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Ground tests with active neutron instrumentation for the planetary science missions

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ABSTRACT

We present results of experimental work performed with a spare flight model of the DAN/MSL instrument in a newly built ground test facility at the Joint Institute for Nuclear Research. This instrument was selected for the tests as a flight prototype of an active neutron spectrometer applicable for future landed missions to various solid solar system bodies. In our experiment we have fabricated simplified samples of planetary material and tested the capability of neutron activation methods to detect thin layers of water/water ice lying on top of planetary dry regolith or buried within a dry regolith at different depths.

1. Introduction

Today several space missions with nuclear instruments successfully continue exploration of planets and small bodies of the Solar System. The broad spectrum of tasks accomplished within these missions is informally described as “Nuclear Planetology”. The major tasks are dedicated to the measurement of bulk elementary composition (major, minor and trace soil constituent elements such as Si, O, Fe, Al, Mg, Ti, K, Th, U. etc.) and the detection of subsurface water distribution down to depths 1–2 m. Current space-based nuclear experiments include the Gamma-Ray Suite onboard Mars Odyssey (gamma spectrometer and two neutron spectrometers) for the mapping of elemental composition and water content in the Martian subsurface [5,6,33,34,20,9] the active neutron spectrometer Dynamic Albedo of Neutrons (DAN) onboard the Curiosity rover for monitoring of bulk water distribution along the rover's traverse on the Martian surface [39,41,22,24]; the collimating neutron spectrometer Lunar Exploration Neutron Detector (LEND) onboard the Lunar Reconnaissance Orbiter for identifying local areas enriched with water ice at the Moon's polar regions [35,36,39,23,51]; gamma-ray and neutron spectrometers onboard the MESSENGER mission for investigating bulk elemental composition of Mercury and detection of water ice in permanently shadow regions [11,19]; the Gamma Ray and Neutron Detector (GRAND) onboard the DAWN mission to measure elemental composition of the small planets Ceres and Vesta [48,49,47]; the Board Telescope of Neutrons (BTN) onboard the International Space Station (ISS) for monitoring the neutron component of radiation background environment [57]. This list will be updated in near future with new instruments, selected for the BepiColombo mission [37], the orbiter and lander on ExoMars missions [25,42] and for the future Russian Moon polar landers [12].

The physical and measurement principles of the current nuclear experiments are basically the same. Solar System planets and bodies with little or no atmosphere (for example Moon, Mars, and Mercury) emit gamma rays and neutrons due to continuous bombardment by high energy charged particles of galactic cosmic rays (GCR) or due to natural radioactive decay processes (see, for example, [1]). The presence of nuclear lines in the measured gamma-ray spectrum tells us about elemental composition of the subsurface. The regional variations of the neutron spectrum indicate changes in hydrogen-rich materials content (primarily water ice or bound water). For the surface missions such measurements could also be enhanced with methods of active neutron and gamma-ray spectroscopy. Instead of GCR flux, active neutron or gamma-ray spectrometers use a pulse neutron generator to produce secondary neutron and gamma emission in the irradiated subsurface. For a long period of time this approach has been used in various Earth applications such as geological neutron well logging in the oil industry or security

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screening in airports for detection of explosives (see, for example, [7,10,15,8,13,53,54–55]; [49,50]). Decades ago several studies considered the possibility to use neutron die-away experiments for lunar and planetary surface analysis (see, for example technical reports prepared by [30–32, 26]). Now development of modern technologies has shown that it is feasible to create flight qualified active neutron and gamma spectrometers for extra-terrestrial exploration, for example, onboard various landed missions to Moon, Mars and Venus [22,38,43,16,17,44,12]. Thus, Russian Dynamic Albedo of Neutron (DAN) instrument is already operating for more than two years onboard the Martian Science Laboratory (Curiosity rover) mission launched in 2011; see [22] and [39]. It is the first active neutron spectrometer flown to another planet to investigate subsurface water distribution. Now analogs of this instrument are supplied with gamma-ray spectrometer and are being manufactured and tested for the future Russian lunar polar missions [12]. The similar Probing In situ with Neutrons and Gamma rays (PING) instrument developed by Goddard Space Flight Center (GSFC) is also proposed to measure the bulk elemental composition of the subsurface of any solid solar system body. It has passed series of ground field tests and proved that it could be an effective tool for detailed local geochemistry analysis[43,45,4].

In this paper we present the results of field tests performed on soil targets with known elemental composition and structure using the spare flight model of the DAN instrument. The primary objective of these tests is to investigate capabilities of active neutron spectrometers to detect water/water-ice layers on the top of the surface or buried at some depth.

2. Instrumentation

According to the agreement between Russian Federal Space Agency and NASA the DAN instrument was specially developed for the MSL mission to measure the bulk hydrogen content of the Martian regolith along the path of the Curiosity rover, see [22,39]. As we already noted in the previous section, DAN consists of two components: DAN-PNG and DAN-DE separately integrated onto the two sides of the Curiosity rover.

DAN-PNG consists of a vacuum tube equipped with a source of deuterium ions and a tritium target behaving as a small particle accelerator. A high and short voltage impulse ($\sim$120 kV) is applied along the tube accelerating deuterium ions (simultaneously released by the ion source located inside the tube) above the threshold energy required to initiate nuclear reaction in the tritium target: $D+T\rightarrow{}^4He+n$, $Q=17.6$ MeV, where total energy release $Q=17.6$ MeV is shared between products of the reaction, ^{4}He nuclei and neutrons at 3.5 MeV and 14.1 MeV, respectively. As a result DAN-PNG can produce short (<2 μs) and strong neutron pulse ($>10^7$ neutrons per pulse).

The DAN-DE consists of two proportional counters filled with ^{3}He gas at a pressure of 3 atm. The detection of neutrons occurs through the capture reaction $n+{}^3He\rightarrow{}^3H+p$, $Q=764$ keV. One of the proportional counters is wrapped in a cadmium enclosure with a thickness of about 1 mm to absorb thermal neutrons. The other proportional counter is without cadmium enclosure and is sensitive to both thermal and epithermal neutrons. The difference in counting rates between the two detectors provides estimates of thermal neutron counts. More details of DAN design, the principles of operations and main science tasks are also presented in Livak et al. [21] and [39].

When DAN-PNG produces pulses of high energy neutrons a significant fraction of these neutrons penetrate into the subsurface and lose energy through nuclear reactions (inelastic scattering and radiative capture) with soil nuclei. Moderated neutrons may leak back out of the subsurface and the time profile of emerging neutrons may be detected by DAN-DE. This time history of neutrons is called a die-away curve. It could be schematically divided into two major parts: time window for the detection of epithermal neutrons (the first several tens of microseconds) and time window for the detection of thermal neutrons (extends from first few hundreds of microseconds up to several milliseconds). The duration, shape and amplitude of die-away curves depends on how and where in the subsurface neutrons are moderated providing information primarily about hydrogen depth distribution, as the neutron moderation is most sensitive to hydrogen content distribution in the subsurface. The presence of elements such as Cl, Fe, Ti, Mn, and Gd may also influence the curve's shape because they are strong absorbers of thermal neutrons and their presence at varying levels may change the subsurface thermal neutron flux (for the illustration of H and Cl dependence see following publications: [22,14,39,24,52].

Mars surface operations with DAN onboard the Curiosity rover during one Martian year have revealed small variations of bound water and chlorine along several km of rover traverse [41,24]. But in this work our major objective is to use the spare flight model of DAN as a prototype of future active neutron instruments to test the capabilities in detection of water/ice layer in the subsurface of a planetary body.

3. Test facility

To conduct a feasibility study of active neutron and gamma-ray spectrometers, a test facility has been developed and built at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia. It is a hangar with a total area of about 62 m^2 and with height from floor to roof of about 3.5 m. Its walls and roof are assembled from thin (<3 mm) steel plates to provide protection of measurements from the outside environment (rain, wind, snow, etc.) and to minimize local neutron background (count rate due to backscattering of neutrons in the building structure). Schematically facility consists of two approximately equal volumes. The first one is an entry room supplied with automatic doors, engineering communications and radiation (neutron and gamma) monitors. The second one is an experimental room occupied with soil target (with total area about 12.5 m^2 and located near the center of the room, about 1 m away from the walls, see Figs. 2 and 4) and measurement equipment. To suppress the neutron background for the science measurements and reduce radiation environment for the participating personnel this hangar was placed far away from the main institute facilities. To meet state radiation safety standards it is surrounded with two keep-out radiation zones. First radiation zone covers the hangar itself and personnel access into this zone is prohibited during the neutron generator operation. The radiation dose rate within this zone can exceed the permissible dose limit for personnel. This zone is equipped with automatic system radiation monitoring with restricted access through locking mechanisms controlling entrance to the hangar (installed in the entry room). This system operates the neutron generator power switching on/off, acquires information from radiation detectors, and manages light and sound signaling devices. The second radiation zone includes close vicinity (radius of the zone $\sim$25 m) around test facility and surrounded with a protective fence. The neutron effective dose rate at the outer boundary of this second zone should not exceed 2.5 μSv/h. Second keep-out zone is also controlled with independent certified stationary detectors of gamma and neutron radiation to monitor radiation dose during measurements. The schematic view in scale of the test facility and its surrounding is shown on Fig. 1.

All measurements in our tests were done with DAN instrument installed on a mechanical frame above the center of the soil target,