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Energy Spectra of Light Species of Primary Cosmic Rays in the Energy Range from 100 GeV to 100 PeV

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Abstract—Experimental results obtained a few decades ago associate the knee with the bending of the light component (*p* and He), and are compatible with a rigidity-dependent cut-off at 3–5 PeV. On the contrary, new experiments obtained by arrays located at high altitudes indicate that the light component cuts off well below 1 PeV. We re-analyze the energy spectrum of light nuclei obtained by the MAKET-ANI experiment at Aragats Mt. in Armenia and put them in the context of new experimental evidence.

Keywords: energy spectra, primary cosmic rays, neural networks, classification, extensive air showers

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INTRODUCTION

The integral parameters of the cosmic ray flux, such as energy spectra and mass composition deliver useful information on CR origination. Especially useful was an approach to disentangle the overall cosmic ray flux and obtain separate energy spectra of different mass groups. The MAKET-ANI surface array operated on Aragats Mt. in Armenia from 1997 to 2004 turned out to be very well suited for the energy and composition measurements at the "knee" of the cosmic ray spectrum. The problem of event-by-event classification of EAS has been solved by applying Bayesian and neural network techniques, that allow for the first time to obtain energy spectra of light and heavy nuclei separately. In the new era of EAS studies by HAWK, LHAASO, and other experiments aimed to detect point sources of ultra-high energy gamma radiation (PeVatrons) to solve the millennium problem of cosmic ray origin, it is interesting to present and analyze the full pattern of available energy spectra in the energy range from 10^{11} to 10^{17} eV.

MAKET-ANI EXPERIMENT

In 1997 the MAKET-ANI [1] surface array in Armenia was launched in its full configuration with ~100 plastic scintillators of 1 m^2 area each. The efficiency of extensive air shower core selection from the surface of ~1000 m^2 around the center of the array was above 95% for EASs generated by primary particles with energy $\geq 5 \times 10^{14}$ eV. More than a million EASs detected in 1999–2004 have been carefully examined and used for the estimation of energy spectra of light and heavy nuclei. Using the non-parametric multivariate methodology of data analysis [2, 3], in 2004, MAKET-ANI detector presents light and heavy nuclei energy spectra [4]. In Fig. 1 we show the output of a neural network performed with the ANI package [5]. The network was trained with samples of "light" and "heavy" primary nuclei obtained with CORSIKA simulations. As we see in Fig. 1, the trained neural network can be used for the classification of experimental EAS data by defining the boundaries for selecting 2 types of primary nuclei. The purity of the samples (fraction of true classified events in an actual sample allocated to a given class) can be noticeably improved without a drastic reduction of the efficiency (defined as a fraction of true classified events of the total number of events of a given class). The purity and the efficiencies are obtained by classifying 35000 light (*p*, He) and 17000 heavy (O, Si, Fe) control events, which are not used for the training of the neural network. The neural classifier selects the "light" component with an efficiency of ≈75%, and purity of ≈85%, and the "heavy" component with an efficiency of ≈75%, and purity of ≈57%. The physical inference from the MAKET-ANI experiment was made not only by multiple comparisons with CORSIKA simulations but also by regular cross-calibrations, checks of efficiency, and uniformity in detector response eventually for retaining stability and reliability of detector operation. All methodic errors were carefully revealed and checked. Excellent agreement of the measured shower lateral distribution with simulation was achieved [6, 7]. The main experimental results on energy spectra of light and heavy mass groups measured in the MAKET-ANI experiment, as shown in Fig. 2, evi-

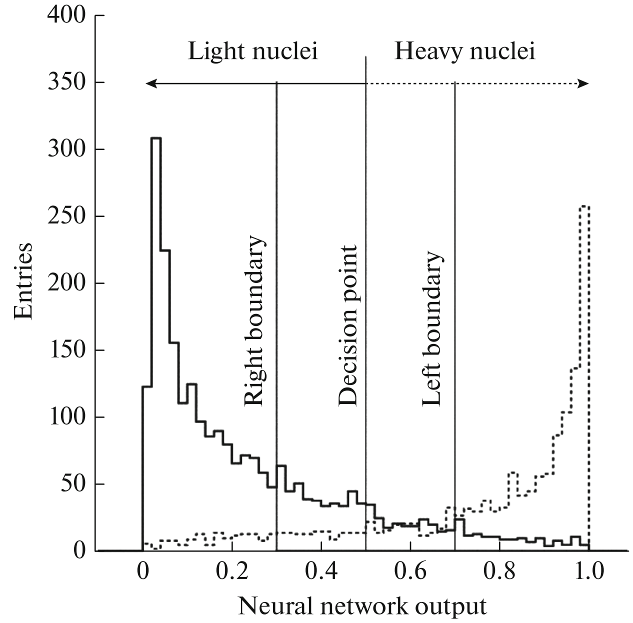

Fig. 1. The output of the Neural Network trained to distinguish "light" and "heavy" nuclei (shower age and size were used as input parameters). By vertical solid lines are shown the decision boundaries corresponding to purified selection of primary nuclei (0.3 and 0.7) and to the overall classification into 2 nuclear groups (0.5).

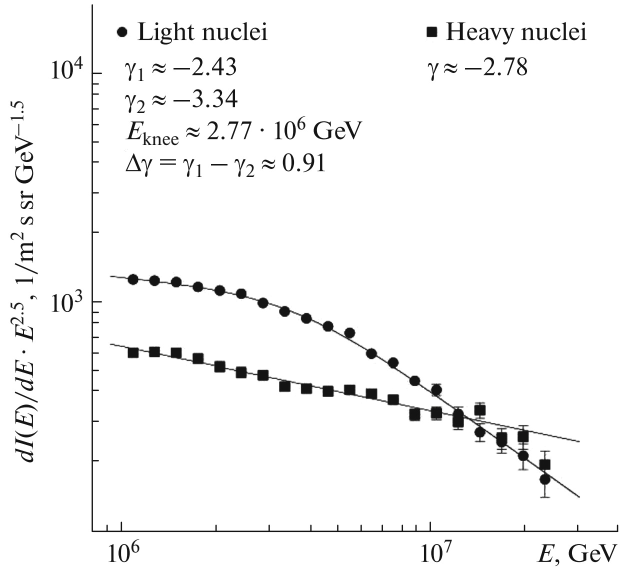

Fig. 2 Energy spectra of light and heavy nuclei obtained by neural classification and energy estimation. The EAS characteristics used are shower size and shape (age parameter).

dence was in favor of the rigidity-dependent knee position at ≈3 PeV. The estimated energy spectrum of the light mass group of nuclei shows a very sharp knee: ≈0.9, in contrast, the energy spectrum of the heavy mass group shows no knee in the energy interval of 10^{15}–10^{16} eV. Further results from the KASCADE array [8] and the AGILE and Fermi orbital gamma ray observatories, as well as several theoretical extensions of the Fermi mechanism, support MAKET-ANI results.

DIFFERENTIAL ENERGY SPECTRA OF LIGHT NUCLEI (p + He)

Until recently, it was assumed that primary cosmic rays in the low-energy region (up to 100 TeV) are described by a power-law with a single spectrum index ~–2.6–2.7. Energy spectra studies were mostly concentrated in the region of the so-called "knee" of the all-particle spectrum, around 3–4 × 10^{15} eV, where the primary cosmic ray (PCR) spectral index changed from –2.7 to –3.1. Recently, direct measurements with excellent space-borne detectors [9–13] revealed new features in the PCR energy spectra. As we can see in Fig. 3, around 580 GeV the spectral index changes from –2.83 to –2.55 (i.e., a reverse break is observed in the CALET data [9]), and in the region above 9.3 TeV the spectral index is –2.89. The spectrum derived from the CREAMI-III data [10] in the energy region from 2.5 to ~10 TeV can be approximated by a power law with exponent –2.65, and energies above 10 TeV are systematically below the approximation function: i.e., a "break" in the spectrum is observed.

In the energy spectra derived from CALET [9], CREAM I-III [10], DAMPE [11], HAWC [12], PAMELA [13], NUCLON [14], a knee is observed in the energy spectrum of primary protons around 10 TeV. This situation has already been considered in the framework of several theoretical models in search of a consistent pattern of cosmic ray acceleration (eventually including new sources), and propagation (or reacceleration) in the Galaxy.

The light component measured by the MAKET-ANI array quite accurately agrees with the HAWC(p + He) spectrum. However, the fluxes of protons and helium measured by HAWK are equal, which contradicts the "normal" composition of primary cosmic rays in the energy range of (10^{14}–10^{15} eV). Possibly, because of incorrect primary nuclei classification, HAWC gives a ≈twofold increase in intensity compared to MAKET-ANI, KASCADE, EAS-TOP, and HEGRA. However, the proton component of HAWC agrees well with the PAMELA, DAMPE, CREAM I-III, and CALET measurements. According to the CREAM I-III data, in the energy range of 1.0–60 TeV/nucleon, the average p/He ratio is estimated to be ~9.6. The "reverse kink" in the proton spectrum is also observed in the GRAPES-3 data [15] in the energy region of ≈200 TeV.

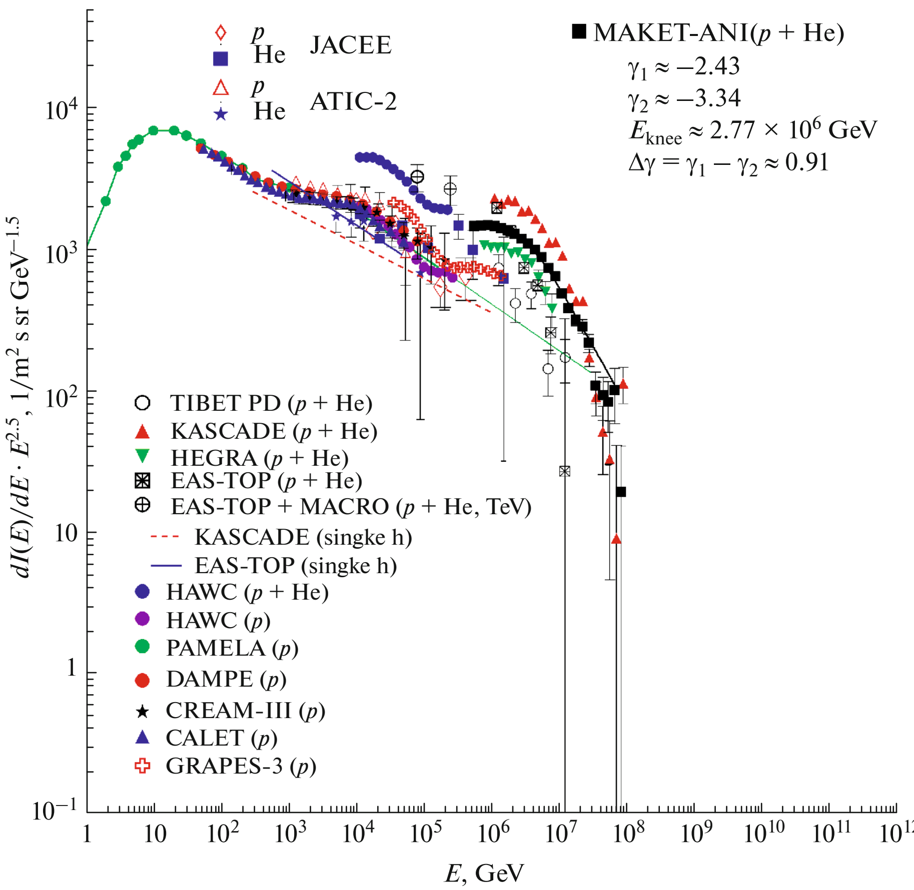

Fig. 3. Primary light nuclei (p + He) spectra measured by the MAKET-ANI [1] detector in comparison with the spectra reported by KASCADE, EAS-TOP, HEGRA, EAS-TOP+MACRO, TIBET experiments (all spectra were obtained with CORSIKA QGSJet01model). The direct balloon measurements by ATIC-2 and JACEE are related to the energies of 10^2–10^5 GeV (all data taken from [1]). The modern experiments HAWC [12], PAMELA [13], DAMPE [11], CREAM I-III [10], CALET [9], GRAPES-3 [14] are included as well.

CONCLUSIONS

Measurements of the CR energy spectra from 10 to 1000 TeV with EAS arrays operated in the last century were scarce due to the high energy threshold (usually above 1 PeV). New detectors located at high altitudes (>4000 m) overcome this difficulty significantly lowering the energy threshold down to a few tens of TeV. We compare energy spectra observed by a compact array MAKET-ANI (operated on 3200 m, energy threshold of few hundreds of TeV) with high altitude EAS arrays. As we show in Fig. 3 the hardening of the light nuclei spectrum around the TeV region, observed by PAMELA, ATIC, CREAM, CALET, and DAMPE, has now been confirmed by EAS arrays operated on Tibet and Sierra Negra. Data at energies above a few tens of TeV, in contrast, show softening of the energy spectrum, which again changed to hardening in a few hundreds of TeV energy range. New models, including, simulation of the proton acceleration in the strong winds of young stars in the galaxy plane are required for explaining the rather complicated shape of light nuclei spectrum below the knee of all particle spectrum. The QGSJet-II and QGSJet-III models [16] predicted 10% higher number of muons and electrons. This should impact the energy reconstruction and thereby rescale the MAKET-ANI spectrum, bringing them closer to the shown in Fig. 3 lower energy proton spectra.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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