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Measuring the Isotopic Composition of Superheavy Nuclei of Galactic Cosmic Rays in the NUCLEON-2 Experiment

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Abstract—A brief survey of the data on the isotopic composition of superheavy nuclei in galactic cosmic rays is presented. The scientific goals of the planned experiment are outlined, and the design of the NUCLEON-2 scientific equipment is given.

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Most of the data on fluxes of heavy and superheavy nuclei in galactic cosmic rays (GCR) were obtained in four experiments. The LDEF experiment [1] was based on long-term exposure of a solid-state track detector in open space. The experiment was designed to determine the chemical composition of low-energy GCRs in the subactinide ($70 \le Z \le 87$) and actinide ($88 \le Z \le 103$) regions. It recorded 35 actinide events in the energy range of 1–2 GeV/nucleon and acquired a great many statistics in the subactinide region. The abundances of superheavy elements in GCRs and the Solar System were compared.

Superheavy nuclei were measured at the HEAO-3 astronomical observatory [2] using the C3 detector based on a combination of Cherenkov counters, gas proportional counters, and hodoscopes from multiwire ionization chambers. The charge spectrum of superheavy nuclei in the charge range of 40 to 62 was determined. A plateau in the abundance of different nuclei was detected in the charge range of 44 to 60. In this region, the experiment recorded from 10 to 30 events for the main even nuclei.

The balloon-borne superTIGER stratospheric experiment [3] was also based on using the Cherenkov technique. Charge distributions in a wide range of charges for superheavy nuclei with charges above $Z = 40$ were obtained for nucleus energies above 2–3 GeV/nucleon, with statistics comparable to those obtained earlier in the HEAO-3-C2 experiment.

Information on isotopes of superheavy nuclei in cosmic rays was also obtained in the CRIS experiment on board the ACE spacecraft [4]. The experiment used an approach based on recording the Bragg peak of the complete stopping of nuclei in an array of thin silicon detectors. The spectrometer was carried into orbit in 1997 and is still in operation. The CRIS spectrometer obtained unique charge spectra of isotopes of superheavy nuclei up to $Z = 32$ for energies of several hundreds of MeV/nucleon. It should be emphasized that there are no experimental data on the isotopic composition of nuclei with $Z > 32$.

Data on the isotopic composition of superheavy nuclei in the GCR are of considerable interest in the physics of the origin of cosmic rays and astrophysics in general. Superheavy nuclei in the GCR travel very short distances before they fragment (at $Z > 40$, they can travel ~1 kpc), so their intensity is sensitive to the local environment of the Sun. There are several convenient radioisotope clocks among isotopes that can be used to study their age. The diffusion coefficient of nuclei in the interstellar medium in the local environment of the Sun can be determined by the abundance of secondary isotopes. Knowledge of the local environment of the Sun is in turn important for correctly describing the abundance of electrons and positrons in cosmic rays. This is of great importance in investigating such nonstandard and exotic sources of cosmic rays as neutron stars and dark matter.

In a number of current models, supernova explosions occur in a medium enriched with heavy elements from earlier supernova explosions and stellar winds, rather than the standard interstellar medium. This could generate a variety of anomalies in GCR charge and isotopic composition in the region of superheavy elements that require investigation. Models of nonstandard mechanisms of cosmic ray acceleration in

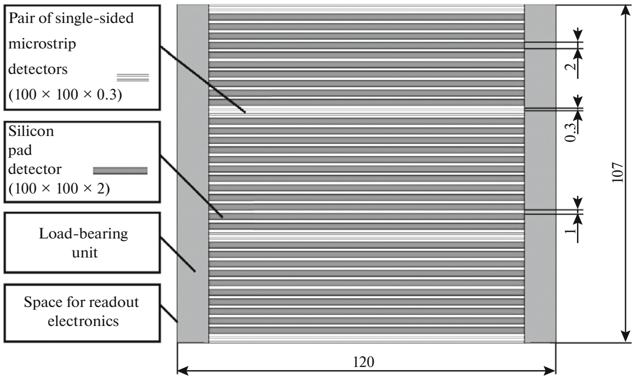

Fig. 1. Schematic diagram of the NUCLEON-2 spectrometer.

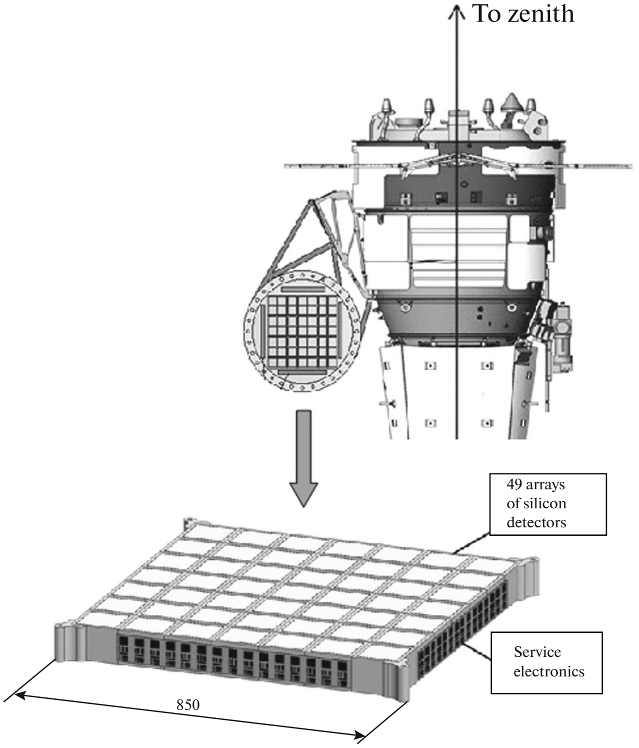

Fig. 2. Layout of the of NUCLEON-2 scientific equipment; possible arrangement of scientific equipment in normal operation.

OB associations where the abundance of heavy nuclei in cosmic rays serves as a marker must also be studied. Investigating the isotopic composition of cosmic ray nuclei in the charge range of 40 to 65 is also important from the viewpoint of examining the mechanisms of nucleosynthesis, as this range contains the double peak of element abundance corresponding to the fast *r*-process of neutron capture and the slow *s*-process. These are the basic scientific tasks in this field; since no experiments are planned along these lines for the near future, a new experiment would be of great interest.

Considering the drop in GCR intensity with increasing charge, the continuation of studies requires an experiment with exposure several tens of times larger than that of the CRIS ACE experiment. The proposed spectrometer included in the scientific equipment of the NUCLEON-2 experiment has such exposure. The spectrometer's geometric factor must be at least 1.5 m^2 sr, which for a period of active operation of at least 5 years yields a factor at least 20 times greater that of the CRIS ACE experiment.

The main approach used in the scientific equipment of the NUCLEON-2 experiment is the E-dE telescope technique. This method is based on simultaneously measuring total energy E deposited by a nucleus in the silicon total absorption spectrometer and energy losses dE/dx in one of the spectrometer's detectors with thickness dx. The product $E(dE/dx) \sim MZ^2[\ln E + \text{const}]$ depends on Z and M.

The scientific equipment is based on a spectrometer module (Fig. 1) consisting of 40 silicon *p*-*i*-*n* detectors with areas of 100 × 100 mm^2 each. These are 32 pad detectors (one pad per detector) 2 mm thick and 8 microstrip detectors (strip step ~1.5 mm) ~0.3 mm thick. The spectrometer has two symmetric input windows (top and bottom).

The energy range of the spectrometer is 100–1000 MeV, and the measurement error does not exceed 0.4%. The requirements for precision are determined by the Rayleigh criterion in separating neighboring isotopes up to nuclei with $Z = 60$.

A Monte Carlo simulation for a wide range of isotopic spectra ($Z = 42$–64) in the energy range of 300–600 MeV/nucleon was performed for this spectrometer design. The simulation was performed using the GEANT3, GEANT4, and FLUKA codes in combination with different processing methods (neural networks and multidimensional analysis based on the maximum likelihood method). A model-independent result for reliable isotope separation up to $Z = 64$ was obtained.

It has been proposed that the NUCLEON-2 scientific equipment consist of 49 independently operating modules (Fig. 2). The principles of operation, control, and monitoring would be taken from the NUCLEON scientific equipment as much as possible [5]. The basic characteristics of the NUCLEON-2 scientific equipment are a mass of no more than 220 kg, overall dimensions no larger than 850 × 850 × 120 mm, no more than 27 thousand amplitude channels, and energy consumption no higher than 200 W.

To minimize the cost and reduce the time of preparing the cosmic experiment, it has been proposed that the NUCLEON-2 scientific equipment be launched in a Russian commercial satellite as an additional payload. Mathematical simulations show that at

Expected statistics N

Nucleus, Z	N	Nucleus, Z	N
Fe 26	3×10^7	Zr 40	500
Co 27	1.4×10^5	Nb 41	150
Ni 28	1.1×10^6	Mo 42	230
Cu 29	1.6×10^4	Ru 44	100
Zn 30	1.6×10^4	Ag 47	140
Ga 31	2000	Cd 48	120
Ge 32	2300	Sn 50	120
As 33	350	Te 52	140
Se 34	1400	Xe 54	80
Br 35	200	Ba 56	180
Kr 36	830	Ce 58	50
Rb 37	250	Nd 60	40
Sr 38	1000	Dy 66	180
Y 39	250		

orbits above 400 km, it is quite feasible to use a two-sided detector oriented horizontally with respect to the Earth. The geometric factor would exceed that of a single-sided device oriented vertically by ~60%. One possible arrangement of the NUCLEON-2 scientific equipment now in operation is shown in Fig. 2. It is planned to start the project in 2016 and launch it in the period leading up to 2022.

The expected results after five years of exposing the NUCLEON-2 scientific equipment are given in the table. Unique data for different nuclei with $Z = 26–66$ would be obtained over 5 years. The statistics on the charge composition obtained in the best HEAO-3-C3 and SuperTIGER experiments would be surpassed by a factor of approximately 5.

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