Astroparticle Physics 90 (2017) 69–74

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys

The NUCLEON experiment. Results of the first year of data acquisition

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A R T I C L E I N F O

Article history:
Received 18 August 2016
Revised 18 February 2017
Accepted 22 February 2017
Available online 24 February 2017

Keywords:
Galactic cosmic ray
High energy physics
Direct investigation

A B S T R A C T

The NUCLEON experiment aims to study chemical composition and energy spectra of galactic cosmic rays for nuclei charges $Z = 1 - 30$ and energies $10^{11} - 10^{15}$ eV. The research is conducted with the help of the NUCLEON scientific equipment installed on the Russian satellite “Resurs-P” No. 2 as an additional payload. This article describes the results of the first year of the space experiment NUCLEON, including methodological features of data acquisition mode setup, evaluation of the equipment’s performance and methods it provides, as well as preliminary results of data analysis.

1. Introduction

The NUCLEON experiment is designed to study composition and energy spectra of galactic cosmic rays (CR) with energies approaching the so-called “knee”, i.e. $10^{11} - 10^{15}$ eV.

The CR energy spectrum has a near-like power law behavior with a steepening at energies around $10^{14} - 10^{16}$ eV, a feature that is commonly called “knee”. The problem of origin of this “knee” is one of the most pressing unsolved problems of astrophysics. To test various modern models of this phenomenon, more detailed information on composition of the CR in this energy range is necessary, and such information may be obtained by direct measurement of the CR spectrum on a spacecraft. A number of space experiments (CALET [1], ISS-CREAM [2], DAMPE [3]) are already collecting such information or plan to start collecting it in the near future.

The spacecraft with the NUCLEON detector was launched on December 28, 2014 and has already collected statistics during its first year of work (out of the planned 5 years of operation). The detector is positioned on the near-Earth sun-synchronous orbit with an altitude of about 475 km and an inclination of 97°.

In order to study composition and energy spectrum of the CR, the NUCLEON detector includes several sub-systems:

- the charge measurement system (ChMS);
- the energy measurement system utilizing the new Kinematic Lightweight Energy Meter technique (KLEM system);
- the energy measurement system utilizing the ionization calorimeter (IC);
- the trigger system.

Each of these systems includes several planes of particle detectors. All the planes are assembled in a “bookcase”, where the four upper planes are the charge measurement system, below is the carbon target and 6 planes of the KLEM system, and 6 planes of the ionization calorimeter are located in the lowest part. Three double layer planes of the trigger system are inserted at different depths between planes of the KLEM system. A simplified layout of the detector is shown in Fig. 1. Detailed description of the

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http://dx.doi.org/10.1016/j.astropartphys.2017.02.006
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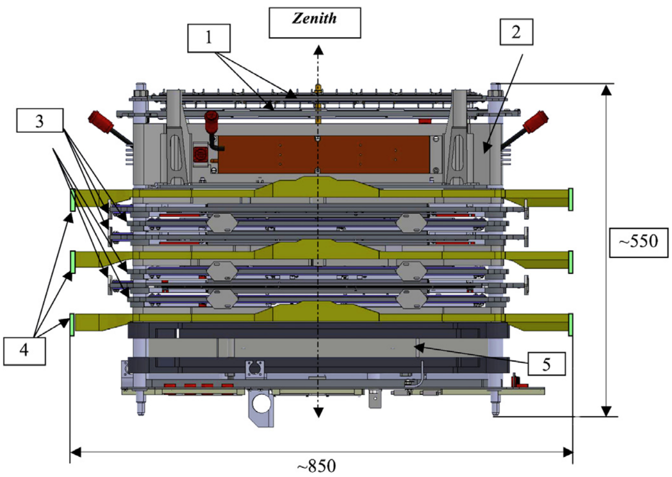


Fig. 1. Simplified layout of NUCLEON detector. (1) - two pairs of charge measurement system planes; (2) - carbon target; (3) - 6 planes of energy measurement system utilizing the KLEM technique; (4) - 3 double trigger system planes; (5) - calorimeter.

detector design, its technical parameters and test results (including tests on the SPS beams to confirm the basic parameters) are presented in [4]. In Table 1 technical characteristics which are necessary for further understanding are summarized.

The presented parameters show that the carbon target provides a probability of hadron interaction for an incident proton of about 20%, while the total thickness of all systems is 17 X0 (including 12 X0 of the calorimeter.). The aperture of the NUCLEON experiment is 0.24 $m^2 \times sr$ without calorimeter and 0.06 $m^2 \times sr$ with it.

The instrument is placed in a container attached to the spacecraft, which main task is remote Earth photograph. This limits the mass and total power available to the scientific equipment to less than 360 kg and to less than 160 W, respectively, explaining the limited size of the calorimeter. In addition, certain restrictions were imposed on the amount of daily data volume delivery.

2. Results of the initial phase of the experiment. The trigger system setup.

After the launch in late December 2014, the “Resurs-P” No. 2 spacecraft has been under flight tests for about three months. During this period, the NUCLEON detector was occasionally powered-on, mainly to check state of the detector and correctness of command and data exchange with the spacecraft. Regular collection of scientific information was not carried out. During this work, the NUCLEON detector was tested, including all channels of read-out-electronics for all systems and the functionality of the data quality monitoring software.

Fig. 2 shows a boron event as recorded by the NUCLEON instrument. On the right side of the picture, 18 histograms show the width (in mm) and the energy deposit (in the nominal amount of minimum ionizing particles) in the planes of the trigger system, the KLEM system and the calorimeter. Two columns of the histograms represent X and Y orientation planes. The vertical position of the histograms corresponds to vertical location of corresponding planes in the detector. Bin width of the histograms corresponds to the strip pitch of the planes. In the upper left corner planes of the charge measurement system are shown (top view). Particle hits in ChMS planes are shown by circles (4 colors correspond to the number of planes), the diameter of each circle is proportional to the signal value. The shaded areas correspond to faulty detectors. To the bottom and to the right of the ChMS image, each system’s cross section is drawn according to the geometry, and the shower axis is calculated from the data from these planes. The axis allows to localize the point of hit of the primary particle in the planes of the charge measurement system and to separate it from electronic noise background and back-scattered secondary particles.

The “portraits” of the events suggest the good status of the detector. Note that this conclusion is indirectly confirmed by various telemetry information received from the detector during flight tests. Furthermore, analysis of these data allowed to estimate the number of faulty channels in planes of different systems, which had probably appeared during the spacecraft launch. The total number of faulty channels does not exceed 2%, thus meeting the expectations of the constructors of the detector and has no serious effect on the quality of observations.

Next step of the NUCLEON experiment is a tuning of the trigger system to begin the regular data taking.

The principle of the trigger system operation in the NUCLEON experiment is quite simple:

- in each event, the light from all of scintillator strips of a single trigger plane is routed to a PMT;
- signals from all the PMTs are supplied to a comparison circuit which has a controlled threshold;
- the result of such comparison for all 6 single planes are supplied to a controlled coincidence circuit.

Table 1
Some of the technical characteristics of the NUCLEON detector systems.

System	Design features	Detector features	Passive parts features
Charge measurement system	4 planes with pad silicon detectors. Transverse dimension of the active area of the system is 50 × 50 cm^2	Size of the detector is 62 × 62 × 0.45 mm^3. Size of each pad is 15 × 15 mm^2	Passive components are minimal
Energy measurement system utilizing the KLEM procedure	The carbon target (the first interaction zone). Size of the active area of the target is 50 × 50 cm^2.	No detectors	Thickness of a carbon block is 10 cm
	6 planes, each includes silicon strip detectors and a tungsten converter. Orientation of the strips alternates between X-,Y-directions for consecutive planes.	The detector size is 62 × 62 × 0.45 mm^3 with a 0.5 mm pitch. All strips are interconnected in the longitudinal direction (along the strips) on each plane.	Thickness of the tungsten sheet in each plane is 2 mm
Energy measurement system utilizing the ionization calorimeter	As for the KLEM system, but the size of the active area is 25 × 25 cm^2	As for the KLEM system, but thickness of the detectors is 0.3 mm and a pitch is 1 mm	Thickness of the tungsten sheet in each plane is 8 mm
Trigger system	3 double layer scintillator planes. Orientation of the strips in each layer is perpendicular to the other. Locations of the planes: under the carbon target, between the 3rd and 4th planes of the KLEM, and above the first (upper) plane of the calorimeter. The active area is 50 × 50 cm^2	The width of the scintillation strips is 30 mm, thickness is 7 mm	Passive components are minimal

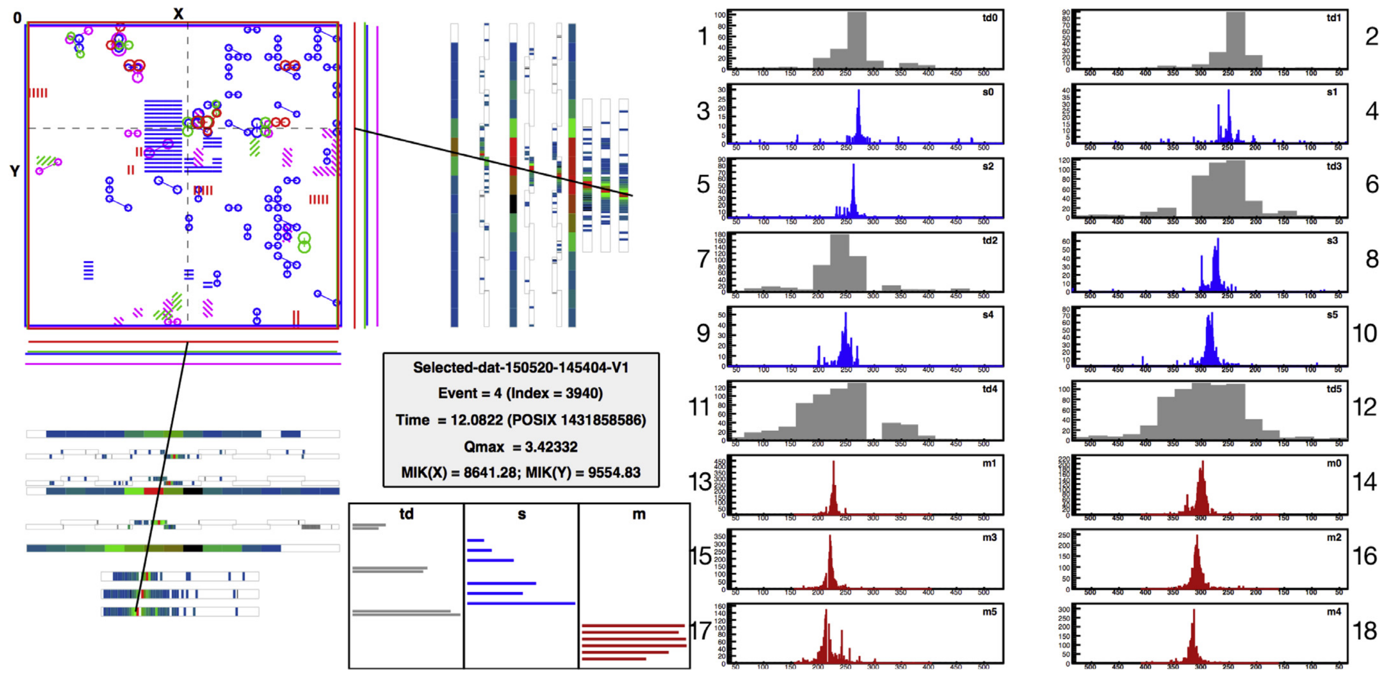


Fig. 2. “Portrait” of hadron cascade caused by the boron nucleus. (1), (2) - X and Y layers of the first (upper) trigger plane; (3), (4), (5) - three planes of the KLEM system; (6), (7) - the second trigger plane; (8), (9), (10) - three lower planes of the KLEM; (11), (12) - lower trigger plane; (13)–(18) planes of the calorimeter. For more details see the text.

For each event the trigger signal is generated if signal values in a selected combination of planes are higher than corresponding thresholds. Thus, adjustable parameters of the trigger system are thresholds for each of 6 single planes and a combination of channels in the coincidence circuit.

From a physical point of view, the trigger system should select particles with energies $> 10^{11}$ eV. In this case, it is achieved by setting different thresholds for planes at different depths of the detector. And the threshold in the first trigger plane pair (after carbon target) should be higher than typical signals from a noninteracting primary particle to provide selection of events with hadron interaction in the carbon target. In the second plane pair (in the middle part of the apparatus), the threshold should correspond to a higher energy release due to the development of the shower, and in the third (bottom) plane pair it should be higher than the second one to reject short (not deep) showers of low-energy particles. The coincidence circuit requires a response from the comparison circuits for all six planes.

Even such simplified description indicates some problems, as the efficiency turns out to be higher for heavy nuclei than for light ones, since the threshold of the first plane may be exceeded by a strongly ionizing heavy nucleus even without its interaction in the target and creation of a developed shower. Thus, process of reconstruction of the energy spectra for various nuclei have to take different trigger efficiencies into account.

To solve this and other problems of experimental data processing, special simulations (using GEANT4 and FLUKA frameworks) of the NUCLEON experiment were performed. These simulations take into account:

- design features of the detector, including distribution of material and dead zones of detectors;
- partial shading of the detector by the Earth and the spacecraft body;
- the shape of the CR spectra (according to previous experiments);
- calibrations of detectors.

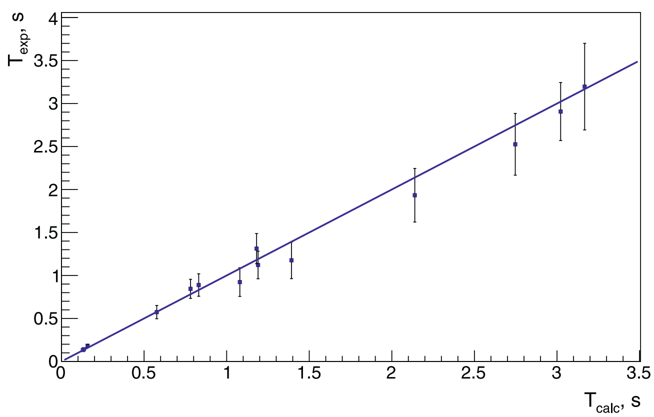
Correctness of the simulation for the trigger system has been tested on the initial stage of data taking in orbit by comparison of the model and experimental rates of trigger signals at different levels of thresholds. The results presented in Fig. 3.a show good agreement between the simulation and the experimental data.

Settings of the trigger system for regular data taking were chosen according to results of the simulation. Three requirements were taken into account :

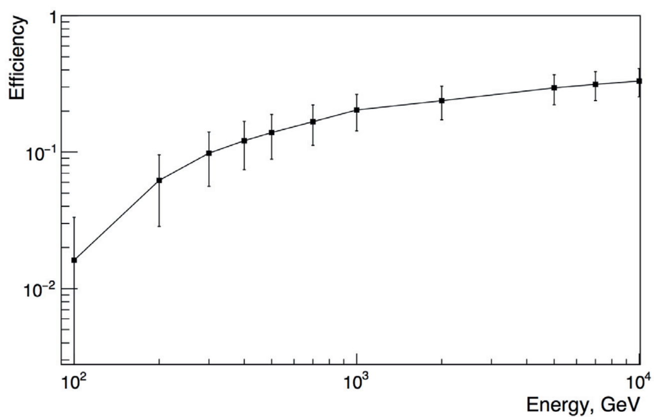
- maximum registration efficiency for events passing through the charge measurement system and the energy measurement system;
- minimum lower limit for energy of recorded particles;
- trigger generation rate $<\sim 0.5$ events/s.

The meaning of the latter requirement should be clarified specifically. It is related to a low rate of event processing in top level control units of the detector. At the design stage, analysis of data communication between recording systems and the control unit has shown that for error-free data transfer the transmission time should be at least 400 ms/event (note that interference from the main apparatus can affect this value). It determines the “dead” time of the detector. The full experiment simulation found that, for our aperture and exposure time of 5 years, we can measure energy spectra in 10^{15} eV area if the ratio of “dead” and astronomical time will not exceed 25%, or in other words, the ratio of processed to generated triggers must be higher than 75%. Bearing in mind this consideration, as well as results of detailed simulation of electronic units, we have determined that an acceptable ratio is achieved if the trigger rate does not exceed 0.5 events/s.

Currently, the trigger system's parameters are close to optimal (within simulation accuracy). The thresholds on planes are (from top to bottom) 20, 200, 260 MIP. These settings account for the reasons discussed above, but the upper plane threshold is set even lower than ionization of a nuclei with $Z > 4$ and without a shower. The model shows that more pedantic adherence to “qualitative” arguments and setting a rather high threshold value on the first plane leads to a strong suppression of proton registration efficiency



(a)



(b)

Fig. 3. (a) - comparison of experimental and simulation average intervals between trigger signals for several settings of the trigger thresholds; (b) - efficiency of proton registration for “working” parameters (in text) of the trigger system.

at low energies, and thus complicates comparison of the NUCLEONs data with data from other experiments. These thresholds are supposed to be changed after accumulation of required statistics at the lower boundary of the energy. Fig. 3.b shows the expected detection efficiency of protons with the current settings of the trigger system. During reconstruction of final energy spectra we accounted for this dependency, as well as similar dependences for other nuclei.

3. Determination of primary particle charge.

Determination of the primary particle charge occurs as a result of data processing from 4 planes of the ChMS. However, as can be seen in Fig. 2, there is a considerable amount of false hits in these planes, which are associated both with electronic noises and a flow of back scattered secondary particles from the hadron cascade. Data from the KLEM system can be used to resolve this problem by reconstructing the shower axis and extrapolating it to the ChMS planes. Accuracy of the extrapolated impact point is $2-10$ mm, it depends on a number of planes in which the shower was measured (when the shower hits all planes of the calorimeter, the accuracy of axis reconstruction is 2 mm).

The algorithm of primary particle charge identification starts after selecting pads with a signal from primary particles in planes of the ChMS. It comprises of the following stages:

- conversion of signals in hit pads of ChMS to charge units (based on an electronics calibration characteristics);
- normalization of all signals by track length (based on tilt of shower axis and on detector thickness);
- conversion of all signals from charge units to a nominal charge of the primary particle (based on dependence of ionization of the primary particle on Z^2); Note, that a nominal charge of the primary particle on this stage may be a fractional value.
- application of the rank statistics (described below) to nominal charges from 4 planes of the ChMS.

Details of these steps are presented below.

On the stage of conversion of original signals to an ionization charge results of front-end electronics calibrations, obtained directly in flight, are used. Those calibrations are updated every two hours. For each channel, results of the calibration are electronic responses to voltage pulses with known amplitudes. For each channel, a voltage pulse is applied to an input of a charge sensitive amplifier via a calibration capacitor with known capacity. It defines the calibration charge for each pulse. To clarify, the charge measurement system uses a 16-channel CR-1 chip as its front-end electronics (also used in other experiments such as ATIC [5], PAMELA [6]), and each channel is a charge sensitive amplifier with a dynamic range of 1000 mip (for a thickness of the silicon detector 450 μm).

The rank statistics method is used in determination of the charge as follows: nominal charges from 4 planes of the ChMS (after calibration and normalization) are arranged in ascending order, minimum and maximum values are dropped, remaining values are averaged. This approach allows to discard events with delta-electrons and extremely high ionization. Also, removing minimal value removes empty events in a plane from analysis, when there is no signal in a plane for various reasons, for example, when an inactive (dead) area of a plane is hit.

In reality, data processing of the charge measurement system consists of two phases. In the first phase, when the approach described above has been applied to a small set of data of the first 2–3 months of work, the available statistics even for abundant nuclei (C, O, Ne, Mg, Si) was not high enough to compare the signals of different nuclei in each detector reliably. Because of this, averaged values of the calibration capacitors (2 *pF*) and the thickness of the detectors (450 μm) were used for the calibration and normalization of signals. This approach achieved separation of abundant nuclei with an accuracy of 0.3 charge units.

When the statistics for each individual detector has reached several hundred events for each of the abundant nuclei, the analysis has been refined: comparison of average ionization from identical nuclei in different detectors allowed to introduce a correction factor for individual detector thickness and for individual calibration capacitor value (there is one capacitor for two detectors). Note that expected variability of the capacitors' values is 2%, and variability of the detector thickness is up to 3%. With these amendments, accuracy of charge measurements reached 0.2 charge units. Fig. 4 shows the result. Dynamic range of the system allows to detect nuclei with charges up to 30, but the current statistics provides enough information to identify nuclei only up to $Z = 26$ (Fe).

4. Primary particle energy reconstruction

4.1. The ionization calorimeter

An ionization calorimeter is a well-known device to measure the energy of relativistic particles. The calorimeter of the NUCLEON experiment is a typical example of “first interaction” or “thin” calorimeters, which are described by a small number of active layers and low thickness. Well-known procedures, used, in particular, to analyze the data from the ATIC experiment [5], can be applied

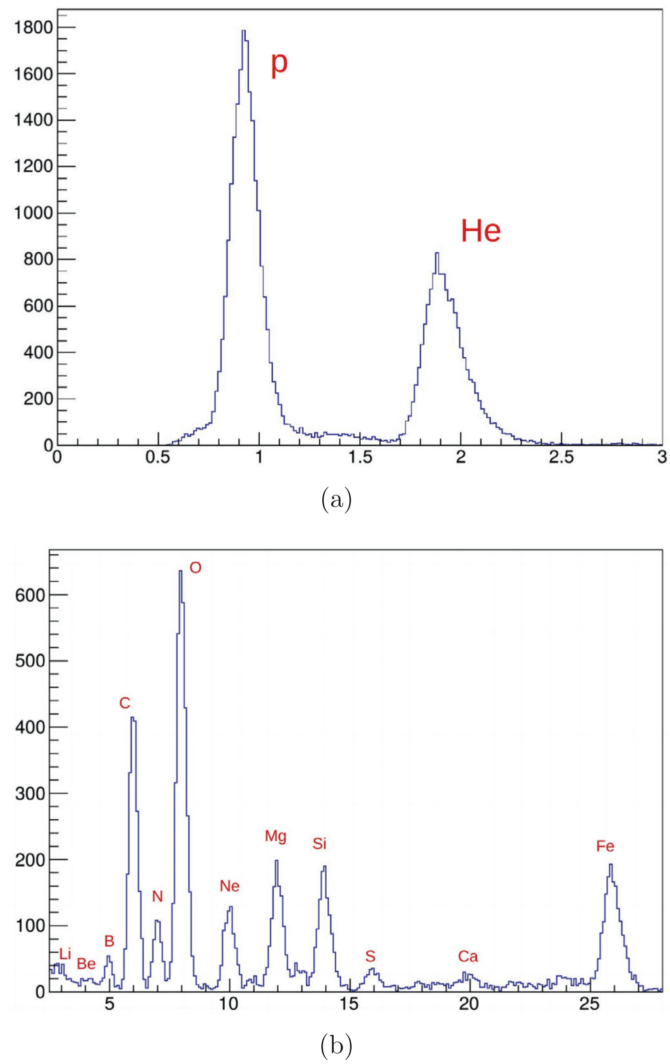


Fig. 4. (a) - the charge resolution for protons and helium; (b) - the charge resolution for Li-Fe nuclei.

here as well. In a few words, currently used preliminary procedure of nuclei energy spectra reconstruction consists of several steps:

- Measurement of energy losses in the calorimeter for every event;
- Calculation of a most probable primary particle energy from a sum of energy losses. Value of the conversion coefficient depends on the energy losses and is determined by simulation for every charge of primary particles and for every configuration of the trigger settings;
- Energy spectra reconstruction, taking into account
  - the aperture of the device;
  - the "dead time" of the device;
  - the trigger efficiency (individual for each nuclei and energy range);
  - the charge reconstruction efficiency.

It has to be noted that a large amount of technical analysis is performed to select channels with signal from a secondary particle shower on a background of noisy channels before the first step of the analysis.

Simulation shows that expected accuracy of relativistic nuclei's energy measurement in the NUCLEON's calorimeter (half width of the response function) is approximately 50%, which is confirmed by the results of ground tests with SPS hadron beams.

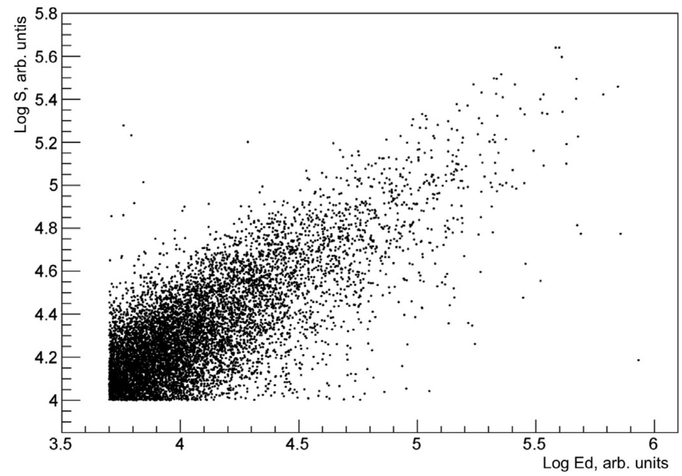


Fig. 5. Comparison of experimental values of the calorimeter energy deposit (Ed) and the KLEM system S functional (S).

4.2. The KLEM procedure

The kinematic method of energy measurement is reviewed in [7] in full details. In a few words: to determine the energy, we use the fact that in the first hadron interaction the portion of secondary particles with high pseudorapidity grows with the growth of primary particle's energy. In other words, with the growth of primary particle's energy portion of secondary particles with small relative angles also grows. Technically, the method is based on the analysis of the S functional:

$$S = \sum \left[I_k * ln^2(2H/x_k) \right],$$

where I_k corresponds to energy deposit at the x_k distance from the shower axis, H corresponds to the distance from the interaction point to the current plane. Applied to the NUCLEON device I_k corresponds to the energy deposit in the channel k which is at x_k distance from the shower axis in case of X oriented plane, or y_k in case of Y oriented plane.

It is important to note that the functional includes energy deposit from all the products of the first hadron interaction, including secondary gamma rays. Considering that efficiency of gamma ray detection in silicon is low, each plane has a tungsten plate installed to convert the gamma rays to a charged component.

The simulation shows that expected accuracy of energy measurement with the KLEM procedure (half width of the response function) is approximately 60% for energies higher than 1 TeV, which is confirmed by the results of ground tests on SPS hadron beams.

Before continuing to the results of energy spectra reconstruction by the KLEM system, let's show that the S functional is related to the energy of a primary particle. To achieve this, we have selected events registered in both the KLEM system and the calorimeter. Fig. 5 presents experimental values of the S functional compared to the energy deposited in the calorimeter. The Pearson product-moment correlation coefficient for E_{KLEM} and E_{IC} is equal to 0.82.

To get energy from the S value the following expression is used:

$$E_{KLEM} = aS^b,$$

where the values of a and b parameters are determined from the simulation individually for all nuclei, values of the parameter b are between 1 and 1.5.

The next stage is to obtain energy spectra. On this stage the KLEM system data are processed in the same way as the

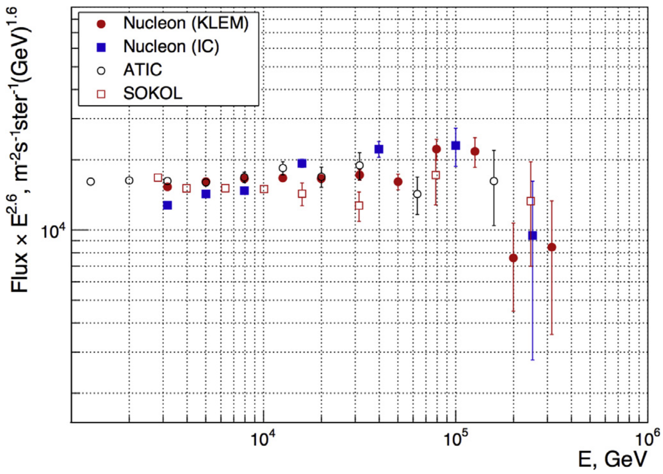


Fig. 6. Preliminary all-particle spectra for the KLEM system and the calorimeter compared to other experiments.

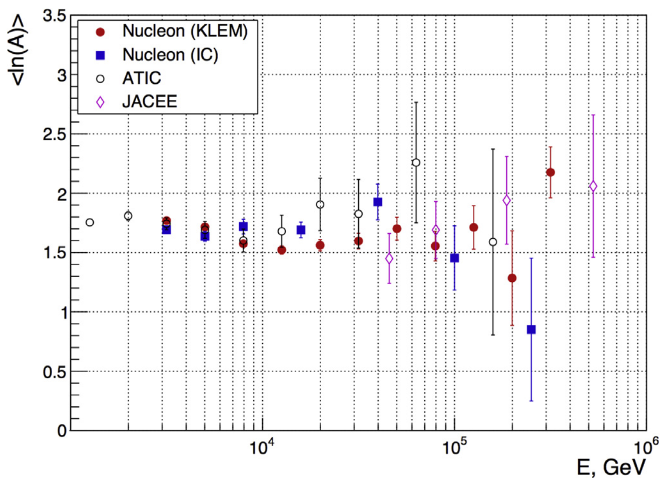


Fig. 7. Preliminary mean logarithm of atomic weight energy dependence.

calorimeter data. The differences are aperture value for the KLEM system (0.24 m^2sr for the KLEM system compared to 0.06 m^2sr for the calorimeter) and a number of technical variables determined by differences of the KLEM and the calorimeter simulation.

4.3. First results

The first result of the presented work is a preliminary energy spectrum of all particles obtained by two different methods from the statistics of the first year of data acquisition of the experiment. Considering the duration of flight tests and trigger configuration, the real time of data acquisition is approximately half a year. Obtained spectra are presented on Fig. 6 in comparison with the data of two other experiments - ATIC [5] and SOKOL [8]. These experiments are closest to the NUCLEON experiment in terms of their physical goals. A conclusion can be made that the presented data reproduces the results of previous experiments within statistical errors and has already progressed into a new energy region - beyond 3×10^{14} eV.

Separate energy spectra of different nuclei will be published later with larger statistics.

The other result, the energy dependence of mean logarithm mass versus energy per particle is presented in Fig. 7 together with data of ATIC [5] and JACEE [9]. It should be pointed out that the data are still very preliminary. The statistics will be improved by a factor of approximately five, the methods will be improved and justified too and an estimate of the systematic errors will be done. One can estimate current level of the systematic errors in the presented data of the NUCLEON by the difference between the results of KLEM and IC methods.

Despite preliminary character of the data one can note some hints of interesting physics in them. First, there is an indication of a break in the all-particle spectrum above 100 TeV. Second, the ATIC experiment observed some wave-like structure in behavior of mean logarithm of atomic weight at E ~ 100 Tev/n (Fig. 7) and the Nucleon data do not clearly contradict this structure. But let us emphasise again that all these observations are very preliminary.

5. Conclusion

The NUCLEON experiment has begun its data acquisition in the beginning of april 2015. The presented results outline the analysis of the detector characteristics and the data acquired, and lead to the following conclusions:

- The detector has successfully survived shocks and vibrations of the satellite's launch and remained fully functional;
- The trigger setup for data acquisition in the required energy range with close to optimal efficiency was completed;
- Data collected during the first year confirms the ability of the apparatus to identify nuclei with $Z = 1 - 30$ and accuracy better than 0.2 charge units;
- The two implemented methods of energy measurement (the KLEM system and the calorimeter) allow to reconstruct energy spectra of CR particles and agree with each other and with other similar experiments.

The last point is the most important methodological achievement of this initial stage of the experiment. The new KLEM method opens the way to make direct CR spectra measurements (both in orbit and on balloons) for experiments with high aperture and low weight (in comparison with traditional calorimetric techniques).

Unfortunately, no firm conclusions can be drawn from the current state of analysis, but new physical data can be expected on later stages of development of this experiment.

Acknowledgments

We acknowledge support from the Russian Space Agency (RosCosmos), Russian Academy of Sciences (RAS), JSC SRC Progress.

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