ISSN 1062-8738, Bulletin of the Russian Academy of Sciences: Physics, 2007, Vol. 71, No. 4, pp. 500–502. © Allerton Press, Inc., 2007.
Original Russian Text © D.M. Podorozhnyi, V.L. Bulatov, N.V. Baranova, A.V. Vlasov, A.G. Voronin, N.N. Egorov, S.A. Golubkov, V.M. Grebenyuk, D.E. Karmanov, M.G. Korolev, N.A. Korotkova, Z.V. Krumshtein, E.G. Lyannoy, M.M. Merkin, A.Yu. Pavlov, A.Yu. Pakhomov, A.V. Romanov, A.B. Sadovskii, L.G. Sveshnikova, L.G. Tkachev, A.V. Tkachenko, A. Turundaevskiy, 2007, published in Izvestiya Rossiiskoi Akademii Nauk. Seriya Fizicheskaya, 2007, Vol. 71, No. 4, pp. 518–520.

The NUCLEON Experiment: The Current Status

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Abstract—The main purpose of the NUCLEON experiment is direct measurements of the energy spectra of cosmic rays in the range 10^{11}–10^{15} eV with the use of the lightweight facility during a prolonged orbital flight. The energy is determined using a technique based on the measurement of the spatial density of secondary particles produced in the initial event of inelastic interaction. The schematic diagram of the NUCLEON facility, the current status of the project, the results of testing the prototype, and plans are presented.

DOI: 10.3103/S1062873807040181

1. INTRODUCTION

Information on the spectra of various nuclear components of the cosmic rays in the energy range 10–1000 TeV is required to elucidate the origin of the high-energy cosmic rays and to interpret the knee phenomenon. In order to collect statistically significant data, it is necessary to use facilities with a large geometric factor. In this case, problems arise associated with the orbital injection of “thick” facilities. Since 1999, the technique under consideration has been developed as an alternative to the ionization calorimeter method for energy measurements of cosmic rays in the range 1–1000 TeV [1]. The advantage of the proposed technique is the small weight and small sizes of the equipment used. In 2001–2003, the NUCLEON project had been included in the R&D Federal Space Program of the Russian Federation. Since 2004, this project has been in the construction stage. The scientific equipment is installed on a new serial remote sensing spacecraft as an additional payload. The NUCLEON instrument is scheduled to be launched in 2009. The exposure time will amount to five years. The project is directed at measuring the spectra of various nuclear components at energies ranging from 1 to 1000 eV, the energy dependence of the ratio between secondary and primary nuclei in the range $E > 100$ GeV/nucleon, and the spatial anisotropy of nuclear groups in the range 1–10 TeV. A 5-year long flight will make it possible for the first time to perform the monitoring of high-energy cosmic rays in outer space.

2. THE GENERAL CONCEPT

A new approach, namely, the Kinematic Lightweight Energy Meter (KLEM) technique, was proposed for the design of the energy spectrometer of the NUCLEON project [1, 2]. The energy is determined from the spatial density distribution of secondary particles that are produced in a thin target in the first event of an inelastic interaction and then multiplied in a tungsten converter. The spatial density is measured by silicon strip detectors with a spatial resolution of several tens of micrometers. The accuracy in the determination of the energy was investigated both in numerical experiments [2] and in three tests on accelerators [3, 4].

The charge is measured by pad silicon detectors (the pad size is approximately equal to 2.5 cm^2), which were used earlier in the ATIC experiment [5]. These detectors have worked fairly well and offered certain advantages, because their use makes it possible to reduce the errors arising from reverse current. Note that, in the NUCLEON experiment, the reverse current is even smaller owing to the absence of a heavy absorber. Moreover, four detector arrays will be used to reliably determine charges [4]. The charge measuring system was tested on an ion beam ($Z = 1$–30) with energies of ~158 GeV [6, 7] on the SPS accelerator at the CERN. The trigger system was constructed with the use of strip scintillator detectors arranged in six 0.5-cm-thick layers. The thicknesses of different experimental setups are compared in the table.

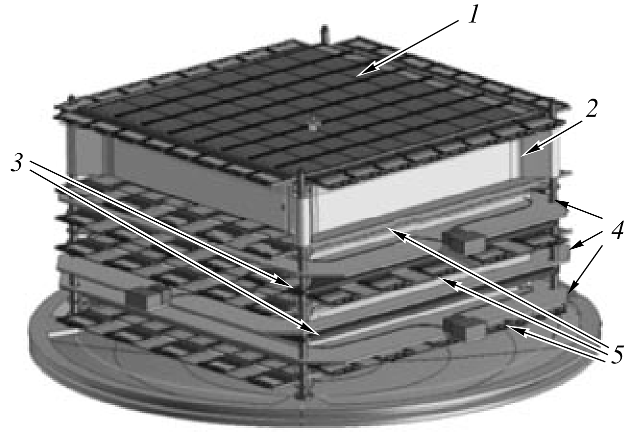

Fig. 1. Schematic diagram of the NUCLEON device: (*1*) charge measuring system, (*2*) carbon target (~20 g cm^{-2}), (*3*) tungsten converter (~20 g cm^{-2}), (*4*) scintillation system of the fast trigger, and (*5*) tracker and energy measuring systems.

3. DESIGN OF THE NUCLEON DEVICE

The schematic diagram of the NUCLEON device is depicted in Fig. 1. The device has a "layered" structure in which the active part of the spectrometer measures ~500 × 500 × 270 mm. Each system represents an individual device, which is fabricated and tested individually. The equipment involves a 10-cm-thick carbon target and two 0.5-cm-thick tungsten layers used for converting gamma rays into charged particles. The charge measuring system consists of four layers of silicon detectors located on two plates. Each layer is constructed from eight ladders in the form of strips bearing eight silicon detectors 6.2 × 6.2 × 0.3 cm in size. Each square is divided into 16 pads with an area of 2.4 cm^2 each. A signal is read from each pad. The total number of readout channels is equal to 4096. The tracker (particle track reconstruction) and energy measuring system is composed of six layers consisting of microstrip silicon detectors. Each layer involves 72 detectors 6.2 × 6.2 × 0.3 cm in size (nine ladders, each containing eight detectors). The readout pitch amounts to 0.46 mm, and the total number of readout channels is equal to 6912.

The fast trigger system consists of three double layer composed of 16-strip scintillator detectors (500 × 30 × 0.5 mm in size) with 1-mm WLS KURARAY Y-11 fibers. A light signal coming from each layer is detected by one sixteen-channel and two one-channel photomultiplier tubes. The signal (approximately ten photoelectrons) is generated upon traveling a singly charged particle. Two systems of one-channel photomultiplayer tubes are used for producing the total signal from each plane with a time resolution of 50 ns.

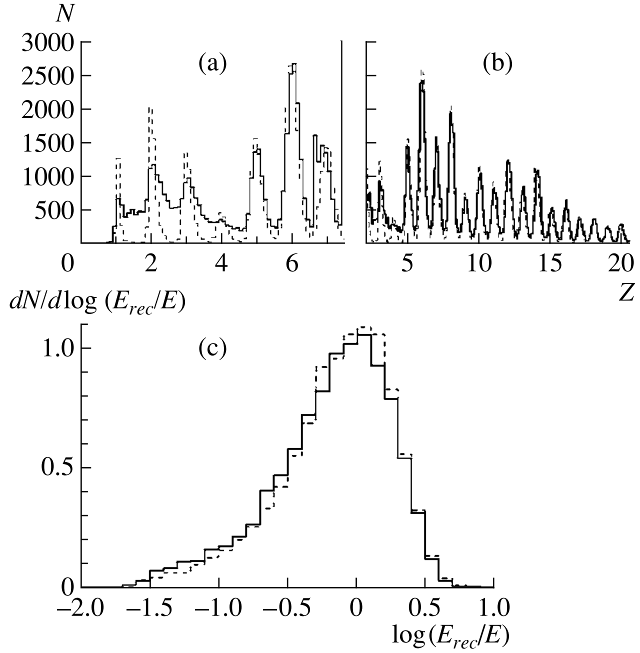

Fig. 2. Charge distributions of fragments with due regard for the rank statistics for (a) sensitive and (b) rough channels. (c) Pion distributions over the reconstructed energies. Solid lines are experimental data, and dashed lines represent the results of the calculations.

4. TESTING OF THE CHARGE MEASURING SYSTEM

In our experiments, a beam of indium nuclei (energy, ~158 GeV/nucleon) was directed to a 4-cm-thick beryllium target. Secondary charged particles and nuclear fragments were separated in rigidity with a magnetic deflection system. Particles with a rigidity corresponding to a particular mass-to-charge ratio were selected [7]. The prototype of the setup involved (along the direction of the beam) four layers of pad detectors, a 10-mm-thick graphite target, a 10.5-mm-thick tungsten converter, and two layers of microstrip detectors. The measurements were performed with rough and sensitive detection channels.

The charge spectra for four detectors were brought into coincidence with the use of the rank statistics method [6, 7]. The described technique made it possible to suppress substantially both the ionization fluctu-

Different experimental setups

Experiment	Depth of the spectrometer material, g cm^{-2}
Thick ionization calorimeter (SOKOL)	~700
Thin ionization calorimeter (ATIC)	~220
X-ray emulsion chamber (JACEE)	~100
X-ray emulsion chamber (RUNJOB)	~60
NUCLEON	~40

ations and the influence of accompanying particles. The mean error in the determination of the charge was approximately equal to 0.2. Examples of the charge distributions thus obtained are given in Figs. 2a and 2b.

5. TESTING OF THE ENERGY MEASURING SYSTEM

The energy measuring system in the NUCLEON experiment is based on a new principle. Hence, the experimental testing of this system is of considerable interest.

The setup prototype was tested using a pion beam at the CERN [7]. The prototype consists of the charge measuring system, the microstrip silicon detector system, and the fast trigger system based on scintillation counters. In a 1- to 10-cm-thick carbon target, the primary particle experiences a nuclear interaction. A tungsten layer with a variable thickness is located at some distance from the target. This layer converts gamma rays into e^+e^- pairs. A microstrip detector system able to determine the density distribution of secondary charged particles is positioned in the rear of the converter.

In order to reconstruct the energy from the spatial distribution of secondary particles, we used the parameter S, which can be represented in the form $S = \Sigma \ln^2(2H/X_i)N_i$, where X_i is the distance from the strip to the shower axis and N_i is the total ionization proportional to the number of singly charged particles arrived at the strip. The databases for events corresponding to energies of 100, 200, 350, and 700 GeV were obtained by the simulation performed with the GEANT3.21 package. These data were used to construct the calibration dependences for the average parameter $\langle S(E)\rangle$. The energies were reconstructed and the distributions over $\log(E_{rec}/E)$ were determined from the calibration dependences. The distributions for the primary pion with an energy of 350 GeV are plotted in Fig. 2c. The mean energy measured with the technique under consideration amounts to $\langle E_{rec}\rangle = 334$ GeV with the root-mean-square deviation $\sigma = 0.79$. In the case of the simulation, these parameters are as follows: $\langle E_{rec}\rangle = 350$ GeV and $\sigma = 0.78$. The distribution shape is sensitive to the shape of the calibration dependence. The fact that the obtained distribution coincides with the model distribution suggests the correctness of the proposed method.

6. THE CURRENT STATUS OF THE NUCLEON EXPERIMENT AND PLANS

The NUCLEON equipment will be installed on a new Earth remote sensing spacecraft designed by the Federal State Unitary Enterprise KB Arsenal. The additional payload weight amounts to 265 kg (scientific device, 165 kg; telemetry system; installation system; cables). The active part of the spectrometer measures ~500 × 500 × 270 mm. The power consumption of the scientific device is 120 W. The duration of the space experiment is approximately five years. The NUCLEON instrument is planned to be launched in 2009.

In 2005, the design works were completed, several operating layers were fabricated, specific systems were partially tested, and engineering specifications were developed. In 2006, it is planned to fabricate a full-scale model and to test all three systems of the device on an accelerator. In 2007, it is planned to complete the fabrication of the pilot sample and to begin to fabricate the flight variant of the device. In 2009, the fabrication of the flight variant of the device will be completed and the device will be launched.

7. CONCLUSIONS

The NUCLEON experiment will make it possible to verify the validity of different models of the formation of galactic cosmic rays, as well as their closely related models providing an explanation of the origin of the knee. The testing of the method for determining the particle energy on acceleration beams with known energies confirmed both the validity of the chosen algorithm for determining the energy and the reliability of the operation of the prototype equipment. The results obtained permit us to draw the conclusion that the orbital experiment can be performed with the designed device and that the posed scientific problems will be solved.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research, project nos. 05-02-16781a and 05-02-16783a.

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