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Main Results from the NUCLEON Experiment

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Abstract—A report is given on the main results from the NUCLEON space experiment. The composition and spectrum of cosmic rays is measured in the range of 2 to 500 TeV. Spectra of particular nuclei, including nickel and secondary nuclei, are obtained. The dependence of the ratio between the fluxes of protons and helium nuclei on magnetic rigidity is investigated. A universal knee is found in the magnetic rigidity spectra of different nuclei.

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INTRODUCTION

The NUCLEON instrument [1–4] was developed in cooperation between the Skobeltsyn Institute, the Joint Institute for Nuclear Research (Dubna), and a number of other Russian scientific and manufacturing centers. The apparatus was mounted onboard the RESURS-P2 satellite. The satellite was placed in a synchronous solar orbit with an inclination of 97.276 and an average altitude of 475 km. It was launched on December 26, 2014, and operated for about 3 years. The aim of the experiment was to measure the chemical composition and energy spectra of cosmic rays in the region of 2 to 500 TeV. Energies were measured using both a traditional ionization calorimeter and a new KLEM kinematic lightweight energy meter [1, 5]. The effective geometric factor was more than 0.2 m^2 sr for the KLEM system and about 0.06 m^2 sr for the calorimeter. The charge measureing system ensured a resolution of 0.15–0.20 charge unit.

SPECTRA OF DIFFERENT COMPONENTS AND THEIR RATIOS

Investigating the spectra of component nuclei is part of studying the region of energies preceding the main knee in the spectrum [2–4]. Important results have been obtained for the proton–nucleus component of cosmic rays. A new universal knee was found in all groups of nuclei from protons to iron when processing the NUCLEON data [2]. Universality means the same position of the knee at 10 TV in the magnetic rigidity scale for all groups of nuclei. The knee is observed in particle energy measurements made by the NUCLEON observatory via both calorimetry and the kinematic KLEM technique. The new cosmic-ray knee is probably associated with the limit of acceleration by a generic or nearby source of cosmic rays. A proton spectrum with the knee is shown in Fig. 1a.

Since processes of cosmic ray acceleration and propagation are governed by the magnetic rigidities of particles, it is logical to consider and compare the measured spectra in terms of rigidity as well.

As was noted above, all spectra of abundant nuclei have a magnetic rigidity kink in the region of ~10 TV [2]. However, spectra of different components have notable differences made visible by analyzing their ratios.

The spectra of protons and helium nuclei are compared to data from other experiments. In AMS02 [6, 7], magnetic rigidity spectra of cosmic rays were obtained for protons up to 1.8 TV and for helium nuclei up to 3 TV. The spectra themselves and their ratios were parametrized, and both spectra become harder at magnetic rigidities above 200–350 GV. The slope of the spectrum ratio dependence diminishes from 0.15 at 10 GV to 0.077 in the region above 45 GV. NUCLEON data are obtained for magnetic rigidities above 2 TV, which is beyond the working range of the AMS02 experiment.

One of the main characteristics of the chemical composition of cosmic rays reflecting physical processes of their acceleration and propagation is the ratio between the fluxes of protons and helium nuclei at different magnetic rigidities. The dependence of this ratio on magnetic rigidity is shown in Fig. 1b. The points for rigidities below 2 TV are from the AMS02 data [6, 7]. A comparison of the data from different experiments shows that the fraction of protons falls with as the rigidity rises in the range of 0.1–1 TV and comes to an almost constant level at high rigidities (above a few TV).

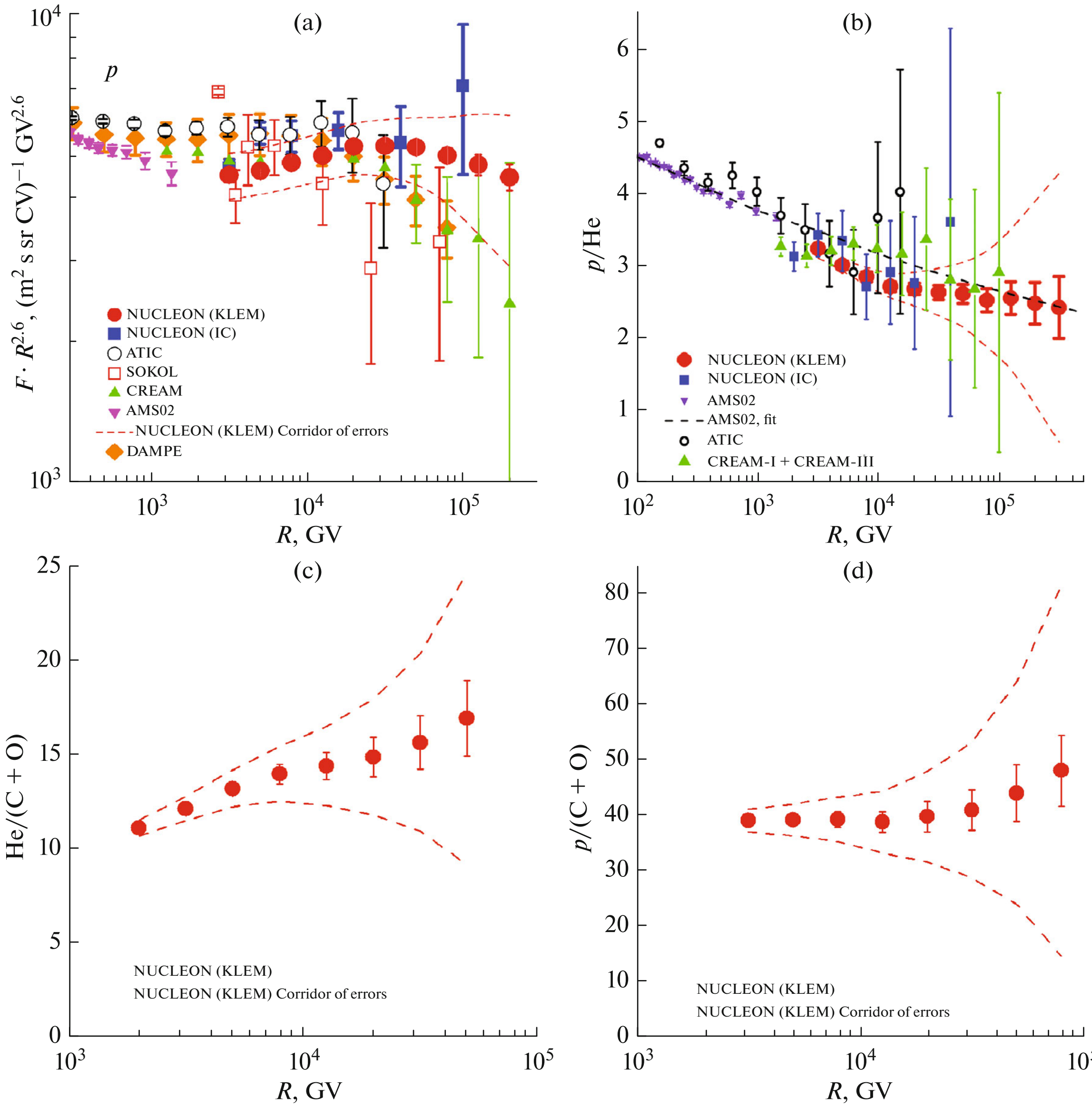

Fig. 1. (a) Proton spectrum; (b) ratio of p and He spectra; (c) ratio of He and C + O spectra; (d) ratio of p and C + O spectra.

The slope of the dependence of the proton-to-helium flux ratio on magnetic rigidity was estimated and found to be 0.063 ± 0.010 (stat.) ± 0.031 (syst.) for KLEM and 0.095 ± 0.163 for the ionization calorimeter in the region above 4 TV.

The charge composition of cosmic rays in the kink region differ appreciably from the charge composition in the ~100 GV region of magnetic rigidity measured in the AMS02 experiment. The ratio of the proton and helium fluxes is 2.98 ± 0.03 (stat.) ± 0.09 (syst.) at $R \sim 5$ TV and 2.68 ± 0.07 (stat.) ± 0.20 (syst.) at $R \sim 20$ TV, while it is 4.46 ± 0.20 at ~100 GV [8].

Magnetic rigidity spectra of carbon and oxygen nuclei were investigated in [9] using data from NUCLEON and a few other experiments. The spectra in the region of rigidity above 300–500 GV are less steep than those measured at lower rigidities in different experiments. A kink similar to the knee in the spectra of other components is observed in the region of ~10 TV. Figure 1c shows the magnetic rigidity dependence of the ratio between the helium spectrum and the summed spectrum of carbon and oxygen nuclei, and Fig. 1d shows a similar ratio between the proton spectrum and the same carbon and oxygen spectrum. The spectrum of carbon and oxygen nuclei is seen to be softer than the helium spectrum in the region preceding the kink, but the slope of the C and O spectrum does not differ from the proton spectrum in the region that precedes the knee.

The NUCLEON data allowed direct measurements of the full-particle spectrum to be compared for

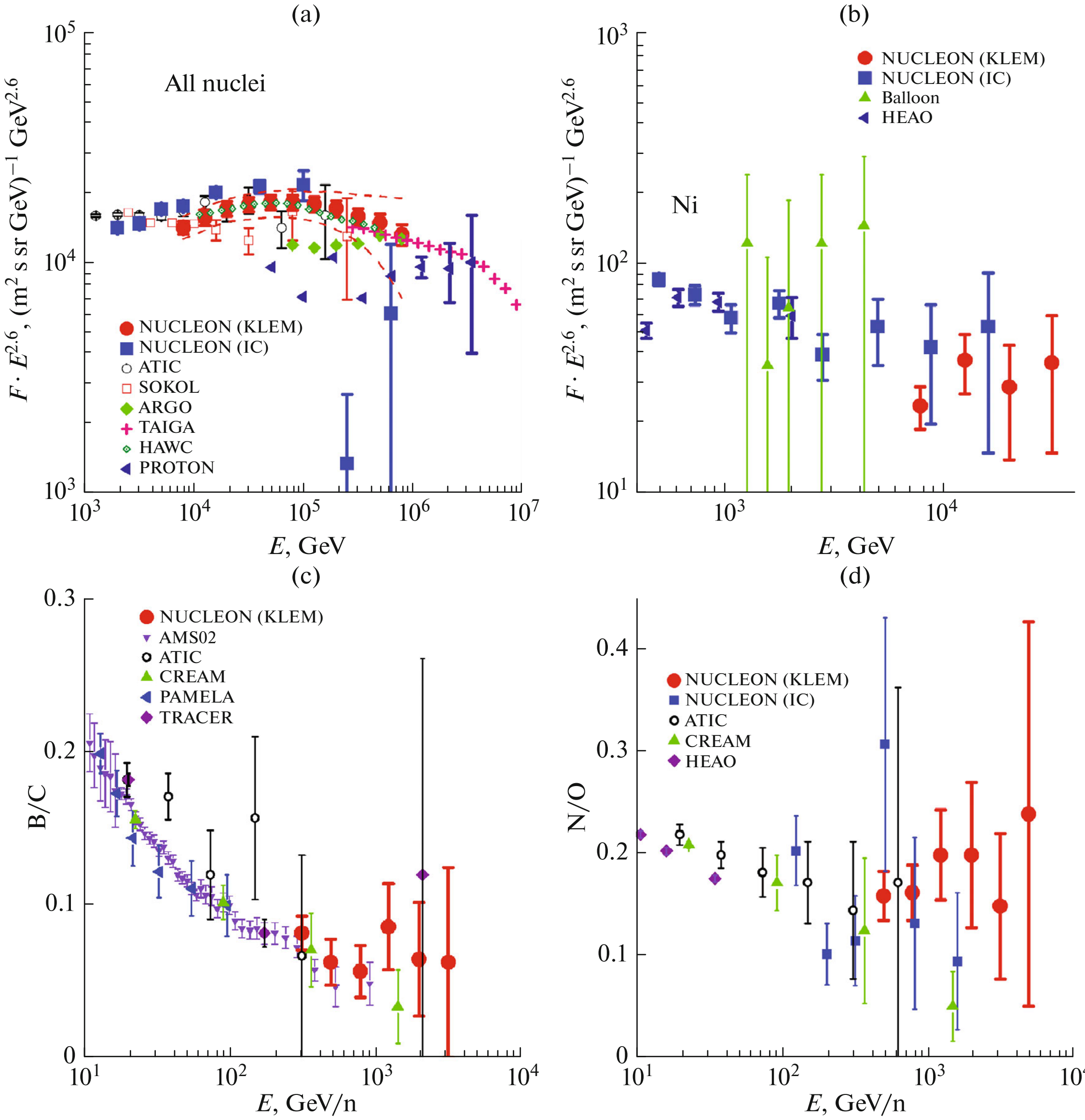

Fig. 2. (a) Energy spectrum of all particles; (b) Ni spectrum; (c) B/C spectrum ratio; (d) N/O spectrum ratio.

the first time to EAS (extensive air shower) data. Unlike direct measurements, these experiments yield high statistics, but their results depend largely on the models of nuclear interaction that are used, and it is impossible to identify the type of particle in each individual case. At best, we can determine the average logarithm of the mass number as a characteristic of the cosmic-ray flux.

The data from these experiments agree with the NUCLEON data in both the absolute intensity and shape of the spectrum in their region of intersection (see Fig. 2a). The energy spectrum's deviation from the power-mode type is notable, due to the kink in the rigidity spectrum. The energy spectrum of all particles is superpositioning of spectra of different components, so its slope grows steeper more smoothly than on the rigidity scale. Combining data on the composition of cosmic rays from the direct NUCLEON experiment and the results from detailed statistical measurements of the summed energy spectrum in EASes yields new astrophysical information.

The spectrum of high-energy nickel nuclei (up to ~40 TeV; see Fig. 2b) was measured in the NUCLEON experiment, providing important information on processes of nucleosynthesis. The nickel spectrum has a slope of 2.83 ± 0.09 [11], which differs from the iron spectrum's slope of 2.64 ± 0.02 [11]. The difference between the spectra could reflect properties of the processes of nucleosynthesis and cosmic ray acceleration.

Spectra of high-energy secondary nuclei and their ratios to those of primary nuclei (B/C, N/O; see

Figs. 2c and 2d) are obtained with reliable statistics [12]. These ratios flatten out in the region of high energies (>500 GeV/nucleon); i.e., the spectra of these nuclei become similar to those of primary nuclei, due possibly to astrophysical processes. At high energies, the range of primary nuclei in the interstellar medium is be comparable to the range in their sources, and we observe the spectrum of secondary nuclei produced in the sources and accelerated together with primary nuclei.

CONCLUSIONS

A universal knee was found in the magnetic rigidity spectrum. Spectra became softer in the region of ~10 TV. A comparison of the AMS-02 data and C and O spectra revealed flattening of the spectra in the region of 200 to 300 GV. The ratio between the proton and helium spectra fell as the rigidity rose, but it came to a constant level in the knee region. The fraction of helium grew in the region preceding the knee, which could indicate a nearby helium-rich source. The energy spectrum of all particles was in good agreement with the data from terrestrial experiments. There were notable differences from the power-mode type. The spectrum of high-energy nickel nuclei (up to ~40 TeV) was measured, providing important information on processes nucleosynthesis. Spectra of secondary nuclei and their ratios to primary nuclei were obtained. These ratios flattened out in the region of high energies (>500 GeV/nucleon).

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