NEUTRONIUM lunar observatory for studying galactic cosmic rays of high and ultra-high energies.

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Proposals for the creation of the NEUTRONIUM lunar observatory are given. Simulation results and the design of the observatory are presented. An original idea of cosmic ray particle energy measurement for high and ultrahigh energies is proposed. According to this idea, radiation scattered in the opposite direction relative to the direction of arrival of particles (radio waves, neutrons, gamma, charged particles) from hadronic and electromagnetic cascades created by the primary particle in the lunar regolith is registered on the Moon surface.

1. INTRODUCTION

It has been established that cosmic rays (CR) of ultrahigh energies carry information about the main sources (accelerators) and characteristics of the interstellar Galaxy — the world in which we live. The findings of studies on such cosmic rays are indispensable for the development of models of the Galaxy and the Metagalaxy, including their energy balance. The most pressing objective in experimental studies of CR is the determination of their chemical composition with the maximum possible advance up the energy scale [1].

A new approach to the study of high and ultra-high energy CR is proposed. Albedo is registered on the surface of the Moon. Albedo is the radiation that is born from hadron and electromagnetic cascades created by the primary particle in the lunar regolith which is scattered in the opposite direction relative to the direction of arrival of the primary particle. The analysis showed that the most effective is the registration of such albedo components as radio waves, neutrons, gamma and charged particles. This will allow energy measurements in the energy range of 10^{14}-10^{17} eV/particle with individual particle charge resolution. On an area of ~100 m^2 it is proposed to place 100 identical autonomous modules. Each module functions as an autonomous device with a maximum weight of 100 kilograms. A distinctive feature of the project is the use of lunar regolith as the main working substance of the device. This approach allows to reduce the mass significantly and increase the geometric factor of the device.

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2. METHODS OF NEUTRONIUM LUNAR OBSERVATORY

A key feature of CR research is a sharply decreasing energy spectrum, which requires the use of bulky equipment as one moves up the energy scale. This makes such research extremely expensive.

Table 1 shows the main characteristics of recently carried out and planned CR space experiments.

The "new generation" space experiments (NUCLEON, CALET, DAMPE) have a total exposure factor of less than 3 m^2sr year. This allowed us to conduct studies (energy spectra and chemical composition) of CR up to energies of ~$5*10^{14}$ eV/particle.

The planned experiments (HERD, HERO) give hope to bring the research to the limit of ~10^{16} eV/particle.

The ionization calorimeter technique is used in one form or another to register the energy of the primary particle for all the experiments listed in Table 1. This technique remains the only universal technique for constructing a spectrometer in ultra-high energy physics today. However, further advancement along the energy scale using the ionization calorimeter technique is quite difficult. Advancement up the energy scale by another order of magnitude (up to 10^{17} eV/particle) would require launching equipment weighing several hundred tons. That is currently unrealistic.

Exploration of the Moon provides unique opportunities to pursue experiments in this area that cannot be done on Earth or in Space.

A new method of energy measurement is presented for the NEUTRONIUM project. This method involves the use of regolith as an absorber for an ionization calorimeter. The NEUTRONIUM project proposes the original idea of determining the primary energy not by recording particles of all or a significant part of the cascade. The primary particle energy is determined by the albedo flux on the lunar surface. The primary energy is determined independently for three albedo components: secondary neutrons, charged particles, and radio waves emission from a cascade at frequencies ranging from 1 to 10 GHz.

Monte Carlo simulation was conducted with the GEANT and FLUKA packages to estimate the magnitude of signals for each of the named components. The GEANT code was supplemented with programs for calculating the electric field strength [12] to calculate the radio waves emission. These programs were written to calculate radio pulses from extensive air showers and were modified for the conditions the NEUTRONIUM experiment.

2.1 Estimation of neutron albedo.

Monte Carlo simulations allow us to study in detail such characteristics as the position of the maximum of the particle cascade, the number of neutrons generated at each depth of the cascade development, the time of neutron diffusion to the surface, the spectra and parameters of the spatial distribution of neutrons on the lunar surface depending on the nature and energy of cosmic ray particles. It was found that for cosmic ray particles coming from the upper hemisphere, the total number of neutrons reaching the surface can be estimated by a simple formula [13]:

$$N_{tot} \sim 10^4 (E_0/100\ \mathrm{TeV})^{08}$$

This constitutes ~10% of the total number of neutrons generated in the regolith Fig.1.

On the moon surface the number of neutrons can be hundreds of thousands for particles with energy > 10^{14} eV/particle. The thermal neutron flux is an order of magnitude smaller. The energy-determining accuracy is contingent upon the type of particles. For example, the neutron flux fluctuations are ~20% for iron nuclei, ~30% for carbon nuclei and ~60% for protons at energy >10^{14} eV/particle. The neutron diffusion time to the surface of the Moon is about 300 μs. The neutron flux decreases approximately according to a logarithmic law from the cascade start time. During this time, the observatory records quite a few background albedo-neutrons resulting from cosmic ray particle interactions across the entire cosmic ray energy spectrum. The calculation showed that the number of background neutrons will be less than several thousand with a registration time gate of 300 μs. Such an amount of background neutrons practically does not introduce additional errors in registration.

The accuracy of primary particle track determination is rather low when using neutrons, less than 1 m. It is necessary to use all the charged particles of albedo to localize a particle track. Fig. 3.2.a shows the spatial distribution of the albedo neutrons, and Fig. 3.2.b shows the spatial distribution of the charged albedo particles in case of registration of an iron nucleus at $E_0 = 3•10^{14}$ eV/particle.

2.2. Estimation of charged albedo particles

Charged albedo particles are produced mainly from the gamma-ray flux from the electromagnetic cascade, which is transformed into a flux of electrons/positrons. The proton component is the most difficult to register. The flux of charged albedo particles was estimated for primary protons with energies up to 10^{15} eV [13]. The accuracy of the primary particle energy reconstruction is low and is about 100% at $E_0=10^{14}$ -10^{15} eV. Analysis of the shape of the spatial distribution of charged albedo particles allows us to confidently determine the slope of the event (i.e., the cascade axis). It is important for determining the energy and charge of the primary particle using the other components. The slope of the trajectory can be determined from the asymmetry of the spatial distribution of charged albedo particles, Fig. 3.3. The start of the track is determined by the charge in the coordinate-sensitive detector for nuclei with $Z \geq 2$. The start of the track cannot be determined by the charge signal in the case of the primary proton. The start of the track is chosen based on the geometric center of the albedo, Fig. 3.3.

In determining the charge of the primary particle, distortions due to albedo are possible. The most likely error occurs in the separation of protons and helium nuclei. The probability of simulation of an alpha particle by a proton is about 0.6 at $E_0 = 10^{15}$ eV with a detector cross section size of 1x1 cm^2. By using a multilayer detector array, these distortions can be reduced to fractions and units of percent.

The charged albedo particles reach the Moon's surface from the cascade in tens to hundreds of nanoseconds. It can be argued that the background does not have a significant effect at rather narrow temporal gates of registration, e.g., 1 μs.

3.3. Estimation of radio emission albedo

In Monte Carlo simulations, the threshold energy of charged particles was assumed to be E_{cut} = 50 keV. At low energies $E_0 < 10^{14}$ eV, the calculation of the radio field strength can be performed within the framework of the microscopic approach, where the field is calculated from each particle of the shower. At high primary energies the simulation time becomes too long, so the so-called macroscopic approach was used. In this case, the cascade is represented as a continuous system of currents, and the field is calculated by numerically solving Maxwell's equations for these currents. Details and main results of the calculation can be found in [12]. The simulation results indicate that at frequencies exceeding 1 GHz the field strength exhibits an increase with increasing frequency. It can be attributed to the presence of a coherent radiation mode. At frequencies from 10 to 100 GHz, the reduction of the radio emission field is mainly due to the violation of coherent emission conditions. At frequencies above 100 GHz, the spectrum decreases mainly due to absorption. Thus, the 1-10 GHz range is optimal in terms of maximizing the radio signal. The primary particle energy reconstruction error depends significantly on the cascade slope. Indeed, vertical showers can multiply the amount of radio emission “backwards” many times over, given the reflection of radio emission from internal boundaries in the regolith. Therefore, correction factors are required depending on the trajectory angle. Analysis of the charged albedo particles allows us to determine the track direction of the primary particle. The parameters of the radio signal exhibit a strong dependence on the energy at a known slope. Fig. 3.4 shows the dependence of the recovered energy for protons with different energies when using a radiofrequency signal.

3.4 Analyzing the methodology of the NEUTRONIUM experiment

The analysis of the NEUTRONIUM experiment methodology showed the principal possibility of registering cosmic ray particles of ultrahigh energies by the albedo of the cascades developing in the regolith. The most promising way is to conduct research on several components: neutrons, charged particles, and radio waves. These components complement each other, which increases the accuracy and reliability of research. The lower threshold of cosmic ray particle registration for each component is about 10^{14} eV. The accuracy of primary energy determination is estimated to be 20-60% for neutrons, 100% for gamma rays, and 40% for radio waves. These measurements are based on the registration of particles generated in a separate cascade, so they reflect its fluctuations in each case. However, the correlation of the output of energy measurements based on different methods is not absolute, so to improve the accuracy of registration it is promising to develop a mathematical apparatus for finding a single functional when three components are used simultaneously.

3. DESIGN OF THE NEUTRONIUM LUNAR OBSERVATORY

To register ultrahigh energy cosmic ray particles, the NEUTRONIUM scientific equipment should include at least two detectors - a charge detector and an energy detector. As an energy detector it is proposed to use three types of particles from the albedo cascade, each of which requires its own detector for registration. Thus, the equipment should include at least four recording detectors.

3.1 Primary particle charge detector

As a detector of charged particles it is proposed to use a multilayer (at least 4 layers) matrix of thin segmented silicon detectors. Based on the high probability of imitation of an alpha particle by a proton, the size of a single active segment should not exceed 1x1 cm^2, which significantly reduces the probability of such imitation. Each segment is an independent ionization loss detector. Highly integrated multi-channel microelectronics are used as readout electronics to accommodate about 40 thousand amplitude channels per 1 m^2. When recording a useful event, compression takes place and only channels where the signal is above a threshold, which is determined by the signal from a single relativistic particle, are recorded. According to the estimation, this number does not exceed several thousand channels on the area of 1 m2. Such equipment is successfully used in space experimental equipment, for example, [2, 3, 4 and others].

3.2 Gamma detector.

Traditional gamma spectrometer construction methods, which require the use of inorganic scintillators with a high density of matter, require a spectrometer of considerable mass. This requirement violates the general concept of equipment construction – the lightest possible module. However, for the NEUTRONIUM space experiment the task of spectral resolution of gamma-ray flux is not set, i.e. it is not required to determine the energy of albedo gamma-ray spectrum – only their quantity. Therefore, it is proposed to use a charged particle detector as a gamma-ray spectrometer. The main part of the albedo gamma-ray emission is concentrated in the range of 0.1-10 MeV. It is proposed to place tungsten layers of different sizes in front of the silicon matrix layers on the side of the lunar surface. In the indicated energy range in tungsten, the main channels of gamma-ray interaction are the Compton effect (up to E ~ 5 MeV) and the production of electron-positron pairs (at E>5 MeV). Thus, the thickness of the layers should alternate from 100 μm to several mm so that the maximum number of electrons/positrons can leave the absorber and register in the silicon matrix layers (each 300 μm thick). The total thickness of the tungsten absorbers should be at least 3.5 mm.

3.3 Neutron detector

The number of slow neutrons (with energies less than 0.1 MeV) is about 10% of the total number of neutrons escaping from the cascade to the Moon's surface. If a high hydrogen content absorber (e.g., polystyrene) with a thickness of about 2 cm is introduced into the equipment, a large portion of these slow neutrons will be slowed down by Rayleigh scattering to thermal energies. When a material with a high capture cross-section, such as B-10, is introduced into the absorber, the energy of reaction products (for B-10 – 2.31 MeV) is released at almost a single point, on the order of a few microns, during the capture process. Using these properties in the

NEUTRONIUM apparatus, it is proposed to use an organic scintillator with the addition of B-10. Boron is not a transparent element, therefore in scintillation technique orthocarborane, $B_{10}H_{10}C_2H_2$, is usually used, addition of which in the amount of ~5% by mass allows to obtain a scintillator with light output of 50% in comparison with the initial plastic. Using light-transmitting fibers to collect the light and small thickness detectors (1 cm), the losses are insignificant, and practically all thermal neutrons are captured by B-10. Thus, it is proposed to use two layers of scintillation strips 1 cm thick and about 2-3 cm wide to measure the neutron spatial distribution.

3.4 Radio emission detector.

The analysis of charged particles and gamma-rays from albedo allows us to determine the direction of the primary particle track. With a known slope, the parameters of the radio signal are quite rigidly dependent on energy. During the measurement it is necessary to avoid weakening the received power due to the mismatch of the polarization characteristics of the antenna and the incident electromagnetic wave. Therefore, it is necessary to have an antenna that operates on any polarization. For this, circular polarization antennas are used. One of the varieties of antennas of this class is a spiral antenna with a cylindrical resonator.

3.5 Preliminary design of the NEUTRONIUM module

Fig. 3.5 shows the preliminary design of the NEUTRONIUM module.

Evaluation of the characteristics of the module S=1 m^2

Mass; (~10 g/cm^2) -100 kg

Number of channels ~$5*10^4$

Power consumption less than 100 W

When evaluating the module characteristics, experience in creating similar equipment for space experiments using only available and proven technologies was taken into account.

The NEUTRONIUM project will require 100 standard modules to be delivered to the lunar surface. This is a large-scale technical task. The operation of scientific instruments on the surface of the Moon, given the enormous labor-intensive nature of the delivery, should be as simple and reliable as possible. These modules should have a long service life when used in lunar surface environments and, if necessary, be maintained with minimal labor.

This approach forms the technical and technological requirements for the NEUTRONIUM module:

1. Each standardized NEUTRONIUM installation module (NIM) shall be designed as a monoblock with mechanical, electrical and data interfaces.

2. Each NIM has a direct (or indirect – using transit through similar NIM modules) information connection with the complex of radio communication with the Earth, as well as with the power source (for example, with the lunar power plant on the surface), which are not part of the scientific equipment.

3. Each NIM is a non-serviceable structure in space. Only module interfaces are subject to maintenance: mechanical clamps, electrical connectors.

4. The scientific equipment, in addition to the detector part, may include interface units for wireless data transmission to the main lunar infrastructure objects, as well as to provide each NIM with electrical power supply.

5. Transportation and installation of the NIM modules to their places on the lunar surface is provided during the development of the lunar station.

4. SUMMARY

The NEUTRONIUM science complex defines an unprecedented advancement of direct measurements of cosmic rays with elemental resolution in the region above 10^{16} eV, which opens up opportunities for solving the most fundamental problems of high-energy astrophysics. The peculiarity of the project is the step-by-step creation of the observatory as the International Scientific Lunar Station develops.

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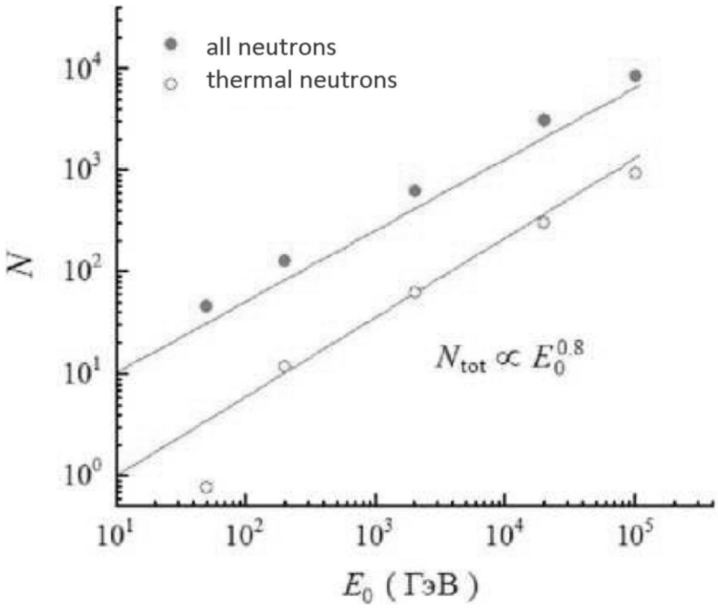

Fig.1. Dependence of the number of neutrons N crossing the surface of the Moon on the energy of the incident proton $E_0 = 3 \cdot 10^{14}$ eV.

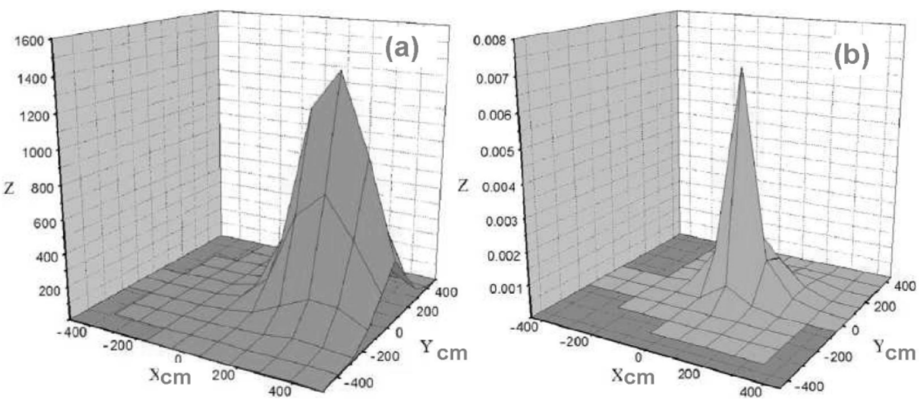

Fig.3.2 Spatial distribution of neutron albedo spot (a), spatial distribution of charged particle albedo spot (b)

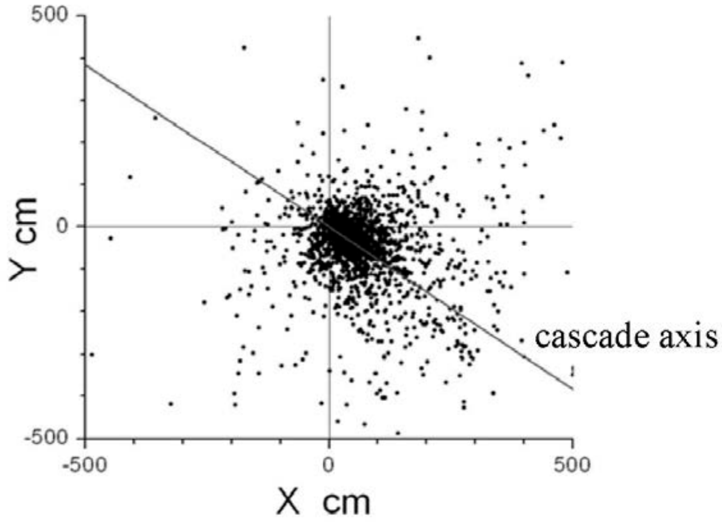

Fig.3.3 Spatial distribution of charged particle albedo for proton $E_0=10^{14}$ eV

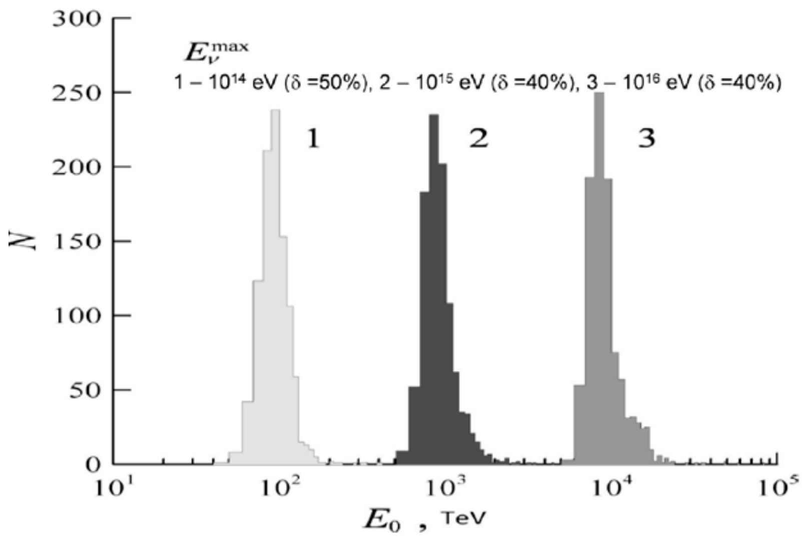

Fig. 3.4 Dependence of the albedo for protons with different energies when using a radiofrequency signal

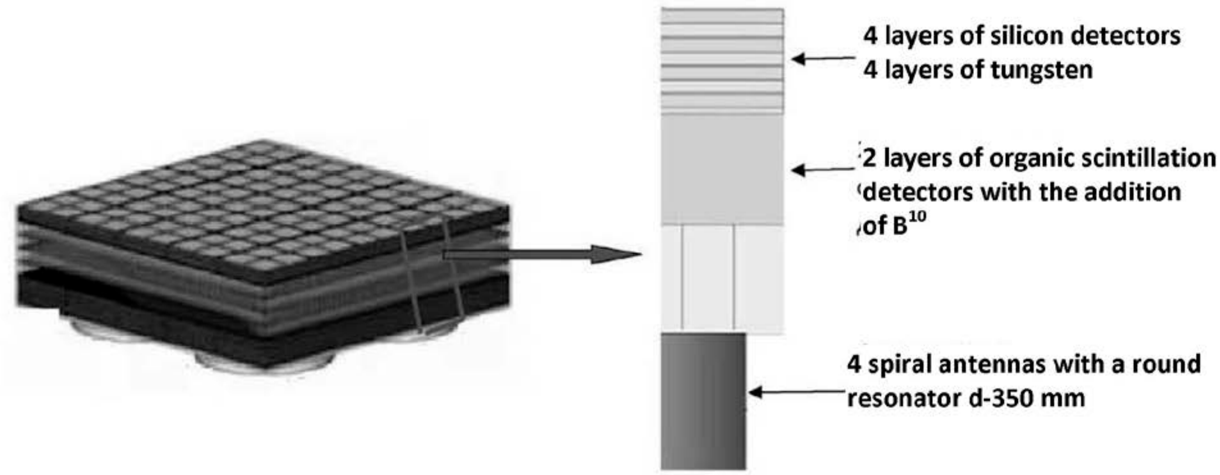

Fig. 3.5 Preliminary design of the NEUTRONIUM module.

Table 1

Main characteristics of recently carried out and planned CR space experiments.

Title	Years	m^2sr year	Range eV/p
PAMELA [2]	to 2008	0.02	$<2*10^{11}$э
CREAM [3]	to 2012	0.5	10^{11}-10^{14}
NUCLEON [4]	To 2018	2.4	10^{11}-$5*10^{14}$
CRIS [5]	since 1997	0.38	10^{7}-10^{8}
Fermi [6]	since 2008	10	$2*10^{7}$-$3*10^{12}$
AMS02 [7]	since 2011	5	$<2*10^{12}$
Calet [8]	since 2015	0.5	10^{9}-$2*10^{13}$
Dampe [9]	since 2015	1	10^{11}-10^{15}
HERD [10]	~2027	10	10^{11}-$5*10^{15}$
HERO [11]	>2030	>200	10^{11}-10^{16}