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Review of the Results from the NUCLEON Space Experiment

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Abstract—The NUCLEON space observatory was developed to measure the spectra of cosmic ray nuclei with individual charge resolution in the energy range of several TeV to 1 PeV per particle. The NUCLEON was launched into a heliosynchronous orbit as an additional load on the Resurs-2P production satellite on December 28, 2014, and it is still in operation (2019). This work is a brief review of the results from the NUCLEON observatory over three years of operation in orbit. The spectra of the main primary abundant nuclei and product nuclei of cosmic rays (CRs) are presented. Some new interesting features of the CR spectra found in the NUCLEON data are discussed.

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Two different ways of measuring the energy of particles are used in the NUCLEON space spectrometer. The first to use an ionization calorimeter; the second, using the KLEM (Kinematic Lightweight Energy Meter) [1, 2], which is based on measuring the multiplicity of product particles after the first nuclear interaction of a primary particle with a target in a spectrometer. The KLEM approach is fundamentally new, and was used in a physics experiment for the first time. The main spectrometer systems are four planes of the charge measuring system, a carbon target, six planes of the KLEM energy measuring system (KLEM tracker), three two-layer planes of the trigger system based on scintillators, and a small aperture ionization calorimeter (25×25 cm^2). The KLEM spectrometer in the NUCLEON experiment has a geometric factor eight times that of the calorimetric system (depending on the type of nucleon). However, the KLEM energy resolution is around 60%, while the resolution of the calorimetric system is 50 to 35% (depending on the type of nucleon). The KLEM approach still has a higher energy threshold for heavy nuclei than calorimetry, so they complement each other. In addition, the new KLEM approach can be calibrated and studied by familiar calorimetric means. Design features of the spectrometer and details of the implementation of both methods for energy measurement were discussed in [3, 4].

The first results from the NUCLEON experiment were published in [5] (the first few months of a standard set of statistics and a preliminary spectrum of all particles were presented), followed by two reviews on the NUCLEON results ([4] and [7]). They corresponded to approximately one and two years of statistics. These reviews included all the main types of data provided by the NUCLEON experiment: elemental spectra of the main abundant nuclei of the cosmic rays and some ratios of the product nuclear fluxes to primary nuclei measured in the energy range of 2–3 TeV to several hundred TeV per particle. This work corresponds to approximately the first three years of statistics. Unfortunately, the integrated statistics did not grow very much compared to the last review [7], since much time was devoted to solving the targets of the Resurs-2P satellite in the third year of the observatory's operation. The NUCLEON equipment was turned off while solving these problems. However, the new statistics allowed much deeper analysis of the data. This helped us discover new and very important features of the spectra of cosmic ray nuclei, and to obtain new data.

The spectra of the main abundant nuclei of cosmic rays (p, He, C, O, Ne, Mg, Si, and Fe) were presented in the results from the NUCLEON observatory. A spectral analysis of protons and helium was presented in [6] (an article on the materials of this report was

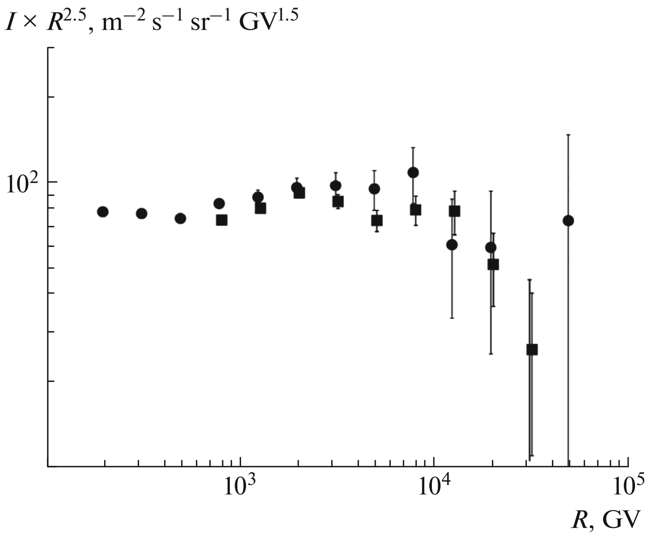

Fig. 1. Combined spectrum of magnetic rigidity (R, GV) of all nuclei with charges of 6 (carbon) to 27 (nickel). Dots are calorimeter data; squares, KLEM data. We can see the lower threshold for the KLEM approach is higher than that of calorimetry.

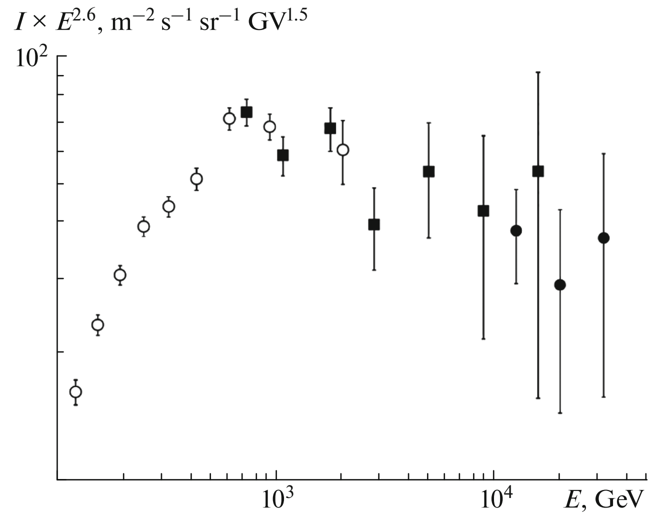

Fig. 2. Spectrum of nickel (energy per particle) according to the NUCLEON experiment (squares are calorimeter data; dots, KLEM data) and HEAO-3-C2 [9] data.

published with pictures of the spectra in this issue of the journal). The results again confirm that helium has a flatter spectrum at energies of less than 10 TeV per particle (this result was first established reliably in the ATIC experiment [8]) and good statistical significance (about four standard deviations). There is a kink in the proton spectrum and helium spectrum near a magnetic rigidity of 10 TV. The magnitude of the kink for the spectral index is 0.5 in scale. It still cannot be determined precisely, however, since it shows the model dependence on the type of function approximating the kink [9].

Elemental spectra were obtained for the nuclei of C, O, Ne, Mg, Si, and Fe. It was noted that the iron spectrum was steeper than the spectra of lighter nuclei in the region of energies higher than several hundred GeV per nucleon, as indicated by the ratio of nuclear fluxes $Z = 6$–14 to the flux of iron nuclei, showing an increase in the ratio with increasing energy. This result is in good agreement with the well-known result from the ATIC experiment [11]. The spectra of less abundant nuclei of S and Ca were also registered. The proportion of primary nuclei in these spectra should be high, but the statistics do not allow us to reach any conclusion on the nature of these spectra.

Starting with carbon, the spectra of heavy nuclei indicate a possible kink in the spectra at energies of hundreds of TeV per particle. An interesting hypothesis is the assumption that all nuclear spectra have a kink with the same magnetic rigidity. Starting with carbon, the combined spectrum of magnetic rigidity for all heavy nuclei was measured for the first time to test this hypothesis (Fig. 1). The KLEM data are in good agreement with those of the calorimeter, and the spectrum kink near the magnetic rigidity of 10 TV is clearly visible in both cases. The statistics of the KLEM data are better, and the statistical significance of the existence of a kink is in this case at least 3.9 standard deviations [9]. This is an extremely important result. Since there is also a kink in the spectra of protons and helium (see above) with the same magnetic rigidity, the kink is universal in rigidity. We are talking here about the discovery of a new low-energy kink of cosmic rays. Features of the spectra associated with the acceleration of particles must be universal in rigidity. It is therefore likely that the kink indicates the acceleration limit of the particles either in some nearby source or in a certain broad type of cosmic ray sources. The analysis of the new 10 TeV kink of cosmic rays was described in detail in [9].

The ratios of the product nuclei fluxes to primary nuclei B/C, N/O, $Z = 16$–24/Fe to record high energies were measured in the NUCLEON experiment. All measured ratios indicate the drop in the ratios that was expected as the energy rose did not occur at the highest energy levels [10].

The spectrum of nickel, measured up to energies of around 30 TeV per particle, is presented for the first time in the NUCLEON data (Fig. 2). This is a very important result, since the earlier ones were obtained in 1990 in the HEAO-3-C3 experiment [12] and had upper bounds of energy more than an order of magnitude lower. The spectrum of nickel is unexpectedly steep: the spectral index is 2.83 ± 0.09 (it is notably steeper than the iron spectrum with a spectral index of around 2.6).

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