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The NUCLEON space experiment

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Abstract. The NUCLEON satellite experiment is designed to investigate directly, above the atmosphere, the energy spectra of cosmic-ray nuclei and the chemical composition ($Z= 1-30$) at energy range 100 GeV–1000 TeV. The effective geometric factor is more than 0.2 m^2sr for nuclei and 0.06 m^2sr for electrons. The planned exposition time is more than 5 years.

1. The aims of the NUCLEON experiment

The NUCLEON satellite experiment is designed to investigate directly, above the atmosphere, the energy spectra of cosmic-ray nuclei and the chemical composition from 100 GeV to 1000 TeV (before the "knee"). The additional aim is the cosmic-ray electron spectrum measurement (from 20 GeV to 3 TeV).

The "knee" energy range, $10^{14}-10^{16}$ eV, is a crucial region for the understanding of the cosmic-ray acceleration and propagation in the interstellar medium. It is important to obtain more data with elemental resolution since the "knee" region is interesting for astrophysics.

New experiments over a wide charge and energy range are needed, as they would help to test existing theoretical conceptions. Balloon experiments like ATIC [1–3], TRACER [4], CREAM [5] have begun to solve the above-mentioned problems. But a real solution to the problems would be possible only with a long-term large aperture satellite experiment. Some important results has been obtained in the past years by the PAMELA satellite [6,7], and recently by AMS02 [8,9] and Fermi-LAT [10], currently taking data.

The NUCLEON experiment on board of the RESURS-P satellite was launched in 26 December 2014. The mission aims to clarify, in the above mentioned energy interval, the essential details of the origin of cosmic-rays, such as the number and types of sources, identification of actual nearby sources, and the investigation of the mechanisms responsible for the knee. Specific features of the NUCLEON instrument are a relatively small thickness (15.2 radiation lengths) and a small weight (375 kg). The satellite restrictions did not allow the creation of a full-aperture calorimeter thus its transversal size was limited to 250 × 250 mm and a weight of ∼26 kg. In this contribution we present the design of the instrument, and some results of accelerator beam tests in terms of charge and energy resolution. The potential of the instrument to achieve the declared goals are also presented.

2. The NUCLEON device

The NUCLEON device was designed and produced by a collaboration of SINP MSU (main investigator), JINR (Dubna) and some other Russian scientific and industrial centers. It is placed now on board of the RESURS-P N°2 satellite (Fig. 1). The spacecraft has a Sun-synchronous orbit with an inclination of 97.276° and a middle altitude of 475 km.

The effective geometric factor is more than 0.2 m^2sr for the KLEM (Kinematic Lightweight Energy Meter) system and near 0.06 m^2sr for the calorimeter. The primary energy is reconstructed by registration of spatial density of the secondary particles. The particles are generated by the first hadronic inelastic interaction in a carbon target. Then additional particles are produced in thin tungsten converter by electromagnetic and hadronic interactions.

The surface area of the device is equal to 0.25 m^2. The charge measurement system must provide a resolution better than the 0.3 charge unit. The NUCLEON device must permit the separation of the electromagnetic and hadronic CR components with a rejection level better than 10^{-3} for the events in the calorimeter aperture. The total weight of the device is about 375 kg. The power consumption is less than 175 W. The planned lifetime is more than 5 years.

The most universal energy measurement technique is based on the use of ionisation calorimeters. This method is reliable but a calorimeter needs a heavy absorber to register high-energy showers. Weight restrictions limit

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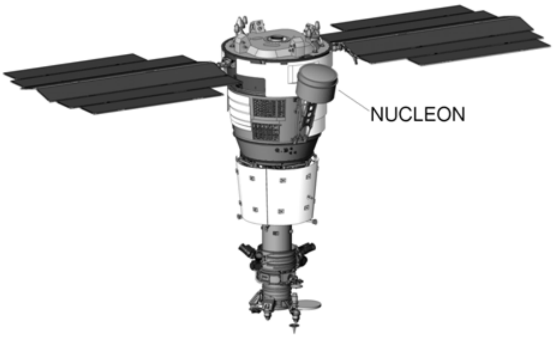

Figure 1. The RESURS-P satellite.

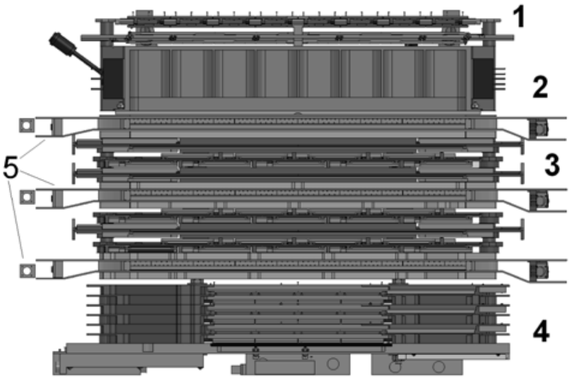

Figure 2. General scheme of the NUCLEON apparatus.

the application of ionisation calorimeters for cosmic-ray investigation on board of satellites at energies >100 TeV.

To solve this problem a new energy measurement method has been proposed. The method reconstructs the primary energy by registering the spatial density of the secondary particles. Secondary particles are generated by the first hadronic inelastic interaction in a carbon target. Additional particles are then produced in thin tungsten converter by electromagnetic and hadronic interactions. In this way it is possible to design relatively light cosmic ray detectors with a large geometric factor.

The proposed technique for primary CR energy measurement is based on the generalized Castagnoli kinematical method (KLEM method) [11] developed for emulsion, and gives an energy resolution of 70% or better according to simulation.

The general concept and the beam tests results are described in [12–20].

The design of the NUCLEON device is described in [21]. The general scheme of the NUCLEON apparatus is presented in Fig. 2. The NUCLEON apparatus includes the charge measurement system consisting of 4 pad silicon detectors layers (1), the KLEM energy measurement system consisting of the carbon target (2) and the silicon microstrip detectors interleaved with thin tungsten layers (3), the trigger system consisting of the 6 scintillator layers (5) and the calorimeter (4). Silicon detectors consist of unified ladders.

The charge detector system is designed for precision measurement of the primary particle charge and consists of four thin detector layers of 1.5 × 1.5 cm silicon pads. Each readout channel is used for the two pads to decrease the number of channels. Signals of the two pads from different parts of detector are summed. The probability of simultaneous registration of two particles is negligible. The charge measurement readout chips CR-1 have a dynamic range ~1000 mip.

The energy measurement system is placed just after the target and consists of silicon microstrip layers (with perpendicular orientation) and tungsten layers to convert secondary gamma-quanta to electron-positron pairs. This increases significantly the number of secondary particles and therefore improves the accuracy of a primary particle energy determination. The pitch of microstrips is equal to 484 μm. Every strip is connected to its own readout channel. The perpendicular strip orientation makes it possible to perform analysis for each X and Y directions independently and improves the primary particle energy resolution.

The microstrips must also be used to determine a secondary particle shower axis for the primary particle trajectory measurement. The spatial distribution of signals is approximated by Gaussian curves for every layer to determine the shower axis coordinates.

There are six layers of scintillator detectors with thickness of 0.75 cm in the trigger system. They aims to generate the necessary trigger signals for the KLEM system. Each of the trigger planes consists of 16 scintillator strips. The light signals from the strips are collected by the wavelength shifting fibers (WLS) to photomultiplier tubes (PMT). A two level trigger system must provide the NUCLEON statistics of more than 10^8 events with energy above 10^{11} eV for 5 years data taking.

The ionisation calorimeter (MIC) has a thickness of 12 radiation lengths. The device's full length, including the target and the energy measurement system, equals 15.2 radiation lengths. The equivalent thickness of the carbon target is equal to 0.23 proton interaction length. The calorimeter base consists of 6 tungsten plane absorbers of two radiation lengths each (Fig. 2). The 6 layers of 300 μm silicon microstrip detectors, positioned between the tungsten planes on textolite leaders, are sensitive elements of the calorimeter. The strip stepping is roughly 1 mm.

The calorimeter must register the secondary particles shower after the KLEM energy measurement system. The calorimeter must be used to select and to measure the electromagnetic component (electrons, positrons, gamma) from the total CR flux. Also the calorimeter allows measurement of the hadronic component energy for onboard calibration of the KLEM method.

3. The NUCLEON device beam tests

The NUCLEON prototypes and the flight model were tested many times at the CERN SPS accelerator high-energy hadron and heavy ion beams.

A beam of indium nuclei with an energy of ~158 GeV/nucleon was directed toward a 4-cm-thick beryllium target. The secondary charged particles and nuclear fragments were then separated according to their rigidity by means of a magnetic deflection system. In the experiment, particles with rigidities of 157.65, 315.5, 319.0, and 339.56 GeV/Z (Z is the nuclear charge) were selected.

Since the energy per nucleon was constant for all the nuclei produced by fragmentation of indium, each value of the magnetic rigidity corresponded to a particular value of the ratio of the mass number to the charge A/Z (1.000, 2.000, 2.023, and 2.154). It is evident that the first value corresponds only to protons; the second, to deuterium, ^{4}He, ^{6}Li, ^{10}B, ^{12}C, etc.; the third, to ^{87}Tc or ^{89}Ru (unstable isotopes with a very short lifetime); and the fourth, to ^{28}Al and ^{56}Fe.

The system for determining the charge consists of four layers of silicon detectors composed of separate pads. Information on the incident particle charge is collected from each array independently of the others, which guarantees a higher accuracy of measurements than that achieved by a single array.

Various algorithms of particle charge reconstruction were worked out. The calibration curves were obtained for all channels.

The charge spectra of the four detectors were matched using the rank statistics method [19]. For each recorded event four charges were measured by the four detectors and arranged in ascending order (regardless of the detector to which a particular charge corresponded). The next step was to determine the charge that is second in magnitude, and this value was used as the estimate for the charge. It should be noted that the rank statistics method provides better results than mere averaging of values, since fluctuations of the ionisation losses have a sharply asymmetrical form, as opposed to the standard distribution of errors. This method decreases the errors caused by nuclear spallation and secondary particles generation in the detector.

The procedure for measuring the charges of various nuclei using four arrays of pad silicon detectors allowed to determine the particle charges. Comparison of the charge distributions obtained in the test experiment on the accelerator to the results of the simulation has demonstrated consistency.

These results lead to the conclusion that the technique for measuring the charge in the NUCLEON experiment, together with the equipment intended for this experiment, will offer a chance to measure the charge composition of high-energy CR with an accuracy of 0.2–0.3 charge unit, which is sufficient both for discriminating separate different CR components and for studying the abundance of secondary nuclei in CR flux at high energies. The total grammage of the Charge Measurement System is about 1.5 g/cm^{2}. Thus the probability of spallation is sufficiently small even for iron nuclei.

In the Charge Measurement System there are peaks from different nuclei up to $Z = 30$ with reasonable separation. The results of measurements are shown on Fig. 3 (solid line) in comparison with a multi-gaussian fit (dashed line). Light nuclei were not investigated, so a value of A/Z equal to 2.1 and a rather hard electronic trigger were used. That is the reason why the proton (deuteron) and helium peaks are not seen on Fig. 3 and lithium/beryllium peaks are suppressed too. Also the channel gain in electronics of the Charge Measurement System is not perfectly linear, the real signal from the heavy nuclei ($Z > 25$) is higher than it should be from the standard dependence of the signal on the square of the nuclear charge. This information will be very useful for our space experiment.

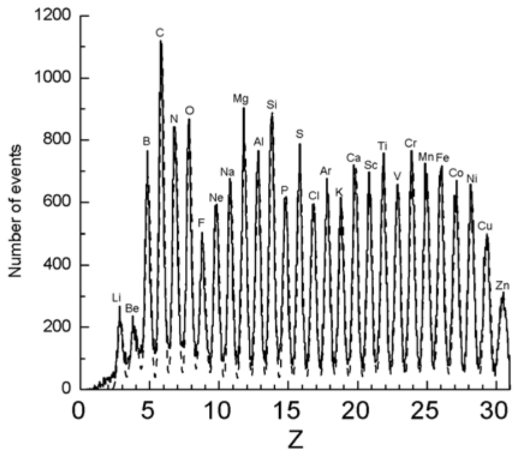

Figure 3. Charge distribution for the NUCLEON device beam test.

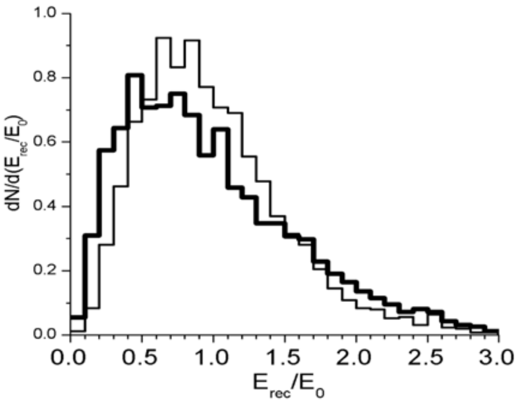

Figure 4. Normalized reconstructed energy distributions for pion beams of 150 GeV (thin line) and 350 GeV (thick line).

The main energy measurement system of the NUCLEON experiment is based on the KLEM method. The practical applicability of the proposed technique was estimated using the results of the simulation.

The NUCLEON flight model was tested in 2012 on pion and electron beams of the SPS accelerator at CERN.

The normalized distributions of the reconstructed energy for primary pions with energies of 150 (thin line) and 350 GeV (thick line) are shown in Fig. 4.

The rms deviation to primary energy ratio is equal to 0.53 for 150 GeV and 0.63 for 350 GeV. The asymmetry of distributions is determined by the asymmetry of multiplicity distributions for hadron interactions.

4. Summary

The NUCLEON device was designed and tested. The expected performance is confirmed by simulation and beam test results. All scientific objectives are achievable. The RESURS-P satellite was launched 26 December 2014. We have already received the first data.

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