature from a decay electron is dependent on the orientation of the electron track relative to the MWPC plane: a track perpendicular to the plane triggers only a few MWPC wires and is difficult to trace. Neutron capture events on the quenching gas nuclei cause point ionization events, probably due to uv irradiation in recoil breaking of the molecules. The signals were indistinguishable from perpendicular electron tracks and required a wire multiplicity cut in the data with the consequent loss of detection efficiency. The loss in order of 10% had to be calculated by a Monte Carlo simulation and a systematic uncertainty of 9s was estimated.

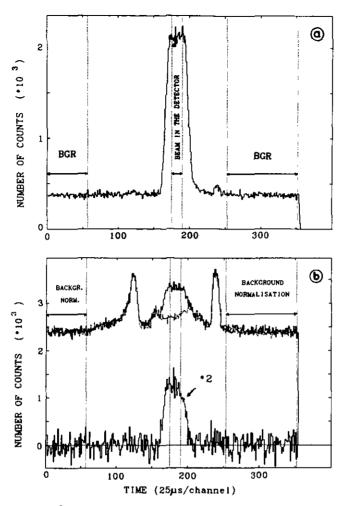


Figure 7. ³He (n, p)t events (a) and decay electron events (b) recorded in the TPC against time of flight of the neutron packet. The background for the electron events (dotted line in (b)) was taken from parts in the TPC not exposed to the neutron beam [23].

The first experiment resulted in a value of

$$\tau_{\rm p} = 878 \pm 27 ({\rm stat.}) \pm 14 ({\rm syst.}) {\rm s.}$$

It seems to be difficult to improve the systematic precision in this method to a level below 10 s, without a major complication of the system such as using additional detectors surrounding the drift chamber.

3.3. Experiments based on decay protons

Compared to decay electrons the detection of decay protons is technically more difficult, but an almost 100% detector efficiency could be achieved under favourable background conditions.

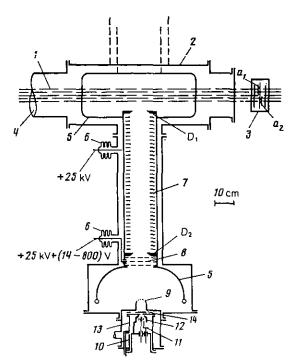


Figure 8. The IAE neutron lifetime experiment counting decay protons [13, 20]. 1, neutron beam; 2, vacuum chamber; 3, monitor chamber $(a_1$ and a_2 are 233 U layers); 4, channel for passage of extracted neutron beam to a trap and to a vacuum post; 5, electrodes; 6, ceramic insulators; D_1 , D_2 , diaphragms; 7, aluminium-foil rings; 8, electrostatic filter grids; 9, hemispherical grid; 10, detector vacuum chamber; 11, detector gas-filled volume; 12, detector comprising a proportional counter with a drift grid; 13, film-covered detector port; 14, valve separating the volumes of chambers 2 and 10.

3.3.1. The experiments at the Atomic Energy Institute in Moscow [9, 13, 20]. Over many years a neutron lifetime measurement by proton counting was developed by the group of Spivak and coworkers at Moscow. The experiments were carried out at the IR-8 reactor. The first version in 1959 gave a value of $\tau_n = 1013 \pm 26$ s [9]. The method was further developed leading to the apparatus shown in figure 8. A collimated thermal neutron beam of 9 cm diameter and a flux of 3×10^8 neutrons/s passed through the decay volume which was at a constant potential of 25 kV. By their recoil energy decay protons passed through the diaphragms, D₁ and D₂, which defined the solid angle under which the proton detection device viewed the decay volume. After passing an electrostatic filter behind the second diaphragm, the protons were accelerated and focused on to the proportional counter, which was at ground potential. The counter gas was CH₄ at 10 mbar pressure, the counter entrance window a 20 µm organic foil. The detection efficiency for the 25 keV protons was very close to 100%. In the decay proton path an electrostatic filter, set at 14 V above 25 kV, prevented low energy ions from reaching the counter. The corresponding loss in the decay proton spectrum was only 0.2%. The background was measured with the electrostatic filter at 25 kV + 800 eV (above recoil proton energy). The transmission of the grids in the proton path was measured by alpha particles as $87.42 \pm 0.28\%$.

For the determination of the neutron density and the solid angle of proton detection the neutron density distribution over the beam cross section had to be determined. For this purpose gold foil activation was used and the activation measured for different sections of the foil. The neutron lifetime was finally evaluated according to the equation:

$$\tau_{\rm n} = \varepsilon \eta Q_{\rm s}/n_{\rm p}.\tag{16}$$

The quantity ε denotes the efficiency for proton detection averaged over the beam, η the grid transmission and Q_s the number of neutrons per cm beam length. The efficiency ε was calculated from the diaphragm collimation and beam density distribution. The 1978 result is quoted as $\tau_n = 887 \pm 8 \, \mathrm{s}$ [13]. The uncertainty was governed by the neutron density measurement, which suffered from epithermal neutrons in the beam, and by the correction for protons scattered at the walls of the vacuum chamber.

This relatively low value for τ_n was not believed for a long time and not included in the evaluation by the particle data group. The more recent neutron lifetime measurements however are consistent with this early measurement (see below) and lead to a full 'rehabilitation' of the experimental result.

In 1988 the result from 1978 was slightly revised when Spivak worked on the potential precision of his method and introduced some corrections. The revised value is cited in [20] as

$$\tau_{\rm n} = 891 \pm 9 \, \rm s.$$

In two subsequent papers [20, 40] Spivak has discussed the improvement in accuracy which could be achieved with his apparatus if it were to be used with an intense cold neutron beam. A final precision of 3 s is quoted after discussing in detail the various corrections and calculations which enter into his method.

3.3.2. The Sussex-Nist-ILL experiment [25]. A first experiment with the storage of decay protons was performed in 1980 by Byrne et al at the ILL high flux reactor [16].

Decay protons were retained by electrostatic and magnetic fields in the form of a Penning trap and emptied after a defined storage time by a high tension pulse. The protons were then accelerated towards surface barrier detectors for protons. By this method protons in the decay volume are collected on the detector and the background is reduced by the ratio of the trap emptying time to storage time. The neutron beam density was measured by the $^{10}B(n, \alpha)^7Li$ reaction in a thin foil as target. In this experiment problems resulted from the precise mass determination of the boron layers, from the evaluation of the effective decay volume and a possible incomplete emptying of the proton trap. The resulting value for the neutron lifetime was $937 \pm 18 \text{ s}$ [16]. After further investigations on the boron targets this result was withdrawn in 1990 [41].

In a new approach the same group, enlarged by a collaboration with NIST, Washington, utilized the original basic idea but changed the device fundamentally. The new experimental set-up is shown in figure 9. Similar to the PERKEO spectrometer for electrons the proton trap consisted of a magnetic field in a superconducting solenoid (field strength 2 T) parallel to the neutron beam and of electrostatic barriers.

To eliminate the problem of defining the decay volume at the ends, the length of

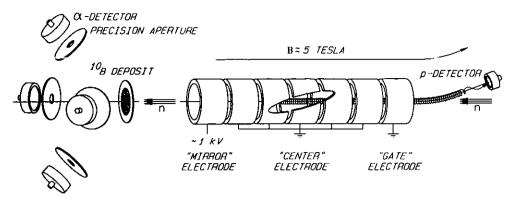


Figure 9. Schematic outline of the Sussex-NIST-ILL neutron lifetime experiment working with a proton trap. The actual trap had 16 independent electrode segments [25].

the trap could be altered by a series of potential cylinders. Assuming that the end effects are independent of the trap lengths, the difference between long and short trap lengths cancelled the end effects and defined the length of the decay volume by geometrical length of the potential cylinders. Figure 10 shows the recorded proton counts as a function of the trap length. The slope yields the proton rate per length, the intersection the end effects of the trap. After a typical accumulation time of 10 ms the proton trap was emptied by changing the electric potential. The protons were accelerated and guided in a slightly bent magnetic field towards a surface barrier detector placed outside the neutron beam. The typical acceleration voltage was 20 kV. The time structure of the collection of the protons on the detector was investigated in detail. The total collection time was less than $100~\mu s$ to compare, for the background suppression, with the 10 ms of accumulation. Care was also taken to empty the trap of electrons since, by the Penning effect, they can ionize the residual gas even in an ultra high vacuum. The ions would give similar signals in the surface barrier detector to the decay protons.

The neutron density was measured, as in the earlier experiment, using the ${}^{10}B(n, \alpha)$ reaction products from a thin foil in the neutron beam, viewed by four solid state detectors. The foil thickness and the surface barrier detector efficiencies

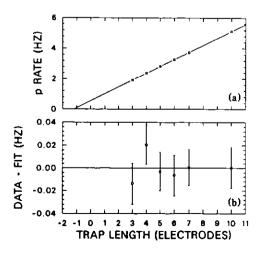


Figure 10. A plot of (a) proton count rate against trap length and (b) residuals. The slope of this line is the decay activity per unit length of the neutron beam [25].

for the alpha particles had to be determined on an absolute scale, which is a difficult task. The device was cross calibrated at NIST with the various high precision neutron standards developed at that institute [33].

A first experiment with this apparatus was carried out at the cold neutron beam H14-PN7 at the ILL, Grenoble. The neutron flux in the collimated beam of 1 cm cross section was 10⁷ neutrons/cm² s. The statistical accuracy was about 2% per day of acquisition. The result of the experiment was [25]

$$\tau_{\rm p} = 894 \pm 5.3 \, \rm s.$$

The uncertainties were composed of a statistical error of 3s and a systematic uncertainty of 4s. The dominant systematic error resulted from the flux measurement. This up-to-date most precise neutron beam experiment on τ_n has the potential for further improvements, although already at the present stage it is very complex and technically difficult to perform. The continuation of the experiment is planned at the NIST reactor.

4. Neutron lifetime experiments using storable neutrons

An alternative to neutron beam experiments as described in the previous section became possible with the availability of very slow neutrons which are storable in a closed volume for long periods and which behave like an ideal gas.

Once neutrons are spatially confined, without any other losses than those due to beta decay, one can count either the decaying or the surviving fraction of the population as a function of time and thus obtain the decay constant from successive storage cycles.

From the decay law, equation (2), follows:

$$\tau_{\rm n}^{-1} = \frac{\ln(N(t_1)/N(t_2))}{(t_2 - t_1)} \tag{17}$$

where $N(t_1)$ and $N(t_2)$ represent the fraction of neutrons which have survived successive storage times t_1 and t_2 . Thus the lifetime is related to a measurement of the ratio of two counts. If the measurements are performed under the same conditions the original neutron density, the decay volume and the detector efficiency are eliminated by this ratio.

The difficulty of storage methods is related to possible UCN losses (bottle leaks) which are not due to beta decay. These losses will inevitably introduce systematic errors unless they can be controlled and the results corrected. The measured total lifetime τ_m in the bottle is then given by:

$$\tau_{\rm m}^{-1} = \tau_{\rm n}^{-1} + \sum \tau_{\rm loss}^{-1} \tag{18}$$

where τ_n represents the neutron lifetime and $\sum \tau_{loss}^{-1}$ the loss probability for neutrons due to various processes other than beta decay. Equation (18) becomes more complicated for losses which depend on the neutron energy.

The proposition of this type of neutron lifetime experiments was made as early as 1959 by Zel'dovich [42] but it took a long time until reasonably long neutron storage times were obtained experimentally and significant numbers of storable neutrons were available for sensitive experiments [43-45]. The first experimental attempts to measure the neutron lifetime with bottled neutrons were published

between 1978 and 1986 achieving errors ranging from 5 to 11% [14, 15, 18]. Only very recently a remarkable effort by several groups has succeeded in obtaining results from storage methods with noticeably higher precision than that achieved in the beam methods.

4.1. Neutron confinement

For a better understanding of the techniques used we give a brief introduction to the topic of storage of very low energy neutrons. Neutrons are subject to the four known interactions. If the resulting forces are repulsive, traps can be constructed for neutrons with low enough energy. The energy in question is as low as 10^{-7} eV in the case of the coherent strong interaction between long wavelength neutrons and matter. It is again 10^{-7} eV for 1 m fall height in a gravitational field or in a $1.7 \, \mathrm{T\,cm^{-1}}$ magnetic field gradient acting on the magnetic moment of the neutron. Each of the three possibilities has been employed successfully in the construction of neutron bottles.

The phenomenon of neutron confinement by material walls is described most conveniently in the following way: when neutrons approach a material wall they interact coherently with a large number of nuclear scatterers. The coherent interaction has been described by Fermi [46] in the form of a complex potential, the Fermi potential:

$$E_{\rm F} = V + iW \tag{19}$$

where the real part leads for V > 0 to total reflection of the incident neutron wave if $E_n < V$. The potential V is proportional to the density and the coherent scattering length of the wall material and independent of neutron energy. The imaginary part of the constituents of the wall potential is responsible for reflection losses which are determined by the neutron absorption and inelastic scattering cross sections of the reflecting material. The resulting energy dependent loss probability per reflection, averaged over all angles of incidence for an isotropic neutron velocity distribution, is given by

 $\bar{\mu}(E_{\rm n}) = 2 \frac{W}{V} \left\{ \frac{V}{E_{\rm n}} \sin^{-1} \left[\left(\frac{E_{\rm n}}{V} \right)^{1/2} \right] - \left(\frac{(V - E_{\rm n})}{E_{\rm n}} \right)^{1/2} \right\}. \tag{20}$

The loss probability $\bar{\mu}$ is on the level of 10^{-6} for some materials (solid O_2 at 10 K) and in favourable cases even smaller.

Neutrons with total energy lower than the highest values of $E_{\rm F}(\sim 3 \times 10^{-7} \, {\rm eV})$ are defined as ultracold neutrons (UCN) with corresponding de Broglie wavelength larger than $\sim 500 \, {\rm \AA}$ and velocities lower than $7 \, {\rm m \, s^{-1}}$. These very low energy neutrons can be stored in containers made of materials with low loss cross sections, for periods determined essentially by the neutron beta decay.

Only very recently densities of the order of 100 ucn/cm³ became available making sensitive neutron lifetime experiments possible. The most intense ucn sources are at LNPI, Leningrad [45] and at the ILL reactor [44].

5. Review of neutron storage experiments determining the neutron lifetime

5.1. Lifetime experiments using magnetic storage—the neutron storage ring NESTOR [22]

The first lifetime result from an experiment using magnetic neutron storage was published in 1978 by Kügler et al [14] from Bonn and was carried out at the ILL

reactor. Though the main emphasis was originally directed more towards the demonstration of the feasibility of magnetic neutron storage the experimenters could already deduce from their careful work a value of $\tau_n = 907(70)$ s [14]. The precision was essentially limited by the low density of the first UCN/VCN (very cold neutron) source available at the ILL reactor and thus the low number of trapped neutrons.

Neutron confinement by magnetic barriers avoids losses originating from wall reflections. However the volume defined by the barriers has to be leak free for trapped neutrons. Up to now the sole magnetic neutron trap reported to have worked successfully in this sense was the neutron storage ring NESTOR (figure 11) designed and built at the University of Bonn by W Paul's group and installed at the ILL [47]. Because of the electric neutrality of the neutron one can only use its magnetic moment μ_n and produce a force $F = \mu_n dB/dr$ by an inhomogeneous magnetific field B. A field $B \sim -r^2$, as formed by a magnetic sextupole composed of six wires with currents running alternatingly in opposite directions, can confine neutrons which have their spin direction opposite to the magnetic field. Paul and his collaborators built a magnetic storage ring by bending such a sextupole field into a torus. The phase space volume for storable neutrons is determined by the strength of the magnetic field. The beam width in the ring is limited by the condition that betatron oscillations leading to uncontrollable neutron losses via beam instabilities have to be avoided. The suppression of betatron oscillations was achieved by adding a damping decapole field to the sextupole field and by beamscrapers limiting the radial velocity component of the neutrons in the ring. Neutron losses due to spin flips should not occur since zero field regions were carefully avoided by the correct injection of neutrons into the ring volume.

Figure 11(a) shows the basic configuration of the superconducting coils. The innermost two current loops are not necessary because the centrifugal force takes over their function. The space they would occupy is needed for the guide system which injects neutrons into the ring (figure 11(b)). The diameter of the ring was 109 cm, the maximum usable field 3.5 T and the corresponding field gradient $1.2 \, \mathrm{T \, cm^{-1}}$ with a coil current of 200 A.

A new series of measurements was carried out in 1987 with essentially the same apparatus at the improved UCN/VCN source of the ILL [44]. An initial number of approximately 10³ neutrons in the velocity range between 10 and 15 m s⁻¹ were stored in the ring. Data were accumulated in successive filling-beam shaping-

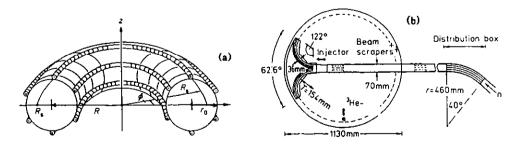


Figure 11. The magnetic sextupole torus NESTOR for neutron storage experiments [22, 47]. (a) Principle of the torus. The superconducting wires are carrying currents in alternating directions. In the actual device the inner current lines were left out since a centrifugal force acts on the circulating neutrons. (b) Top view of neutron lifetime experiment.

storage-counting cycles $(10 \, \text{s} - 10 \, \text{s} - (20 - 4500) \, \text{s} - 10 \, \text{s})$. The influence of all timing parameters was studied carefully. The beam profile and position were varied and measurements were performed with different magnetic field strengths to test whether the measured decay constant includes losses from storage ring leaks. Departure from a pure exponential behaviour of the decay curve was observed during the initial beam stabilization phase only. For this reason, storage times longer than 500 s were used for the final lifetime data. The overall result obtained from all clean runs is shown in figure 12, and yielded $\tau_n = (876.7 \pm 9.9) \, \text{s}$ [22]. This is actually the only neutron bottle experiment free from losses by interaction with the bottle walls.

On the other hand—if one is not excluding extremely small bottle losses inaccessible to experimental verification—this result can be interpreted as a very valuable lower limit to the neutron's beta decay lifetime. The main component of the error still comes from low counting statistics, partly due to the naturally limited phase space density of the neutron source and the reduced beam acceptance of the ring and partly due to the short overall running time caused by difficulties with a complex cryostat. A new design of NESTOR could improve the experimental sensitivity substantially but is not planned.

5.2. Lifetime experiments using storage by material walls

Two directions have been followed for neutron lifetime experiments in material bottles. One philosophy was to develop bottles with negligible wall losses whereas the other was to use wall materials with low reflection losses and to develop techniques to determine those undesired losses by varying the experimental parameters. Both philosophies were combined in some experiments.

5.2.1. The Kurchatov Institute experiment [17, 21, 27]. The first successful neutron lifetime experiments in material bottles were performed by V I Morosov and collaborators in Russia [15]. The experimenters employed well cleaned, low loss materials and controlled the finite bottle wall losses by introducing additional surfaces into the storage volume, thus varying the volume to surface ratio. The work was continued later at the ILL in Grenoble. The earlier studies used an aluminium cylinder, 105 cm in diameter and 75 cm high. The cylinder was closed at the top by gravity (figure 13). The surface could be heated to 750 K for cleaning and cooled to

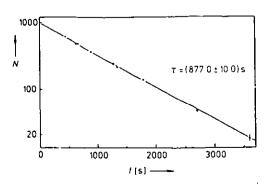


Figure 12. Logarithmic plot of the number of neutrons against storage time in NESTOR [22].

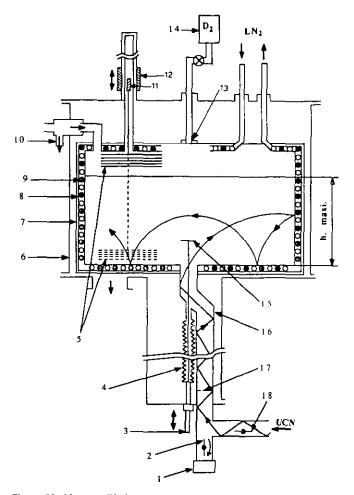


Figure 13. Neutron lifetime measurement using storage in an aluminium vessel [17, 21]. 1, ultracold-neutron detector; 2, detector gate; 3, shaft of disc-shaped gate; 4, bellows unit; 5, packet of plates; 6, vacuum housing; 7, heat-shield; 8, heater; 9, liquid-nitrogen coil; 10, hermetically sealed valve for evacuating the vessel; 11, core; 12, solenoid; 13, D_2 inlet; 14, D_2 reservoir; 15, disc shaped valve; 16, vertical guide; 17, aluminium membrane; 18, UCN inlet gate.

80 K by a liquid nitrogen loop. The surface was prepared and renewed either by evaporation of aluminium or by condensation of heavy ice (D₂O) which has excellent UCN reflection characteristics. A disc shaped shutter at the bottom of the cylinder admitted the UCN to the storage volume and allowed the remainder to exit, after the storage phase, towards a ³He proportional counter. Possible leaks at the shutter could be monitored during the storage phase. An aluminium membrane isolated the clean storage bottle vacuum from the UCN source. The bottle itself was raised to a height such that UCN from the source could reach a maximum height of 48 cm in the bottle. Aluminium sheets suspended on thin aluminium wires could be lowered from the top into the active bottle volume, thereby increasing the total surface. The total neutron loss rate in the bottle was plotted against the wall collision frequency calculated on the basis of the surface to volume ratio of the

bottle. The beta decay loss rate is the remainder of the losses for an infinite large bottle. The reliability of this extrapolation procedure depends on the homogeneity of the bottle surface. The authors obtained from their Al surface runs a value of $\tau_n = 903 \pm 13$ s [17] and from the D₂O runs $\tau_r = 893 \pm 20$ s which gives a combined value of $\tau_n = 900 \pm 11$ s [21].

The most recent experiment which has been performed by Morozov's new group in 1990 at the ILL in Grenoble used a 100 cm height and 30 cm diameter cylinder as the storage volume with otherwise the same characteristics and possibilities as in the earlier arrangement. An important additional feature of the apparatus was the use of ³He detectors (1 m long, 4 cm diameter) which surrounded the storage vessel. The counters detected with about 10% efficiency the losses of UCN when they were upscattered inelastically to thermal energies on the vessel's walls. This measurement provided the control of the main loss channel (at higher temperatures) of stored neutrons as a function of the wall temperature and bottle geometry. The walls were coated with a hydrogen free oil with trade name Fomblin. More details about this oil will be given in the description of the ILL experiment (section 5.2.2) which used a liquid surface [18, 24] for the first time. A smaller diameter cylinder made of 1 mm stainless steel sheet, coated also with Fomblin oil, could be inserted into the storage volume as an additional surface for variation of the neutron's wall collision rate. The surface was thus multiplied by a factor of almost three uniformly at all heights in the vessel. This point is important for a vessel for which, due to the filling procedure and the gravity, the neutron spectrum and thus the bottle losses vary over the height. The measurements were performed at bottle temperatures between -50 and +20 °C.

Though the final result and the discussion of the systematic errors of this experiment has not yet been published at the time of writing a value of $883.2 \pm 2.9 \text{ s}$ has been reported for τ_n at a conference by V Morozov [27].

5.2.2. The ILL experiment [24]. A French-German-British collaboration has performed at the ILL a neutron lifetime experiment using Fomblin oil coating for the first time. The authors developed a room temperature liquid walled bottle with a continuously variable volume to surface ratio. It has the following advantages: a liquid forms an ideally flat and homogeneous surface which is altered only slowly with time by impurities and it can be renewed easily for reproducibility tests. A viscous liquid seals perfectly all the gaps at the moving parts like shutters. The remaining unavoidable surface losses can be removed by extrapolation to infinite bottle size. An earlier simple test experiment showed that the method was promising for a high precision neutron lifetime experiment [18].

Since this extrapolation procedure is employed by several experiments we recall at this point that the measured UCN losses originate in the simplest case from beta decays and wall reflections:

$$\tau_{\rm m}^{-1} = \tau_{\rm n}^{-1} + \tau_{\rm w}^{-1} = \tau_{\rm n}^{-1} + \left[\bar{\mu}(v)\lambda/v\right]^{-1} \tag{21}$$

where $\bar{\mu}(v)$ represents the velocity (v) dependent loss rate per bounce and λ the mean free path between bounces. Since λ depends, except for a small gravity correction, only on the bottle geometry ($\lambda = 4 V/S$; V volume, S surface) one can eliminate the wall loss contribution by measuring $\tau_{\rm m}$ in different sizes of the bottle.

The bottle was formed by a rectangular glass box (figure 14) with height 30 cm,

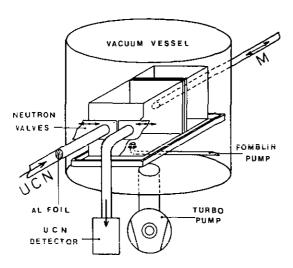


Figure 14. Neutron lifetime experiment at the ILL using a Fomblin coated glass vessel of variable size [24].

width 40 cm and a length which was variable between 0 and 60 cm by means of a piston-like movement of one wall. Two sliding glass plates in conjunction with two holes in the front wall form the inlet and outlet doors for filling the storage volume with UCN from the source and for counting the surviving neutrons in a ³He detector, respectively. Oil could be sprayed, in situ, onto the whole inner bottle surface where it soon reduced to a thin film. The oil used was a hydrogen-free, fully fluorinated polyether known by the trade name Fomblin. The medium viscosity oil has a room temperature vapour pressure of the order of 10^{-8} Torr and an UCN reflection loss probability of about 3×10^{-5} per collision. An initial population of $(1-4)\times10^5$ UCN, depending on the available beam position, was fed into the bottle. They had an upper spectral cut-off at $4.55 \, \mathrm{m \, s^{-1}}$. A vacuum of 2×10^{-7} Torr was maintained during the experiment.

The losses of UCN caused by the wall collisions were about 20% of the beta decay losses in the largest volume of 721 at 10 °C. The longest storage time used was 1.5 hours. The measured loss rate is shown in figure 15 as a function of the inverse mean free path.

Since $\bar{\mu}$ is energy dependent an UCN spectrum of finite width changes during the confinement time. Therefore the lifetime $\tau_{\rm m}^{-1}$, in equation (21), is storage time dependent. To circumvent complications due to time dependent bottle lifetimes which arise when different bottle geometries are compared, the authors scaled all time intervals as the corresponding bottle mean free paths. This means that each velocity group undergoes the same number of wall collisions and thus suffers identical losses in two bottle volumes 1 and 2 provided that the initial UCN spectra are the same and that the confinement times t_1 and t_2 are chosen as:

$$t_1/t_2 = \lambda_1/\lambda_2. \tag{22}$$

The neutron spectra will then be the same in the two bottles at the corresponding times t_1 and t_2 .

Runs were performed at different temperatures and under different experimental

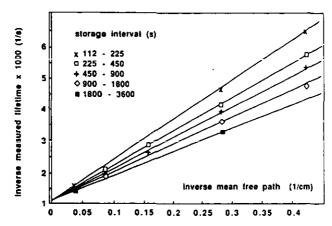


Figure 15. Result of the ILL neutron storage experiment [24]. The storage intervals were scaled to the mean free path in the vessel of variable size.

parameters to check for possible systematic errors. The final result obtained for the neutron lifetime is 887.6 ± 3 s [24]. The error is determined essentially by the uncertainties in a small correction which is related to the influence of gravity on the wall collision rate of UCN for the variable bottle geometry. An improved version of the experiment is in preparation and should be able to increase the precision by a factor of three.

5.2.3. The Leningrad experiment [26]. A further lifetime experiment using neutron storage was proposed by Serebrov and was performed recently at the UCN source of the Leningrad research reactor (LNPI) by a collaboration from Leningrad and Dubna [48, 26]. The storage volume was made of an aluminium sphere with 75 cm inner diameter and a hole in the surface (figure 16). The sphere could be rotated around a horizontal axis which allowed the bottle to be filled with neutrons by positioning the hole downwards to a guide and thus connecting it with the UCN source. Rotating the hole to a higher position closed the bottle by gravity for UCN up to the corresponding maximum neutron energy. An advantage of the gravitational trap over a bottle with a mechanical shutter is the absence of physical leaks. The population remaining after a selected storage period was released and counted by rotating the hole downwards again and channelling the UCN into a ³He detector. The rotatable bottle could also be used for the energy analysis of the stored neutron population. For this purpose the hole was rotated downwards step by step and the UCN are counted as a function of the corresponding height interval.

The inner surface of the bottle was coated in situ with materials of extremely small cross section for neutron absorption like beryllium (evaporation of 3000–5000 Å) or pure solid oxygen (condensation of a layer of 3–7 μ m). The bottle walls were cooled to 10–15 K to minimize UCN losses by inelastic scattering processes on the walls. Originally the authors intended to control the remaining, but extremely small, wall loss component with the help of the well established neutron energy dependence. The measurement of the storage time as a function of the UCN energy makes possible the extrapolation to zero energy, where surface reflection losses essentially vanish. However, the observed losses (3% relative to the beta decay

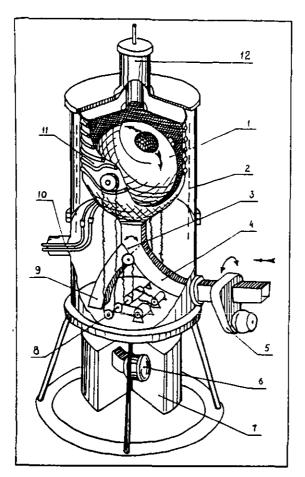


Figure 16. Set-up for the measurement of the neutron lifetime with a gravitational trap [26]. 1, UCN storage trap; 2, nitrogen screen; 3, distribution valve; 4, 9, neutron guide; 5, injection valve; 6, UCN detector; 7, detector shield; 8, system for rotation; 10, cryopipes; 11, cryostat; 12, system for frozen cover.

losses at 10 K), which could be determined with 10% uncertainty, were higher than expected. The UCN count rate per energy bin was also not high enough (30 000 UCN in the whole bottle volume) to achieve the desired statistical accuracy. To improve the precision of the extrapolation the authors replaced the sphere by a flat cylinder, 15 cm high with its symmetry axis horizontal, and with identical diameter and filling hole as the former bottle in order to conserve the UCN spectrum. The cylinder surface was coated in the same way as the sphere. From the measurement of the storage time in the two bottles which depends on the average wall collision rate, the beta decay lifetime was obtained by the usual extrapolation to infinite mean free path (figure 17).

The overall result after combining the beryllium and oxygen runs is $\tau_n = 888.4 \pm 2.9$ s [26]. The authors attribute the error essentially to counting statistics. This elegant method has the potential for improvement in precision by hopefully a

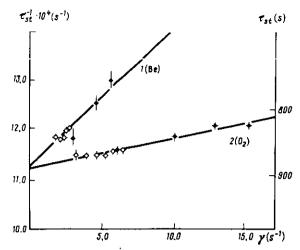


Figure 17. Result of the neutron lifetime measurement [26]. The parameter γ scales the wall losses. The extrapolations $\gamma \rightarrow 0$ (no wall losses) are shown for the Be and solid O_2 coated bottle walls, respectively.

factor of three if the stronger ILL UCN source could be used and if a larger variation of the surface to volume ratio has been made possible without opening the vacuum system as is foreseen in a new design of the bottle.

6. Implications of the neutron lifetime

Comparing the various experimental results on the neutron lifetime we observe a quite satisfactory agreement (see table 1) and the precise value for $\tau_n = 887.4(1.7)$ s provides a number of interesting implications.

The lifetime of the neutron is related to the weak interaction coupling constants in the first generation of particles. Both the Fermi coupling (no spin change from the neutron to the decay proton: vector coupling constant $g_{\rm N}$) and the Gamow-Teller coupling (spin flip: axial vector coupling constant $g_{\rm A}$) are involved. In conjunction with other neutron decay parameters the coupling constants can be deduced individually from neutron decay alone. We find important implications of the neutron lifetime in particle physics, in neutrino induced reactions and in cosmology.

6.1. Implications of the neutron lifetime in weak interaction theory

The decay of the free neutron is a semi-leptonic weak interaction process since both leptons and baryons are involved. In the quark picture a d quark converts into a u quark under emission of a W⁻ boson (figure 1).

In the standard v-A theory of weak interactions only vector and axial vector currents are mediating the weak force. The currents interfere with a phase shift of π . In this framework the neutron lifetime τ_n is related to the corresponding coupling constants g_V and g_A by

$$\tau_{\mathbf{n}}^{-1} = \frac{\ln 2}{K} f^{R} (g_{V}^{2} + 3g_{A}^{2}) \tag{23}$$

with

$$K = 2\pi^{3} (\ln 2) \hbar^{7} / m_{e}^{5} c^{4} = 8.1195 \times 10^{-7} \frac{(\hbar c)^{6}}{\text{GeV}^{4}} = 1.2306 \times 10^{-120} \text{ J}^{2} \text{ m}^{6} \text{ s}^{2}.$$

For the definition and dimension of the coupling constants we use the convention of Wilkinson [49] where $g_V = V_{\rm ud} f_1(q^2 \to 0)$ and $g_A = V_{\rm ud} g_1(q^2 \to 0)$ with the usual weak interaction form factors $f_1(q^2)$ and $g_1(q^2)$ at zero momentum transfer. The suitable radiation corrected phase space factor was evaluated by Wilkinson [49] as $f^R = 1.71465(15)$. The quantity $V_{\rm ud}$ is the element in the Kobayashi–Maskawa (km) matrix which connects the u and the d quarks. It is related to the Cabibbo angle Θ_c by $V_{\rm ud} = \cos \Theta_c$.

The axial vector coupling constant in equation (23) is weighted by $2\Delta L + 1 = 3$ reflecting the $\Delta L = 1$ angular momentum change in the spin flip of a Gamow-Teller type transition. The axial vector current is only partly conserved in weak interaction reactions and renormalized by the strong interaction [50]. On the other hand the standard weak interaction theory assumes a conservation of the vector current (cvc), i.e. g_V .

The neutron lifetime value can be combined with angular correlation measurements in the neutron decay to evaluate the individual coupling constants solely from neutron decay data. The ratio of the coupling constants $\lambda = g_A/g_V$ can be derived conveniently from the beta emission asymmetry A_0 relative to the neutron spin.

$$A_0 = -2\frac{\lambda(\lambda+1)}{1+3\lambda^2}. (24)$$

Following the presentation by Dubbers *et al* [51, 30] the values of g_V and g_A from the neutron decay, equations (23), (24), are plotted in figure 18. The broken contour shows the result of [51, 30] obtained prior to the neutron lifetime data [26, 27] and prior to the recent beta asymmetry measurement by Erozolimskii *et al* [52]. Including [52] the new mean value for λ is $\lambda = -1.2570$ (29).

A substantial shift of the mean value of g_V and g_A between the two data sets can be observed although the 1σ error contours still overlap. The authors in [51, 30]

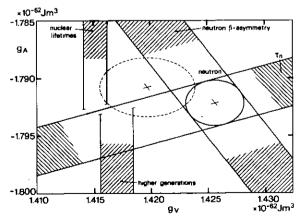


Figure 18. Comparison of experimental weak interaction coupling constants. The ellipsoids show the 1σ uncertainty contour for g_A , g_V deduced from neutron decay data in 1990 [30, 51] (broken curve) and in the present review (full curve), respectively.

deduced from the neutron data alone $g_V^n = 1.4197 (41) \times 10^{-62} \text{ J m}^3$ and $g_A^n = 1.7910 (25) \times 10^{-62} \text{ J m}^3$.

Including the more recent measurements leads now to

$$g_{\rm V}^{\rm n} = 1.4257 \,(28) \times 10^{-62} \,\rm J \,m^3$$
 (25)

$$g_A^n = 1.7922 (20) \times 10^{-62} \,\text{J m}^3.$$
 (26)

According to the CVC theory the value of g_V can also be obtained from superallowed $0^+ \rightarrow 0^+$ nuclear beta decays.

$$ft'(0^+ \to 0^+) = \frac{K}{2g_V^2}.$$
 (27)

The values ft' are deduced from the measured ft values by computing (small) charge and radiative corrections [53-55]. A world average value for ft' was recently evaluated by Hardy $et\ al\ [54]$ with the result $ft'=3073.3\ (3.5)\ s$. This evaluation is in good agreement with that of Wilkinson, $ft'=3070.0\ (2.5)\ s$ [55]. We adopt here an unweighted mean value of these results, i.e. $3071.7\ s$, with an estimate for the uncertainty of 4 s. Using equation (27) we obtain:

$$g_V^{O^+ \to O^+} = 1.4153 (10) \times 10^{-62} \,\text{J m}^3.$$
 (28)

This value is drawn in figure 18.

The Kobayashi-Maskawa matrix mixes the weak interaction and the mass eigenstates of the quarks. For the case of three quark generations the unitarity of the matrix requires for example $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$. In the framework of the standard model the matrix elements can be deduced by comparison of semileptonic and purely leptonic decays. The cvc theorem predicts $g_v^n = V_{ud} g_\mu$, with g_v^n and g_μ the coupling constant in the beta and muon decay, respectively. Thus g_v^n can be predicted from higher generations by [51].

$$g_{V}^{hg} = g_{\mu} [(1 - |V_{us}|^2 - |V_{ub}|^2)(1 + \Delta\beta - \Delta\mu)]^{1/2}$$
(29)

with [56] $V_{\rm us} = 0.220$ (2), $V_{\rm ub} = 0.007$ (3) and [54] $g_{\mu} = 1.435\,863$ (12) \times $10^{-62}\,\rm J~m^3$, and the correction [54] $\Delta_{\beta} - \Delta_{\mu} = 2.37$ (18) \times 10^{-2} . The result $g_{\rm V}^{\rm hg} = 1.4172$ (14) \times $10^{-62}\,\rm J~m^3$ is shown in figure 18.

The new g_V^n value disagrees with $g_V^{O^+ \to O^+}$ and g_V^{hg} at a level of 3.5 σ and 3.0 σ , respectively. Recently Gudkov [57] discussed a common correction term for $g_V^{O^+ \to O^+}$, which would increase that value by 0.24% and reduce the difference to g_V^n to a level of 2.4 σ .

The observed discrepancy among the g_V values was interpreted in terms of possible right-handed currents, i.e. (V+A) contributions [58]. However this interpretation is not consistent with the unitarity of the KM matrix. Also the size of the right-handed currents required is unlikely due to limits from other types of experiments (see discussion in [26]).

Further experiments and calculations of correction terms are certainly necessary to clear up this point before serious doubts on the validity of the standard v-A theory are justified.

6.2. Neutrino induced reactions

The electron antineutrino from beta decay was first detected by Reines et al [59], using a nuclear reactor as a strong electron antineutrinos source from beta decaying

fission products of ²³⁵U, ²³⁸U, ²³⁹Pu and ²⁴¹Pu fission. For the detection of neutrinos the inverse neutron decay process was used

$$\bar{\nu}_{e} + p \rightarrow n + e^{+}. \tag{30}$$

Later on, high precision measurements were carried out on reactor neutrinos to determine the cross section of the reaction (30) and to search for possible neutrino oscillations [60]. The cross section for reaction (30) is proportional to $1/\tau_n$ and within the (v-A) theory given by [61, 62]:

$$\sigma_{V-A}(E_{\bar{v}}) = \sigma_{V-A}^{(0)}(E_{\bar{v}})(1 + \delta_{thr})(1 + \delta_{WM} + \delta_{rec} + \delta_{rad})$$

$$\sigma_{V-A}^{(0)}(E_{\bar{v}}) = C(E_{\bar{v}} - \Delta)((E_{\bar{v}} - \Delta)^2 - m_e^2 c^4)^{1/2}$$

$$C = \frac{2\pi^2 (\hbar c)^2 \hbar}{(m_e c^2)^5 f \tau_n} = 9.55 \times 10^{-44} \text{ cm}^2$$

$$\Delta = (M_D - M_D)c^2 = 1.293 \text{ MeV}.$$
(31)

The constant C is evaluated with the phase space factor value from the neutron decay $f_R = 1.7146$ [49] and the neutron life time of 887.4 s. For the small correction terms δ see [61, 62]. The reaction threshold energy is 1.8 MeV. In the course of the neutrino measurements the recommended neutron lifetime value changed significantly (from 926 (11) s in 1980 to 887.4 (1.7) s in 1991) and hence the comparison with neutrino detector data had to be revised.

The antineutrino spectra from the beta decays following neutron induced fission are known from complementary measurements of beta spectra. The most precise data were obtained at the ILL Grenoble [63]. For fission of ^{235}U the integral cross section for the reaction (30) is predicted with the help of these $\bar{\nu}_e$ spectra and equation (31) as $\bar{\sigma}_{\text{V-A}} = 6.40 \times 10^{-43} \, \text{cm}^2$ per antineutrinos from one fission event, with a precision of 3.2% (90% cL). The corresponding values for fission of ^{239}Pu and ^{241}Pu are $4.19 \times 10^{-43} \, (3.9\%)$ and $5.76 \times 10^{-43} \, (3.6\%)$, respectively [63, 64].

A recent comparison on reactor neutrino data was carried out by Mikaelyan et al [64], under the assumption of no neutrino oscillations. Using the knowledge of reactor neutrino spectra and averaging the available results from neutrino detector measurements the integral cross section for ²³⁵U fission neutrinos was deduced to be:

²³⁵U:
$$\bar{\sigma}_{\text{meas}} = 6.32 \times 10^{-43} \text{ cm}^2/\text{fission} (\pm 3.3\%) = 0.99 \ \bar{\sigma}_{V-A^{\frac{1}{2}}} (1 + H_v^2).$$
 (32)

In equation (32) we allow for the neutrino helicity H_{ν} not being unity, and hence have added the simple reaction balance factor. A direct limit for the electron antineutrino helicity in nuclear beta decays is derived, with the result

$$|H_{\nu}| > 0.95.$$
 (33)

This is the best direct experimental limit presently known for electron antineutrinos. Including the possibility for neutrino oscillations the limit could even be more stringent. The experimental limit for the helicity of the muon neutrino in the pion decay is -0.9975 [65].

The reaction cross section for $\bar{v}_e + d \rightarrow n + n + e^+$ (charged current reaction, cc) and $\bar{v}_e + d \rightarrow n + p + \bar{v}_e$ (neutral current reaction, NC) were also measured with reactor neutrinos, although the statistical accuracy was less than for the \bar{v}_e p reaction. The \bar{v}_e d reaction cross section is proportional to g_A^2 , with the standard

model relations $g_A^{\rm NC} = \lambda g_v^{\rm n}$ and $g_A^{\rm CC} = \lambda g_v^{\rm n} \cos \Theta c$. For the deduction of g_A^2 from the measured $\bar{\nu}_{\rm e} d$ cross sections a complication arises from the strong force in the deuteron leading to a nuclear part in the cross section formula. From $\bar{\nu}_{\rm e} d$ experiments at reactors the reaction cross sections $\sigma_{\rm d}^{\rm NC} = 2.33$ (55) [66], 3.20 (95) [67] and 3.0 (1) [68] were derived (measured with slightly different $\nu_{\rm e}$ spectra). Using the mean of these measured $\sigma_{\rm d}^{\rm NC}$ values and the cross-section calculation of [69], $g_A^{\rm NC}$ can be estimated as

$$|g_{\rm A}^{\rm NC}| = 1.21 \pm 0.11 |g_{\rm v}^{\rm n}|.$$
 (34)

The value is in good agreement with the standard model, $g_A^{NC} = \lambda g_v^n$, $\lambda = -1.25$, within the rather large uncertainty.

The reaction $v_e d \rightarrow ppe^-$, which is related to the cc reaction $\bar{v}_e d \rightarrow nne^+$, is again proportional to g_A^2 . It will be used for solar neutrino spectroscopy at the Sudbury Solar Observatory [70] and is the inverse reaction of the pp fusion process in the sun (see section 6.3.1).

6.3. Cosmology

6.3.1. Solar burning. The first step in solar burning is the pp fusion process

$$p + p \rightarrow d + v_e + e^+. \tag{35}$$

Due to Pauli's principle only protons with antiparallel spin coupling can react with each other. Since the deuteron nuclear spin is one a spin flip of a proton is necessary for the reaction. Consequently the reaction cross section is proportional to g_A^2 . The coupling constant g_A can be best determined by measurements on the neutron decay (see section 6.1). For a given luminosity of the sun the necessary number of pp fusion reactions can be calculated. If g_A would be larger, a lower temperature in the interior of the sun is needed to keep the fusion rate at the required level [71].

In the further fusion process a small branch produces 8B with emission of high energy neutrinos. The fusion rate at the end of the chain is strongly temperature dependent such that the rate via the temperature is roughly proportional to g_A^5 . The so-called solar neutrino puzzle, i.e. much less 8B solar neutrinos are observed on earth than predicted by the standard model, could be due to the use of a too high a value for g_A (i.e. too low a value for τ_n) in the calculations. However the recent neutron lifetime data do not alter the pp rate significantly enough to explain the missing neutrino flux. The neutron lifetime would have to be as low as $800 \, \text{s}$ [72]. This value is definitely excluded by the neutron lifetime measurements, and even by the reactor $\bar{\nu}_e$ measurements discussed in section 6.2.

6.3.2. The ⁴He abundance in the early universe. The big-band model predicts the primordial ⁴He abundance in the universe. It results from a fusion chain of protons and neutrons. It is balanced by the available neutron to proton density ratio which is among other factors determined by the neutron beta decay during the expansion of the universe.

At a temperature of the universe of several MeV the following reactions are in thermal equilibrium

$$n + e^{+} \leftrightarrow p + \tilde{v} \qquad p + e^{-} \leftrightarrow n + v$$

$$N_{n}/N_{p} = \exp - ((M_{n} - M_{p})c^{2}/kT). \tag{36}$$

The quantity M denotes the masses and k the Boltzmann constant.

At these energies deuterons are disintegrated by the large number of energetic photons since the deuteron binding energy is only 2.2 MeV. At lower energies the neutrons decay without being converted back to protons by the reaction (36) and the protons and neutrons can fuse to deuteron and finally to ⁴He, the amount of which depends on the available number of neutrons:

$$p + n \rightarrow d + \gamma$$

$$+ p \rightarrow {}^{3}He$$

$$+ n \rightarrow {}^{4}He.$$
(37)

The ⁴He/¹H ratio emerging from the primordial universe thus depends on:

- (i) the mass density of the universe and the number of relativistic particle species defining the temperature and expansion rate,
 - (ii) the reaction cross sections,
 - (iii) the binding energy of the deuteron
- (iv) the neutron lifetime relative to the expansion/cooling down rate of the early universe.

The topic can now be approached in two ways.

- (i) Assuming that the big-bang process is correct and well understood and that the primordial ⁴He/¹He ratio can be reliably deduced from present observations, one can deduce the number of relativistic particle species present in the early universe, i.e. the degrees of freedom in the thermodynamic sense.
- (ii) Using elementary particle data the consistency of the big-bang model can be checked.

Schramm et al and Pagel [73, 74] evaluated the first approach. Including the new neutron lifetime value in the big-bang model the authors could estimate the possible number of relativistic particles involved in the expansion process of the early universe, obtaining the result of 2.6 ± 0.3 possible neutrino families. This result, from cosmological arguments, was later supported by LEP experiments, where the decay width of the intermediate vector boson Z into $v\bar{v}$ pairs yielded a number of 2.9 ± 0.3 [75] for possible neutrino families.

Turning the argumentation around Olive et al [76] combined the LEP result for the number of neutrino families and the big-bang model and evaluated a prediction for the primordial ${}^4\text{He}/{}^1\text{H}$ ratio of 0.235 ± 0.010 . In view of recent discussions of whether the big-bang model is correct at all (see for instance [77]) the observed consistency is of major importance.

7. Conclusion

After a long period of discrepancies recent neutron lifetime measurement came up with consistent values and reach a level of precision as good as 3 s. The present mean value is 887.4 (1.7) s, or if the preliminary value of Morozov *et al* [27] is not yet included, 889.1 (1.9) s (1σ confidence level). Since methodically quite different experiments came up with consistent results, the new τ_n value can be used with good confidence.

For applications to neutrino induced reactions and to cosmology the precision is largely sufficient compared to the present status of experiments and theories in this field. On the other hand the new data on neutron decay parameters offer the possibility for valuable tests on basic asumptions for the standard model. The main

motivation for new experiments with improved accuracy will certainly emerge from the scope that the first generation of quarks and leptons represents one of the best tools for these tests.

As for the neutron lifetime measurements a precision of 1 s seems to be possible in the near future by UCN storage experiments, where the potential has not been fully exploited.

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