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Direct Measurements of Galactic Cosmic-Ray Energy Spectra and Elemental Composition

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Abstract—The description of the Advanced Thin Ionization Calorimeter (ATIC) experiment and its main results are presented. The ATIC experiment is an important step in Galactic cosmic-ray investigations that use the direct methods that were first carried out in the *PROTON* experiment in the 1960s. We consider the contribution of the ATIC experiment to the understanding of the Galactic cosmic ray origin and propagation.

Keywords: Galactic cosmic rays, energy spectra, elemental composition.

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INTRODUCTION

The study of galactic cosmic rays (GCRs) using direct methods is a priority of the Skobeltsyn Institute of Nuclear Physics of Moscow State University. The basics of this research direction were founded by D.V. Skobeltsyn and S.N. Vernov. The project was headed by N.L. Grigorov for many decades, starting with the first space flights in the late 1950s. In the 1960s–1970s, the research team under Grigorov developed and exposed *PROTON* facilities in near-Earth orbits [1]. An energy-measuring device called a calorimeter was the main element of these facilities [2].

PROTON calorimeters contained scintillators and some amount (several nuclear paths) of passive material (iron) to absorb the particle shower that is produced in this absorber. Scintillators were also used to measure the charges of particles. The *PROTON-4* spectrometer was able to measure the spectrum of all the GCR particles in an extremely wide energy range from 10^{11} to 2×10^{15} eV [3]. These measurements remain the unrivaled experimental result for direct-measurement methods. However, charge separation in the particles proved to be a more challenging task, since the phenomenon of the albedo from a calorimeter was not known at that time. The albedo includes particles that move in the direction opposite to the movement of a primary particle. These particles produced an additional signal in the input scintillator that was used to measure the charge. The signal from the primary particle was distorted and experimenters gained false information about the charge of this particle.

When the influence of the albedo particles on the measurement of the primary particle charge became clear, a new experiment was put into effect by Grigorov, et al. [4]. In this experiment, which was called *SOKOL*, a new detector was developed for charge measurements, namely, the directional Cherenkov counter. This detector consisted of a plastic disk, whose upper surface was painted and absorbed light. The Cherenkov light produced in this detector due to an incoming primary particle was detected by a photomultiplier. The backscatter particles produced light that was absorbed by the upper surface of the detector; and this light did not distort the signal from the primary particle. This instrument was twice exposed in outer space [5]. Some difficulty with the interpretation of the first-flight data arose due to calibration problems. These problems were overcome in the second flight, in which important results on the spectra and elemental GCR composition were obtained; however, the statistics were still insufficient to reveal important properties of energy spectra that were detected in further studies.

Another project was carried out at the SINP of Moscow State University at that time: the Moscow University Balloon Emulsion Experiment (MUBEE). This experiment was aimed at measuring the energy spectra and the elemental GCR composition in the energy range above 1 TeV. The device (the emulsion chamber) was a stack of nuclear emulsions and X-ray films layered by the passive material (lead). The nuclear emulsions were used to measure the charge, while the X-ray films were used to measure the energy of the primary cosmic particle using the method that

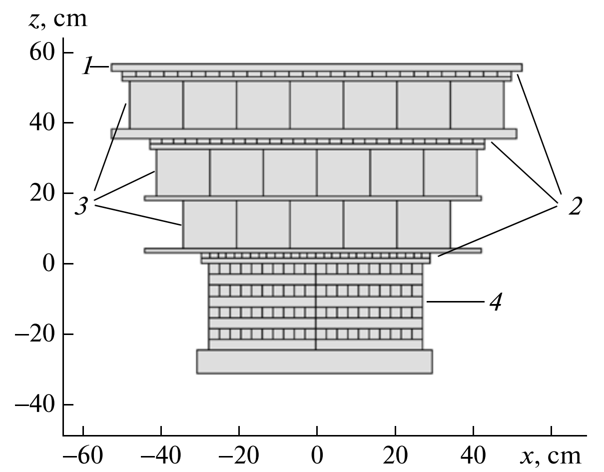

Fig. 1. The scheme of the ATIC device: (*1*) silicon matrix, (*2*) scintillation detectors, (*3*) graphite target, (*4*) BGO calorimeter.

was developed for ground-based experiments shortly before the MUBEE [6]. The chamber had a size of 1×0.5 m^2 and a thickness of 20 cascade units of lead and was able to detect incoming particles in a wide range of zenith angles. This device was characterized by a large geometrical factor (~0.5 m^2 sr). The balloon-borne chamber was repeatedly exposed in the stratosphere at residual depths of 8–11 g/cm^2. Ten stratospheric flights were performed altogether with a total exposure of 532 m^2 h sr in 1975–1987. The measured spectral index for protons with energies above 10 TeV was appreciably higher than the spectral index for protons with lower energies ($\gamma = 3.14 \pm 0.08$). The spectra of heavier nuclei were also measured but their statistics were insufficient [7].

Some years after the MUBEE project, an analogous experiment was started by the Japanese–American JACEE collaboration (1979–1994) [8]. The total exposure of a run of 12 stratospheric flights at a depth of 3–5 g/cm^2 was 644 m^2 h sr. This experiment provided the first indication of the difference between the spectral indices of protons and helium nuclei. The data also indicated that the spectrum of protons was steeper beyond 70 TeV ($\gamma = 3.19 \pm 0.28$), but the statistics were insufficient [9].

Another emulsion experiment was carried out by the Russian–Japanese RUNJOB collaboration in 1995–1999 [10]. A run of ten stratospheric flights at a depth of 9–11 g/cm^2 reached the total exposure 575 m^2 h. The spectra of protons and other nuclei were measured and the conclusion was drawn that the spectral indices of protons and helium nuclei were the same. Again, however, the statistics were insufficient [11].

Apart from the laborious data processing, the main drawback of the emulsion experiments was insufficient charge and energy resolution. Moreover, these experiments were characterized by a high energy threshold (~1–2 TeV) for measuring the energy of an electromagnetic cascade. This circumstance hindered the elucidation of the situation with the energy spectrum of protons in the energy range ~1 TeV. The main conclusion that was derived from the *PROTON* experiments was that the proton spectrum in the energy range > 0.5 TeV was steeper than that in the range of lower energies [12]. Before long, however, this effect was found to be due to the unaccounted impact of the albedo [13]. Thus, the question of whether or not the proton spectrum was steeper and differed from the spectra of other nuclei in the TeV-energy range was not resolved. In this context, Grigorov developed a thin ionization calorimeter (TIC) based on the suggestion of Vernov. It was expected that a simple experiment, which was able to reliably (and with high statistical accuracy) measure energy release in the calorimeter, could (without measuring the charge) answer the question of whether something occurs with the energy spectrum of protons. Since the majority of particles in this energy range are protons, a step should be observed in the composite spectrum of all particles if there is a break in the proton spectrum.

This experiment was carried out by SINP researchers jointly with American scientists in 1993–1995 [15]. The result was opposite from the anticipated one. Instead of becoming steeper and subsequently flatter (the appearance of a step) in the energy range of several hundred GeV, the composite spectrum of all the particles became shallower above 1 TeV. The experiment essentially showed that there was no steepness of the proton spectrum in this energy range. However, this result did not seem to be sufficiently convincing. It was necessary to carry out a more direct and reliable experiment. Such an experiment was put into effect using the Advanced Thin Ionization Calorimeter (ATIC), which became an international project [16].

ATIC EXPERIMENT

The main goal of the ATIC experiment was to measure methodically reliable and statistically ensured spectra of abundant nuclei from protons to iron, to perform measurements as high as possible in the stratosphere, and to expose the device for as long as possible (15–30 days) to obtain the statistics with the best possible quality.

To meet these requirements, a special device was developed whose schematic diagram is shown in Fig. 1. The device consists of three modules: the charge measuring module, the energy measuring module, and the target module. If directional Cherenkov counters, which had been developed for the SOKOL experiment [4] shortly before the ATIC, were used to measure the charge, this would lead to an undesirable increase in the length of the device and, hence, to a decrease in the statistics for a given exposure time. For this reason, we developed an essentially new charge detector for the ATIC experiment, namely, a silicon matrix [17] with a short lengthwise size for a fairly good charge resolution. The silicon matrix is composed of a large number of independently operating silicon cells (pixels), which are essentially a very thin (380 μm thick) plane capacitor to which a voltage of ~100 V is applied. An incident particle produces ionization proportional to the square of its charge as it comes into in the capacitor (pixel).

To operate under conditions of high albedo from the calorimeter, the pixel should have a small size in order to have the required spatial resolution for detecting the entry position of the primary particle in the spectrometer. The silicon matrix, which was constructed to operate as a charge detector in the ATIC experiment, consisted of 4480 pixels, 1.5 × 2 cm each, mounted on 0.95 × 1.05 m printed boards. The signals from the pixels were read by 16-bit amplitude-to-digital converters (ADC). The silicon matrix was an input detector of the ATIC spectrometer (Fig. 1). Energy was measured using the calorimeter.

A differing feature of the calorimeter that was constructed for the ATIC spectrometer was the use of active BGO crystal scintillators as an absorber. The spectrometer included 320 bar-shaped crystals, 2.5 × 2.5 × 25 cm each. These were stacked in eight layers (the ATIC-3 and ATIC-4 spectrometers contained ten layers each), 40 crystals in each layer alternately, in mutually perpendicular directions. Each crystal was viewed by one Hamamatsu R5611 photomultiplier and had a reflecting mirror surface at the opposite end. Three amplification ranges enabled the coverage of the required amplitude interval (altogether, there were 960 amplification channels in the calorimeter). The BGO crystals comprised heavy elements. The density of a BGO crystal was 7.1 g/cm^3. The calorimeter was thin (~1 nuclear pathlength) in order to be able to absorb the energy of the entire nuclear cascade but thick enough to absorb the energy of the electromagnetic cascade that arises in the first nuclear interaction of the primary particle in the target module of the spectrometer (~20 cascade units). The total energy of the primary particle was derived from the measured energy of the electromagnetic cascade. Modeling was used to determine what part of the total energy was deposited to the electromagnetic cascade. It is necessary to have a target of light material so that a greater number of nuclei are able to interact before their ingress to the calorimeter, since the path length of a nucleus before the interaction in this target is less per weight unit, which is essential for balloon and satellite experiments, which allow decreasing the weight of the lifted spectrometer. The target of the ATIC spectrometer was comprised of three graphite blocks (Fig. 1). Bicron BC408 scintillator bars, 2 × 1 cm each, were stacked in two rows under each graphite block in mutually opposite directions. The first two rows contained 84 bars each, the third and fourth rows contained 70 bars each, and the fifth and sixth rows contained 48 bars each. Each bar was viewed from both sides by a Hamamatsu R5611 photomultiplier and had two amplification ranges. This module contained 808 electronic channels altogether. The ATIC spectrometer was successfully exposed three times during balloon-borne flights in the Antarctic, at heights of approximately 37 km (*ATIC-1*, *ATIC-2*, *ATIC-4*). The first flight was technical and will not be considered here, the *ATIC-3* flight failed as the balloon exploded on take-off. The most reliable results on the spectra of protons and other nuclei were obtained during the *ATIC-2* flight, which was performed at the McMurdo Antarctic Research Station (USA) from December 29, 2002 until January 18, 2003. The spectrometer was in the stratosphere at a height of 36.5 ± 1.5 km for 20 days. Several hundred thousand particles with energies higher than some hundred GeV passed through the aperture of the device and were detected over this time.

The data processing includes the following stages: the calibration of electronic channels, the determination of the charge and energy release in the calorimeter, the construction of the energy-release spectrum, the transition from the energy-release spectrum to the energy spectrum of particles of a given kind. The calibration, i.e., the transition from electrical signals to physical quantities (the charge and energy release) was performed using cosmic-ray muons. The spectra of signals produced by muons were detected over some days prior to take-off. The difficulties, which arose after the calibration spectra had been processed, revealed an unexpectedly strong temperature dependence of the electrical signals [18]. The temperature in the flight differed from the ground-based temperature at which calibration spectra were collected by some degrees. The temperature dependence of the spectrometer was tested in a thermal chamber after this flight and this characteristic was confirmed. The final results were obtained after the introduction of a corresponding correction.

To determine an ingress point of a primary particle in the silicon matrix, we acted as follows. First, we detected the symmetrized centroid of the released energy in each layer of the calorimeter (relative to the maximum signal in this layer). Eight layers of the spectrometer yielded four values for each X and Y projection of the particle trajectory. These data were used to determine the ingress point of the primary particle into the silicon matrix. Since the coordinates of the trajectory were determined with inevitable experimental uncertainties, the ingress point for the primary particle was also determined with some uncertainties. We assumed that the primary particle had passed through the cell containing the maximum signal at the selected area. In order not to miss the cell that was the ingress of the primary particle, we chose an area with the size $\pm 4\sigma_x$, $\pm 4\sigma_y$, where σ_x and σ_y represented the absolute uncertainties of the measurements of the X and Y coordinates [19].

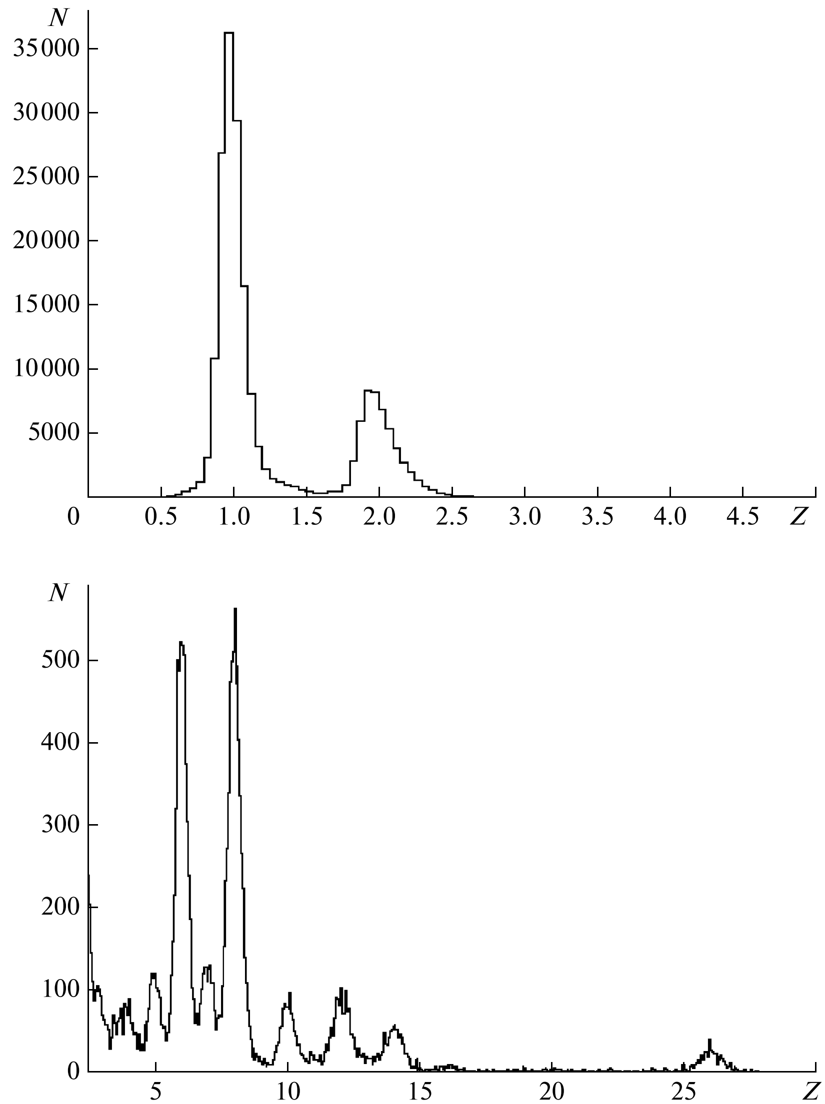

Fig. 2. The charge resolution of different groups of nuclei in the ATIC experiment.

Figure 2 illustrates the charge resolution that was reached using the silicon matrix and the upper row of scintillators in the charge range from protons to iron.

The calibration transforms the electrical signals that were produced in the calorimeter scintillators into physical quantities (i.e., the energy released in a scintillator). The total energy released by a particle of a given charge in the device was determined as the sum of energies released in all the calorimeter scintillators. Such spectra are commonly referred to as energy-release spectra. From the physical point of view, however, the total kinetic energy spectra of cosmic particles outside the device are of interest. We used two methods, namely, those of differential shift and deconvolution, to transit from the measured energy-release spectrum to the energy spectrum of particles. In the first method, the energy of the primary particle E_0 is determined using the formula $E_0 = E_d \times k(Ed)$, where E_d is the energy release in the device, and $k(Ed)$ is determined by modeling with the use of the FLUKA software [20]. In such a way, the spectra for nuclei with the charges $Z > 2$ were obtained. In the second method, the relationship between the spectrum of primary energies and the energy-release spectrum is determined by solving numerically an inverse problem (the deconvolution) using the Tikhonov method [21]. The statistics of the energy spectra obtained for protons and helium enabled the solution of the corresponding inverse problem. This was essential, since the energy spectra proved not to be purely power-law spectra.

In the ATIC experiment, it became possible to separate the electrons that are incident on the device by analyzing the longitudinal and transverse cascade developments. The calorimeter is thick for electrons, i.e., almost all the electron energy is released in the calorimeter. As a consequence, the energy resolution of the ATIC device is very good for electrons.

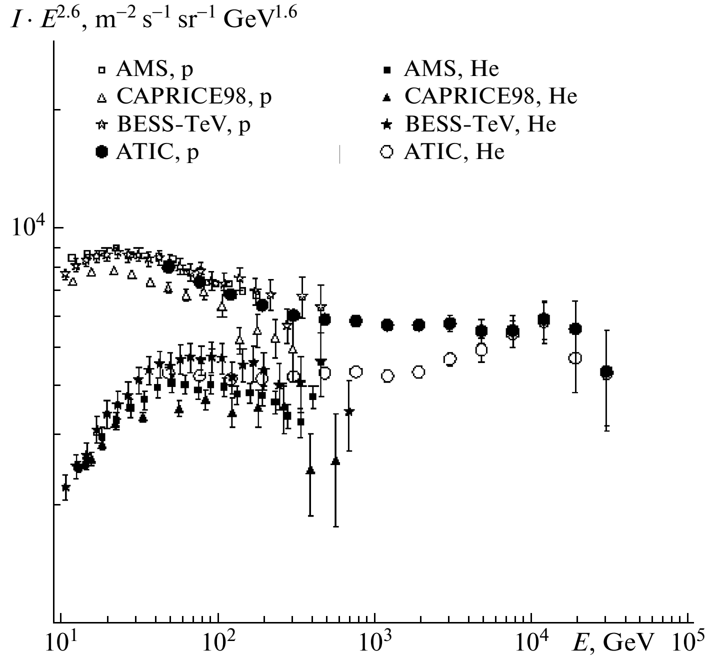

Fig. 3. The energy spectra of protons and helium from previous measurements using magnetic spectrometers and the spectra measured in the ATIC experiment (see the references on the data in [22]).

RESULTS

The ATIC experiment yielded new important results on both the spectra of protons, helium, and heavier nuclei of galactic cosmic rays [22] and on the spectra of galactic electrons [23, 24]. Here, we will discuss only the results that concern the proton and helium spectra. However, we do not consider other results to be less important. For example, the measured electron spectrum proved to have an excess in the energy range 300–800 GeV, which cannot be explained in terms of current considerations on the origin of primary electrons. This result provoked extraordinary activity in the scientific community and stimulated a large number of publications. We will discuss the proton and helium spectra, since these have been intensely studied at the SINP for more than a decade. The proton and helium spectra obtained during the course of the ATIC experiment are shown in Fig. 3. Three important features of these spectra should be indicated. First, it can be seen that the feature near 1 TeV, which has been widely debated for many years, is absent in the proton spectrum. Second, it can be clearly seen that the proton and helium spectra have different shapes. The mean values of the spectral indices differ by $\delta\gamma = 0.104 \pm 0.0085$ [21]. Later, the difference in shapes between proton and helium spectra was reliably confirmed in the PAMELA [25] and CRREAM experiments [26]. Third, the proton spectrum is not a purely power-law spectrum. It becomes more flat in the energy range near 250 GeV and steeper for the energies higher than 10 TeV. The hardening of the proton spectrum was confirmed in the PAMELA experiment with high statistical accuracy. The steepness of the proton spectrum has not yet been confirmed in a methodically reliable and statistically high-quality experiment carried out in the energy range 10–100 TeV. However, it has become evident after the appearance of reliable data for the energy range below 10 TeV that the intensities and slopes of proton spectra that were measured using emulsion chambers are not compatible with the extrapolation of the spectrum whose slope was measured in the ATIC experiment.

The spectra of abundant GCR nuclei that were measured in the ATIC experiment are shown in Fig. 4.

DISCUSSION OF THE SPECTRA OF PROTONS AND HELIUM NUCLEI

Supernova-remnant shocks are currently believed to be the sources of cosmic rays in the Galaxy. It is assumed in the conventional model that all the components should have power-law momentum spectra, with the same spectral indices, without appreciable specific features up to the break in the extensive air shower (EAS). The efforts of theorists have mainly been aimed at the search for parameters at which these shocks can accelerate particles to rigidities that are as high as possible. Until recently, nobody has been interested in spectral features at low energies. For this reason, experimenters themselves have tried to understand what their measurements mean. The phenomenological model that was developed in [27] is one of these attempts. This model describes the GCR energy

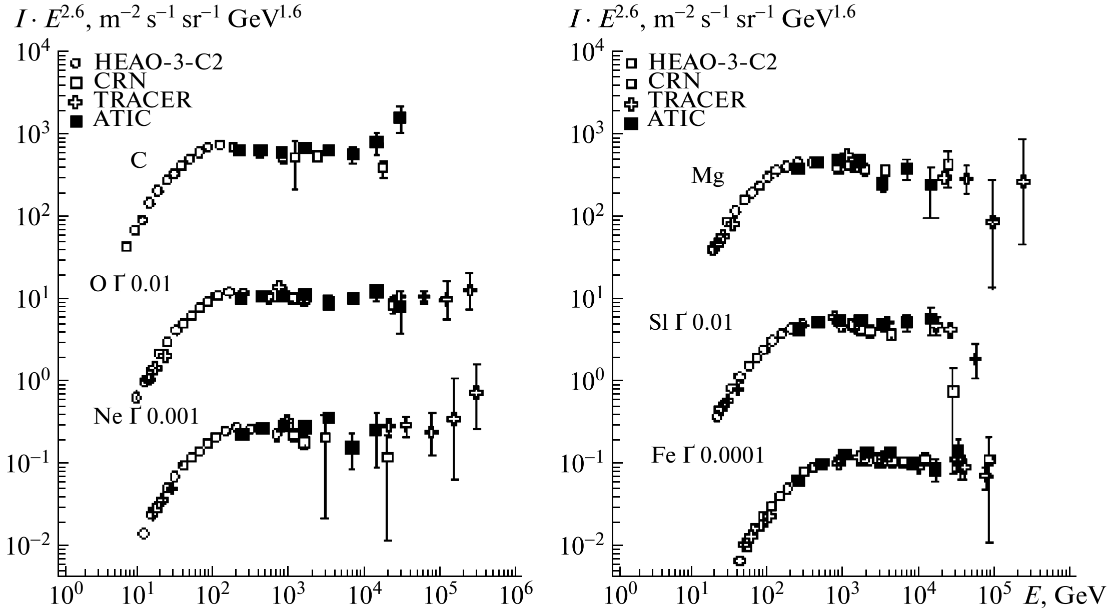

Fig. 4. The energy spectra of abundant nuclei (see the references on the data in [22]).

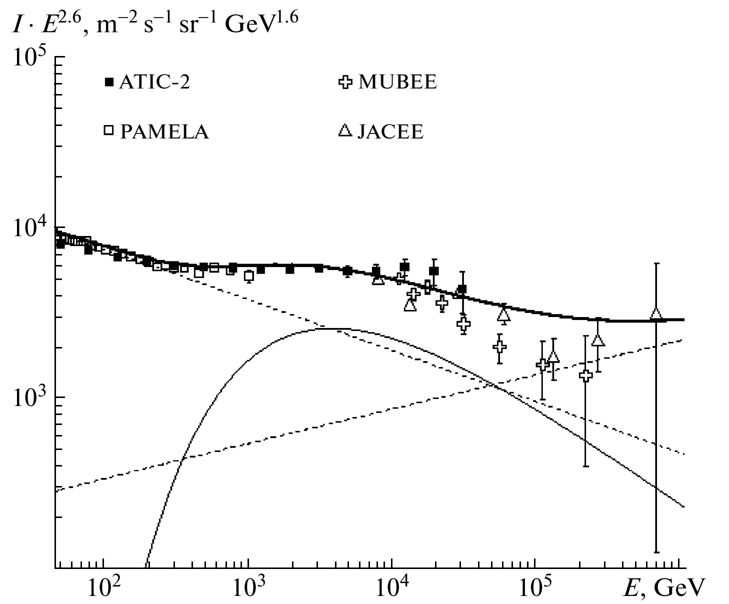

Fig. 5. Fitting of the proton spectrum in the nearby-source model. The experimental data are taken from ATIC-2 [22], PAMELA [25], MUBEE [7], and JACEE [8]. The energy spectrum of a nearby source is shown as the thin curve against the background of two power-law spectra (dashed) with different indices [28].

spectra as a superposition of spectra from three types of sources that accelerate particles to different maximum rigidities that have different spectral indices. The values of the maximum rigidities for three types of sources in this model are 2×10^{11}, 5×10^{13}, and 3×10^{15} V. This model describes the spectra of protons, helium, and other nuclei measured using direct methods well. In the range of higher energies where direct methods are no longer applicable, the model describes the spectrum of all the particles and the value Ln(A) measured in extensive atmospheric showers well.

In the meanwhile, the current experimental data on cosmic-ray anisotropy provide evidence for an unexpected feature in the TeV-energy range: the amplitude of the dipole anisotropy increases with energy toward ~10 TeV and decreases subsequently toward a few hundred TeV. Based on these data, we assumed that the specific features in the cosmic ray spectra and the TeV anisotropy are due to a single factor. In our opinion, this factor can be the influence of a local source near the solar system. We explain both the specific features of the proton spectrum in the TeV-energy range (namely, the fact that the spectrum becomes more flat in the range ~250 GeV and then steeper in the range >10 TeV (Fig. 5)) and the anisotropy observed in this energy range [28]. This explanation does not require that the proposed source should be of any exclusive type. This source may be an ordinary supernova whose parameters correspond to current considerations [29]. We hope that other features that are detected in direct measurements of other nuclei will be explained by the influence of this nearby source as well.

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