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Special Paper

The Dynamic Albedo of Neutrons (DAN) Experiment for NASA's 2009 Mars Science Laboratory

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Abstract

We present a summary of the physical principles and design of the Dynamic Albedo of Neutrons (DAN) instrument onboard NASA's 2009 Mars Science Laboratory (MSL) mission. The DAN instrument will use the method of neutron-neutron activation analysis in a space application to study the abundance and depth distribution of water in the martian subsurface along the path of the MSL rover. Key Words: Mars exploration—Neutron spectroscopy—Neutron activation analysis—Neutron logging. Astrobiology 8, 605–612.

1. Introduction

NUCLEAR METHODS CAN PROVIDER precise quantitative evaluations of the elementary composition of samples of unknown material. These methods are based on the detection of natural or induced nuclear emissions from test samples, which allows for the characterization of the different types of nuclei present in the material. Induced nuclear emission is produced by an external flux of energetic charged particles, neutrons, or gamma rays that interact with nuclei in a test sample and produce radioactive isotopes, exited nuclei, and secondary neutrons through spallation, non-elastic scattering, or capture reactions. A known natural case of induced nuclear emission results from the bombardment of celestial bodies and spacecraft by galactic and solar cosmic rays. Planetary gamma-ray spectroscopy was proposed in the early 1960s (*e.g.*, Arnold *et al.*, 1962), and the first nuclear measurements were made at the Moon as part of NASA's Apollo 15 and 16 missions and the Soviet Luna missions (*e.g.*, Vinogradov *et al.*, 1967; Metzger *et al.*, 1973; Surkov *et al.*, 1973). These missions represent the first milestones in space nuclear physics and nuclear planetary science. In the late 1990s, gamma-ray and neutron spectrometers onboard NASA's Lunar Prospector mission performed the first pole-to-pole global mapping of elemental abundances and neutron-derived composition information of a planet (see Feldman *et al.*, 1999, 2001, 2004b; Prettyman *et al.*, 2006).

The foremost current project in this field is the Gamma-Ray Spectrometer (GRS) suite onboard NASA's Mars Odyssey mission (Boynton *et al.*, 2004). It consists of the Gamma-Ray Spectrometer (GRS), which incorporates high-purity germanium and was provided by the University of Arizona; the Neutron Spectrometer (NS) provided by the Los Alamos National Laboratory; and the High Energy Neutron Detector (HEND), developed at the Space Research Institute (Moscow, Russia) and provided by the Federal Space Agency of Russia. Measurements of gamma-ray and neutron emissions from Mars began in February 2002 and are ongoing. The first weeks of data collection revealed strong evidence of subsurface water ice by finding that provinces above 60°

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latitude in both hemispheres had a very high hydrogen content (Boynton *et al.*, 2002; Feldman *et al.*, 2002; Mitrofanov *et al.*, 2002).

Hydrogen is easily detected with nuclear methods. Even a small amount of hydrogen in the regolith significantly increases the efficiency of moderation of secondary high-energy neutrons, because in each collision an H nucleus removes about half the neutron's energy. Even 100 ppm of hydrogen can decrease the flux of epithermal neutrons by ~5% (*e.g.*, Mitrofanov *et al.*, 2003). Thermal and epithermal neutrons are captured by hydrogen nuclei through capture reactions with the creation of deuterium and a 2.2 MeV photon. The presence of this nuclear line in martian gamma-ray spectra is a unique signature of hydrogen. Both GRS-suite neutron instruments (HEND and NS) have detected a very large deficit of epithermal and high-energy neutron emission over extensive northern and southern provinces on Mars, which has been interpreted to indicate the presence of dirty water ice. The deuterium 2.2 MeV nuclear line was also successfully detected by the GRS gamma-ray sensor over these provinces (Boynton *et al.*, 2002; Feldman *et al.*, 2002, 2003, 2004b; Mitrofanov *et al.*, 2002, 2003, 2004; Tokar *et al.*, 2002; Prettyman *et al.*, 2004; Litvak *et al.*, 2006).

Water is thought to be the most likely substance within Mars' subsurface that contains hydrogen nuclei, so the detection of hydrogen in the soil is interpreted to mean the detection of water. Therefore, the neutron and gamma-ray data from the GRS suite can be used to produce global maps of water content in a shallow layer (~1 m) of Mars' subsurface. However, the data from orbit have only moderate spatial resolution, about 1.5 times the spacecraft altitude (600 km × 600 km for the Odyssey mission). So, the next step in nuclear studies related to the search for water on Mars will be done at the planet's surface.

This paper is devoted to the description of a new space experiment for determining the water content of martian soil from a surface platform, based on measurements of the dynamic albedo of neutrons induced by a pulse generator of 14 MeV neutrons. We will use neutron scattering (produced with a pulse neutron generator) in the martian subsurface to provide an estimation of the concentration of hydrogen in the martian soil at depths <0.5 m. A combination of neutron activation analysis and neutron well-logging principles will be used to determine chemical composition for a vast amount of materials. The principles of neutron activation are a far more powerful method for detecting water and studying its vertical distribution in the soil than the use of measurements of natural neutron emission induced by galactic cosmic rays (see Section 2). In Sections 3 and 4, we present the concept of the Dynamic Albedo of Neutrons (DAN) experiment for NASA's Mars Science Laboratory (MSL) (further details are provided at http://mars.jpl.nasa.gov/msl), and we discuss its capabilities. The DAN experiment brings the method of neutron activation and neutron logging into practical use for Mars exploration.

2. Analysis of Hydrogen Content in the Soil by a Pulse Neutron Generator

Two methods for analysis of elemental composition with neutron sources are commonly called upon to test samples (*e.g.*, De Soete *et al.*, 1972): one uses radioactive isotopes, and another uses a pulse neutron generator. By installing a continuous radioactive source of neutrons (active method) on a lander/rover, as opposed to using a passive method, count rate statistics can be improved in neutron detectors. This active method, however, could complicate spacecraft ground tests and launch preparations by creating a hazardous radiation environment. Using a pulse neutron generator would be better than the continuous-source method mentioned above in 2 respects: the depth distribution of water ice could be studied through the time history of the soil's dynamic albedo following neutron pulses, and radiation hazards would be minimized during ground tests because the pulse neutron generator is not hazardous when it is off (*i.e.*, not pulsing).

There are different types of neutron generators. For measurements of neutron dynamic albedo, it is better to use generators with a relatively high neutron energy and a short duration of the emitted pulse. These requirements lead to the selection of a pulse neutron generator based on the nuclear reaction $D + T \rightarrow {}^4He + n$. Such a generator produces 1–2 μs pulses of emission of nuclei of ^4He (α-particle) with an energy of 3.5 MeV and neutrons with an energy of 14.1 MeV. This reaction takes place in a vacuum tube, when D is accelerated in an electrostatic potential of ~120 kV and collides with a target saturated with implanted nuclei of tritium.

The first industrial applications of pulse neutron generators took place in the middle of the previous century. Later, neutron activation analysis (as neutron well logging) was used in geological applications (*e.g.*, the search for oil and natural gas). Presently, a broad set of modern pulse neutron generators is widely distributed around the world for geophysical and geological applications. A significant part of this instrumentation has been developed in the N.L. Dukhov All-Russian Institute of Automatics. This Russian nuclear institute has been selected as a primary subcontractor for the development of the pulse neutron generator for the DAN instrument. The neutron activation method has not previously been used on interplanetary missions for the study of soil on another celestial body. The DAN instrument will be the first case in which principles of neutron activation analysis and neutron logging are performed *in situ* for determining the soil composition of another planet.

The DAN instrument's neutron generator was developed with the use of heritage from a very reliable industrial instrument, the ING 101 (see http://vniia.ru/eng/ng/karotazh.html#ing101). This unit is presently the best-selling product of the N.L. Dukhov All-Russian Institute of Automatics and is used for numerous industrial applications. ING 101 was especially designed to operate under conditions encountered during the drilling process of test wells. It survives high temperatures and endures heavy vibration.

The industrial ING 101 instrument provides a good resource for neutron generation and produces ~10^7 pulses with the emission of ~10^7 neutrons in each pulse. During its operational lifetime, this generator will emit 10^{14} neutrons with a total energy of 14.1 MeV.

The physics of the measurements can be explained in simple terms. Emitted high-energy neutrons of 14.1 MeV diffuse into the soil and interact with the nuclei of soil minerals. This diffusion could be viewed as a 5-dimensional process: 3 dimensions are related to space, 1 dimension is time, and the fifth dimension is energy. As a high-energy neutron roams in the subsurface, it loses its energy over time through collisions with soil nuclei until it exits the subsurface or is captured. Neutron detectors on the surface observe exiting neutrons (over a given energy range) as a die-away time profile of count rates following each pulse. A simple paradigm can be used for post-pulse neutron-emission analysis: less-moderated neutrons with epithermal energies escape during the first tens of μs after a pulse, while thermalized neutrons leave the subsurface hundreds of μs after a pulse. The amplitude and shape of the die-away time profile strongly depends on the content and depth distribution of water ice/bound water.

3. The DAN instrument

3.1 General science

The DAN instrument was proposed by the Russian Federal Space Agency for NASA's 2009 MSL rover mission. It successfully went through a non-advocate review and was incorporated into the MSL payload as a facility instrument in 2005.

The science objectives of the DAN instrument are as follows:

- Detect and provide a quantitative estimation of the hydrogen in the subsurface throughout the surface mission.
- Investigate the upper <0.5 m of the subsurface and determine the possible layering structure of hydrogen-bearing materials in the subsurface.
- Track the variability of hydrogen content in the upper soil layer (~1 m) during the mission by periodic analysis.
- Track the variability of neutron radiation background (neutrons with energy <100 keV) during the mission by periodic analysis.

3.2 DAN detectors and electronics

The DAN instrument consists of 2 separate units: the DAN detectors and electronics (DAN-DE, Fig. 1), and the DAN Pulse Neutron Generator (DAN-PNG, Fig. 2).

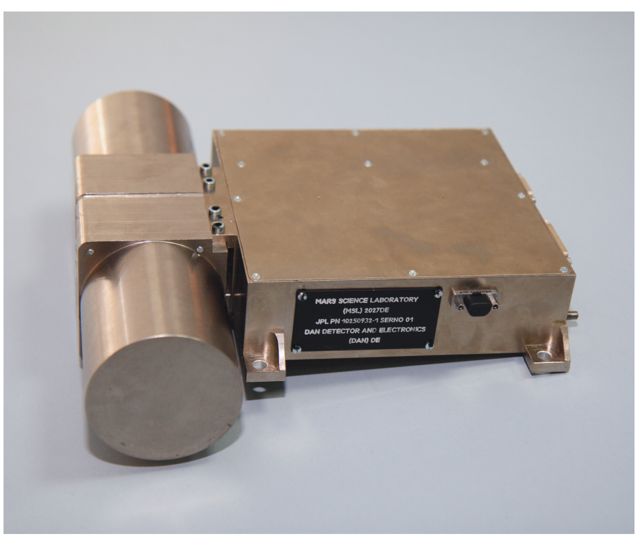

FIG. 1. Photograph of the DAN-DE Engineering Model.

FIG. 2. Photograph of the DAN-PNG Engineering Model.

The DAN-DE's physical principles and design are inherited primarily from the Russian HEND instrument onboard the Mars Odyssey mission (see Mitrofanov *et al.*, 2003; Boynton *et al.*, 2004; Litvak *et al.*, 2006).

The DAN-DE includes two ^{3}He proportional counters, which were specifically manufactured for the DAN instrument by LND Inc. (New York, USA). These counters have a 2-inch diameter and are 65 mm in length (40 mm active length) and are filled with ^{3}He gas up to 10 atmospheres of pressure (the final pressure will be fixed after physical calibration with the DAN Engineering Model). One of the DAN detectors is surrounded with a cadmium enclosure to prevent registration of thermal neutrons and is able to detect neutrons in a broad energy range, starting above thermal neutrons up to and including epithermal neutrons. The second detector (without the cadmium shield) detects both thermal and epithermal neutrons. This design was especially selected to provide independent registration of thermal and epithermal neutrons. For each detector, the DAN electronics accumulate a 16-channel spectra (both in passive and active mode, see Section 3.4) and a neutron activation die-away curve (only in active mode during DAN-PNG operations, see Section 3.4) in 64 lognormal time bins (with the lowest time bin equal to 2 μs) counted out during the moment of the neutron pulse. Signal and data processing are provided with low voltage, high voltage, and digital electronics accommodated inside DAN-DE.

The DAN-DE digital electronics (based on the ACTEL RTAX series FPGA) also serves as the instrument's "brain," which supports the telemetry and commanding interface be-

TABLE 1. DAN-DE PARAMETERS

Parameter	*Value*
Dimensions	204 × 61 × 210 mm
Mass	<1.9 kg
Neutron energy (detected neutrons)	<0.1 MeV (thermal and epithermal neutrons)
Lowest temporal resolution	2 μs
Spatial resolution	<1 m
Power	<3.5 W
Power at standby	<1.5 W
Warranty	5 years
Operation temperature range	[−40 to +50]°C
Survival temperatures	[−55 to +70]°C
Power supply	22–40 V
Readiness to operate after switching power on	<1 s

tween the DAN instrument and the MSL computer. The DAN instrument operation is based on 15 digital and 2 discrete commands. The DAN instrument's telemetry is structured as 3 different types of telemetry frames. The first one is used for standby mode and contains service and housekeeping information only. The second type of telemetry frame is used for the passive regime for recording the service and housekeeping information together with the measurement data in two 16-channel spectra, one from each DAN detector. The third type of telemetry frame is used for the main active mode and contains the service and housekeeping information and data for dynamic albedo of neutrons in the form of two matrixes (16-channel spectra × 64 time bins) from each DAN detector. The data frames will be recorded and transmitted from DAN to the Rover Compute Element each 20 s. The highest telemetry rate in the case for the active mode is estimated at 4 kbits/s. A summary of the main DAN-DE parameters is presented in Table 1.

3.3 DAN Pulse Neutron Generator

The DAN Pulse Neutron Generator (DAN-PNG) is the other key element of the DAN instrument. It is manufactured as a separate unit that will be connected to the DAN-DE through an intra-instrument cable. The DAN-PNG inherits all its major functionality from the industry prototype ING-101 (see Introduction), including its neutron tube (with ion source and tritium target) and high-voltage electronics responsible for the generation of ~120 kV voltage to accelerate D ions inside the neutron tube. During a neutron pulse, accelerated D ions produce an intensive flux of neutrons with an energy of 14 MeV in the tritium target through nuclear reaction $D + T \rightarrow {}^4He + n$. The ING-101 has been significantly redesigned to fit the MSL mechanical, thermal, and electrical requirements applied to the DAN instrument. The accommodation of the DAN instrument onboard MSL required changing the PNG's dimensions to 339 mm in length (along the *z*-axis directed to the martian surface under the MSL rover), 125 mm in width, and 45 mm in thickness (this is compared with ING-101's original length and diameter, which was 1300 mm and 34 mm, respectively; see http://vniia.ru/eng/ng/karotazh.html#ing101). The thermal characteristics of DAN-PNG were another challenge for the specialists from the N.L. Dukhov All-Russian Institute of Automatics because they needed to extend the operational temperature range of DAN-PNG from −20°C down to

TABLE 2. DAN-PNG PARAMETERS

Parameter	*Value*
Dimensions	125 × 45 × 339 mm
Mass	<2.8 kg
Neutron energy (emitted neutrons)	14 MeV
Neutrons per pulse	>1 × 10^7 neutrons at the beginning of lifetime >4 × 10^6 neutrons at the end of lifetime
Pulse duration	1 μs (full width at half maximum)
Frequency	Single pulse up to 10 Hz
Spatial resolution	<1 m
Vertical resolution (maximal penetration depth)	<1 m
Power at 10 Hz	<14 W
Power at standby	<1.5 W
Warranty	3 years
Operation temperature range	[−40 to +50]°C
Survival temperatures	[−55 to +70]°C
Power supply	22–40 V
Readiness to operate after switching power on	<2 s

−45°C to fit the parameters of the MSL thermal interface proposed for the DAN instrument. From an electrical point of view, the DAN-PNG was designed to operate at a wide voltage range from 22 V up to 40 V (instead of 150 V for ING-101) and to meet the MSL electromagnetic compatibility requirements. In addition, all low-voltage commercial electronics used in the ING-101 will be replaced with space-qualified, high-reliability components.

The DAN-PNG is able to generate neutron pulses with 10^7 neutrons per pulse at any frequency up to 10 Hz. The duration (full width at half maximum) of the individual pulse is measured to be <1 μs, which allows the DAN-PNG to be used for neutron activation analysis in the broad energy range starting from epithermal neutrons (they are generated in the soil and detected by DAN-DE during the first tens of microseconds after neutron pulse) up to thermal neutrons (they are generated in the soil and detected by DAN-DE during the first hundreds of microseconds after neutron pulse). The predicted total capacity of the DAN-PNG is about 10^7 pulses (after emission of that number of pulses, the number of neutrons emitted per pulse is expected to decrease by a factor of more than 2). A view of the DAN-PNG design is presented in Fig. 2. A summary of the DAN-PNG parameters is presented in Table 2.

3.4 Accommodation and surface operations of the DAN instrument onboard the MSL rover

The DAN-DE and DAN-PNG are accommodated at different sides of the rear part of the MSL rover. The distance between DAN-DE and DAN-PNG is ~1 m, and the height above the surface for both parts of the instrument is ~0.8 m. This accommodation was selected to locate the DAN instrument far away from the Rover Compute Element and other science instruments in order to reduce their radiation dose from DAN-PNG. The DAN instrument does not have its own thermal stabilization system, so the MSL rover is providing thermal plates (heat pipes) to keep both the DAN-DE and DAN-PNG within a temperature range from −40°C up to +50°C.

It is planned that all DAN operations will be divided into 2 basic groups: active and passive measurements/modes. All active measurements involve DAN-PNG activity. The DAN-PNG will emit neutron pulses with a selected frequency and irradiate the martian subsurface to produce a dynamic albedo of epithermal and thermal neutrons detected by the DAN-DE in the form of die-away curves. This mode will be used during short stops between rover traverses, while parked, and during special inspection activities (long-dura-

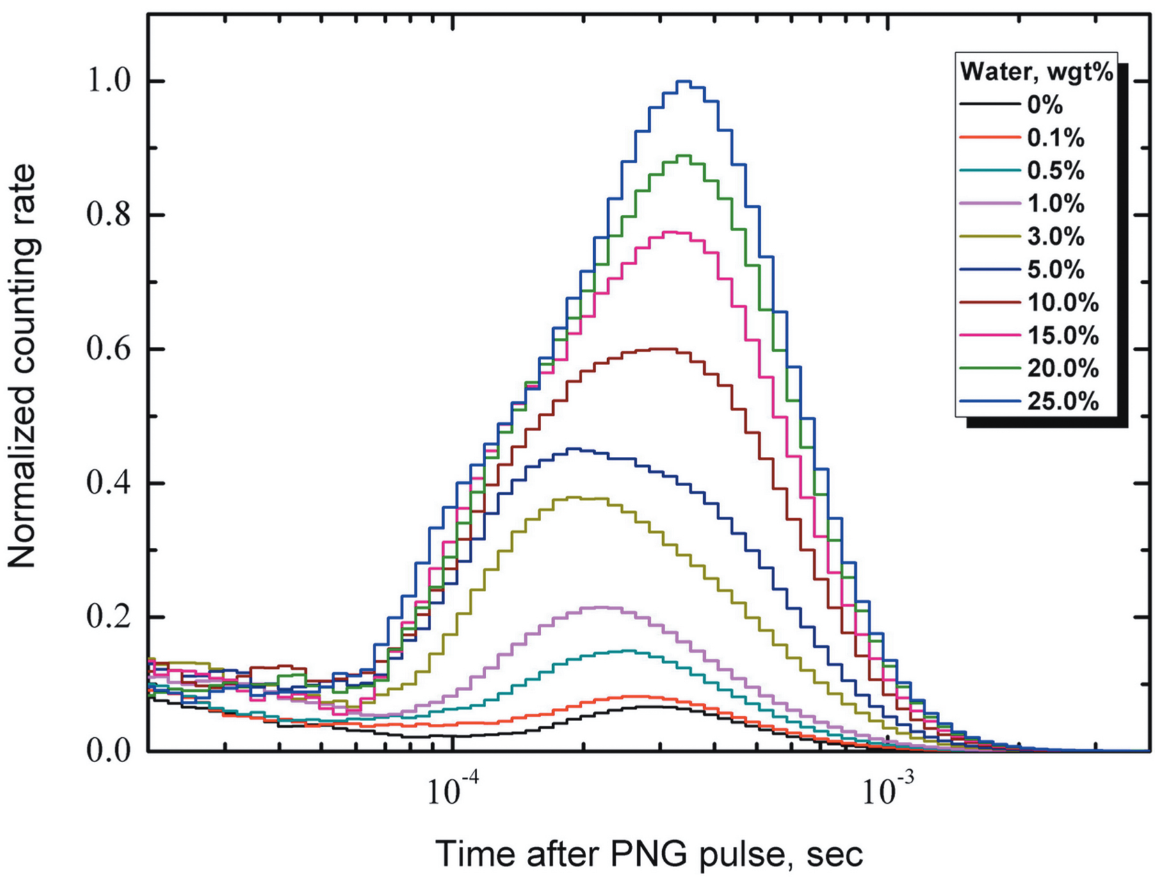

FIG. 3. Die-away curves of thermal neutrons as modeled in the DAN-DE detectors for a homogeneous model of regolith with different water contents (by % weight faction). Black corresponds to 0% of water weight; red, 0.1% water weight; dark cyan, 0.5% water weight; magenta, 1.0% water weight; dark yellow, 3.0% water weight; navy blue, 5.0% water weight; wine, 10% water weight; pink, 15% water weight; olive green, 20% water weight; blue, 25% water weight. All counting rates are normalized to the counting rates in the detector of thermal neutrons for the soil with 25% water weight (the maximum of this curve corresponds to the counting rate 10^6 counts/s/time bin).

tion measurements at specially selected locations). Short-duration (<2 min) measurements will be requested to provide a rough estimate of the water distribution with an accuracy of ~1%. Long-duration (~30 min) measurements will be requested to deconvolve the vertical distribution of water with an accuracy ≥0.1–0.3%.

We plan to use passive measurements to extend our knowledge of the martian subsurface, especially during periods when the pulse neutron generator will be off. In the DAN operation plan, we would like to use passive measurements to monitor the average water content and to make initial assessments of the subsurface structure of the martian soil under the rover (through comparative analysis of thermal and epithermal counting rates). This measurement will require careful calibration and removal of the background radiation produced by the rover's Radioactive Thermal Generator, which could seriously influence the counting statistics in the DAN detectors. The DAN passive measurements can also be used for continuous monitoring of the natural neutron background to estimate the radiation dose. In case of a major solar particle event, DAN passive measurements would help to monitor the temporal evolution (up to several days) of the solar particle event and estimate the neutron radiation dose during solar flare conditions. It is currently planned that passive measurements will be taken whenever the Rover Compute Element is switched on (~6 hours per martian sol).

4. Numerical Modeling of Neutron Die-Away Emission and Expected Results of the DAN Experiment on MSL

To understand the DAN instrument's sensitivity and evaluate DAN's measurements during surface operations, we performed a set of preliminary numerical simulations of neutron die-away emission and laboratory tests with the laboratory prototype of DAN.

In the numerical model, we tried to take into account DAN's position and accommodation onboard the MSL rover (but without modeling of MSL's structure), including orientation and distance between the DAN-DE, the DAN-PNG, and the martian surface. The current physical parameters of the DAN-PNG (number of neutrons in each pulse, the shape of neutron pulse, the suggested frequency of pulsing, and the energy of neutron emission) and the DAN-DE (detector scheme, detector effective volume, gas pressure) have also been used in the numerical simulations. To make our model reflect conditions on Mars as accurately as possible, the average column density of the martian atmosphere (in our case ~15 g/cm^2) and the average chemical composition of the regolith [taken from our HEND/Mars Odyssey calculations; see for example Mitrofanov *et al.* (2004) and Litvak *et al.* (2006)] were added to the numerical model.

Two types of regolith models with different distributions of bound water were used in the numerical simulations. The

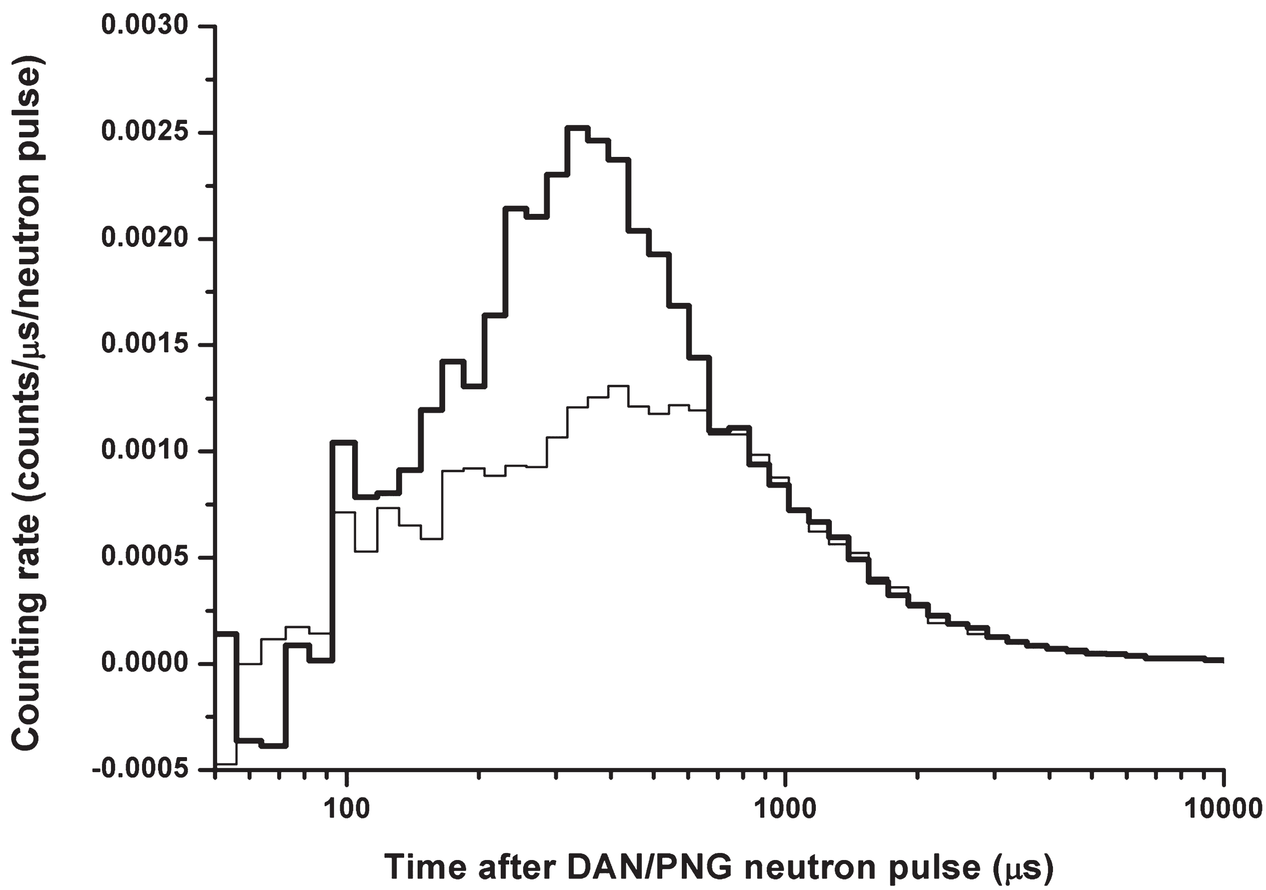

FIG. 4. The comparison between die-away curves (thermal neutrons) gathered for relatively dry soil (3–5% by weight fraction), shown as a thin line, and dry soil with a "water spot" under the rover (thin polyethylene layer with radius <50 cm on top of the surface under the rover), shown as a bold line.

first one is a homogeneous model with a homogeneous distribution of water throughout the soil layer. This model is characterized by only one parameter: the weight fraction of water in the soil. The second model is based on a double-layered structure, with an upper dry layer (maximum water content <2% by weight fraction) and a bottom semi-infinite (saturated) wet layer (with a high water content). For the second model, there are 3 variable parameters: the thickness of the upper dry layer, the content of water in the upper layer, and the content of water in the bottom layer.

The first set of simulations was done with the homogeneous model for different water contents. All simulations were performed with the MCNPX program. [This is a commonly used nuclear modeling program; see Waters (1999)]. The resulting die-away curves for thermal neutrons (difference in counting rate between DAN detectors as a time history after neutron pulse) are presented in Fig. 3. Using these die-away curves, we estimated DAN's sensitivity to the presence of water in the martian soil as the difference between counting rates for dry and wet soil at the statistical level of 3 sigma.

The numerical simulations have shown that precise measurements (to define 0.1–0.3% of water by weight fraction at rover parking places) requires tens of seconds of observation, while standard measurements (to define ~1% of water by weight fraction during traverse of rover) requires ≥10 s.

The second set of numerical simulations were performed with the double-layered model of the martian regolith in order to get preliminary estimations about DAN's depth sensitivity. In the latest calculations, we had a fixed amount of water in the upper layer (0.5–2% by weight fraction), a content of water in the bottom semi-infinite layer (8–15% by weight fraction), and varied water depth (thickness of the upper layer) in the range of 0–90 cm. Simulations for models with different water content have shown that using 1–2 min DAN active measurements (PNG frequency = 10 Hz) is enough to distinguish models with different depths in the range of 0–50 cm. This is the ideal case, which does not take into account the rover configuration, Radioactive Thermal Generator background, and a more complicated subsurface structure.

We also completed a series of preliminary laboratory tests with the industry prototype of the DAN-PNG (ING-101), the DAN-PNG Engineering Model, and a set of proportional counters with different pressures. In the first tests, we simulated the martian soil with an artificial target that was 2 × 2 × 2 m and composed of silicate bricks (estimated water content in the bricks varied in the range of 2–5% by weight fraction). We used a thin (~3 cm) polyethylene layer to serve as the equivalent of a water layer. During the tests, the polyethylene layer was located above the target and inside the target at different depths (5–35 cm) below the surface. During these tests, the detector was placed on the surface of the target, and the pulse neutron generator was placed 1 m above the surface of the target. The tests showed that 2–10 min measurements are able to provide enough counting statistics to distinguish between neutron die-away curves gathered for different water depths (location of polyethylene inside the target).

In the second series of laboratory tests, we tried to simulate the accommodation of the DAN instrument, which is closer to the rover configuration. The DAN-PNG Engineering Model and proportional counter were located 80 cm above the surface and at a distance ~1 m from each other. We put electronic boxes between the detector and neutron generator to simulate the rover's electronics. The results of such tests are illustrated in Fig. 4, which show a comparison between die-away curves gathered for relatively dry soil (3–5% by weight fraction) and dry soil with a "water spot" under the rover (polyethylene layer with a radius <50 cm on top of the surface under the rover).

Ongoing numerical modeling and laboratory tests show that distinguishing between different layering structures of the martin subsurface requires the creation of a numerical/experiment library for different examples of water depth distributions. This will be done as a part of DAN's calibration program and will be verified through a set of field tests (currently planned in the dry Atacama Desert in Chile, ice permafrost regions in eastern Russia, and dry valleys in Antarctica). A combination of the different models taken from such a library will be used to fit experimental data on the martian surface (onboard the MSL rover) and determine the most accurate description of the martian soil in the vicinity of the MSL rover.

5. Conclusions

Here we have applied nuclear methods to planetary science, with a focus on neutron activation analysis that is commonly used in terrestrial geological applications but will now be used for the first time for a planned space application. The DAN instrument will implement these methods onboard NASA's Mars Science Laboratory mission, which is scheduled for launch in Fall 2009. The main goal of the paper has been to summarize the DAN instrument and its capabilities. We have presented DAN as a neutron instrument, which was developed especially for a landed mission with measurement capabilities inherited from the HEND orbital neutron spectrometer (Mars Odyssey mission) and the unique capability to provide neutron-neutron activation analysis of martian regolith in the vicinity of the MSL rover. The DAN instrument consists of neutron epithermal and thermal detectors and a pulse neutron generator. It will be used to measure the water content (with accuracy >0.1% by weight) throughout the rover's path and to deconvolve its depth distribution as deep as 0.5 m.

6. Abbreviations

DAN, the Dynamic Albedo of Neutrons instrument; DAN-DE, DAN detectors and electronics; DAN-PNG, Dan Pulse Neutron Generator; GRS, Gamma-Ray Spectrometer; HEND, the High Energy Neutron Detector; MSL, Mars Science Laboratory; NS, Neutron Spectrometer.

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