Fine structure of all-particle energy spectrum in the knee region

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Abstract. All-particle energy spectrum in the knee region obtained from extensive air shower (EAS) measurements (GAMMA experiment, 700 g/cm², Armenia) is presented. Energies of primary particles in the range of 10⁶-10⁸ GeV were evaluated on the basis of observed shower parameters N_ch, N_µ, s, θ and corresponding parameterisation of CORSIKA simulated database for SIBYLL interaction model. All shower detection and reconstruction uncertainties were included in the simulated showers for four kinds (H, He, O, Fe) of primary nuclei. The reliability of observed all-particle energy spectrum is investigated from viewpoint of methodical errors and statistical fluctuations. Observed fine structure of all-particle energy spectrum can be interpreted by the rigidity-dependent steepening Galactic diffuse nuclei flux and an additional iron component in the region of 70-80 PeV primary energies most likely originated from nearby pulsars.

1. Introduction

All-particle energy spectrum derived from Extensive Air Showers (EAS) measurements in the knee region (~3 PeV) is unique information source about the origin and propagation of primary nuclei in the Galaxy. A lot of experiments performed in the last decades [1-9] unambiguously pointed out to the existence of a fine structure of energy spectrum behind the knee energy region (10⁻¹⁻¹₀⁰ PeV) unaccounted for by the standard rigidity-dependent Peters model [10]. The additional polar cap component proposed by Stanev et al. [11], local cosmic ray sources worked out by the Erlykin and Wolfendale [12] or our 2-component model including Galactic diffuse and iron pulsar components [6] can interpret the obtained spectral fine structure in the frames of model uncertainties and measurement errors. Herein, we present the updated all-particle energy spectrum measured by the GAMMA facility during 2003-2009 runtime.
Mountain location of the GAMMA experiment (700 g/cm²) provides the highest level of correlation (98-99%) of primary energy with detected shower particle flux and along with simultaneous measurements of shower muon ($E_\mu > 5$ GeV) and charge particle ($E_{ch} > 6$-8 MeV) lateral distributions significantly reduce the uncertainties of primary energy evaluation and inverse problem solutions for all-particle energy spectrum reconstruction [5,6,13].

2. GAMMA array

Figure 1. Layout of the GAMMA shower array. Black squares represent detector stations. White circles represent single detectors.

GAMMA is a ground-based EAS array to measure the muon and the electromagnetic components of the EAS [6, 13]. It consists of 33 ground-based scintillator detection station array and underground muon scintillator carpet, located at the southern side of Mount Aragats (Armenia). The layout of the array is shown in figure 1. Each station contains 3 plastic scintillators with dimension of 1x1x0.05 m³. The central nine stations contains additional small detector with dimensions of 0.3x0.3x0.05 m³ for high particle density ($>10^3$ m⁻²) measurements. The muon carpet is made up of 150 scintillation detectors which are compactly arranged in the underground hall under the 2.3 kg/cm² of rock and concrete. The layout of the carpet is shown in figure 2. Dimensions of scintillator, casings and photomultipliers are the same as in the surface detectors. The arrangement of the muon detectors gives the possibility of determining the muon lateral distribution function up to 60m from the EAS core at $E_\mu > 5$GeV. The reconstruction of the EAS size ($N_{ch}$), shower age ($s$) and core coordinates ($x_0, y_0$) is performed based on the Nishimura-Kamata-Greisen (NKG) approximation to the measured charged particle densities. Angular coordinates of the shower axis ($\theta, \phi$) are derived by time delays between various stations. The shower array response and measurement error are taken into account. Details are presented in [6].
3. All-particle primary energy spectrum

The multi-parametric event-by-event method of primary energy evaluation and all-particle energy spectrum reconstruction by the parameterised inverse problem solution are presented in [5,6] in detail. The unbiased energy estimator \( E_1 = f(N_{ch}, N_\mu, s, \cos \theta) \) of the primary energy \( E_0 \) regardless of primary nucleus was obtained using CORSIKA EAS simulation code [14] with SIBYLL [15] interaction model for \( H, He, O \) and \( Fe \) primary nuclei taking into account detector responses and reconstruction uncertainties of shower parameters [5,6,13].

The EAS data set has been obtained for \( 8.46 \times 10^7 \) s runtime (2003-2009). Reconstructed all-particle energy spectrum is presented in the Table.

| \( E_0/\text{GeV} \) | \( \frac{d\Omega}{dE_0} \) | \( \Delta \frac{d\Omega}{dE_0} \) |
|-----------------|-----------------|-----------------|
| 0.135 \times 10^7 | 0.429 \times 10^7 | 0.540 \times 10^7 |
| 0.165 \times 10^7 | 0.431 \times 10^7 | 0.410 \times 10^7 |
| 0.201 \times 10^7 | 0.427 \times 10^7 | 0.320 \times 10^7 |
| 0.246 \times 10^7 | 0.412 \times 10^7 | 0.260 \times 10^7 |
| 0.300 \times 10^7 | 0.409 \times 10^7 | 0.210 \times 10^7 |
| 0.367 \times 10^7 | 0.402 \times 10^7 | 0.150 \times 10^7 |
| 0.448 \times 10^7 | 0.396 \times 10^7 | 0.510 \times 10^7 |
| 0.547 \times 10^7 | 0.388 \times 10^7 | 0.460 \times 10^7 |
| 0.669 \times 10^7 | 0.364 \times 10^7 | 0.400 \times 10^7 |
| 0.817 \times 10^7 | 0.342 \times 10^7 | 0.350 \times 10^7 |
| 0.997 \times 10^7 | 0.312 \times 10^7 | 0.290 \times 10^7 |
| 0.122 \times 10^8 | 0.292 \times 10^7 | 0.280 \times 10^7 |
| 0.149 \times 10^8 | 0.265 \times 10^7 | 0.240 \times 10^7 |
| 0.182 \times 10^8 | 0.246 \times 10^7 | 0.210 \times 10^7 |
| 0.222 \times 10^8 | 0.240 \times 10^7 | 0.200 \times 10^7 |
| 0.271 \times 10^8 | 0.225 \times 10^7 | 0.180 \times 10^7 |
| 0.331 \times 10^8 | 0.220 \times 10^7 | 0.180 \times 10^7 |
| 0.404 \times 10^8 | 0.190 \times 10^7 | 0.150 \times 10^7 |
| 0.494 \times 10^8 | 0.182 \times 10^7 | 0.160 \times 10^7 |
| 0.603 \times 10^8 | 0.201 \times 10^7 | 0.190 \times 10^7 |
| 0.737 \times 10^8 | 0.260 \times 10^7 | 0.240 \times 10^7 |
| 0.900 \times 10^8 | 0.171 \times 10^7 | 0.210 \times 10^7 |
| 0.134 \times 10^9 | 0.149 \times 10^7 | 0.270 \times 10^7 |
| 0.164 \times 10^9 | 0.136 \times 10^7 | 0.300 \times 10^7 |
| 0.200 \times 10^9 | 0.103 \times 10^7 | 0.310 \times 10^7 |
| 0.245 \times 10^9 | 0.844 \times 10^7 | 0.321 \times 10^7 |

In the figure 3 we presented our spectrum in comparison with world data from (cited in the top-down order of the figure) [9, 8, 7, 13, 2, 3, 16-18]. In the table our data are presented. The units are the same as in the figure.

To explain the observed bump in the 70-80 PeV energy region we considered an additional (pulsar) iron components with flat power law energy spectrum \( (\gamma_{Fe} \sim 1 \pm 0.5) \) before the cut-off energy [6].

The average logarithm of primary nuclei mass number as a function of energy is shown in figure 4 in case of hypothesis of a two (Galactic diffusive and pulsar) component origin of the observed cosmic ray flux.
Figure 3. All-particle energy spectrum (circles with dot symbol, GAMMA 12) in comparison with the world data [9, 8, 7, 13, 2, 3, 16-19].

Figure 4. Average logarithm of primary nucleus mass number derived from rigidity-dependent primary energy spectra [13] (dashed line) and 2-component model prediction [6] taking into account additional pulsar component (solid line).
4. Conclusion
The high accuracy of energy evaluations and small systematic and statistical errors point out to the existence of an irregularity (‘bump’) in the 70–80 PeV primary energy region. The bump can be described by a two (Galactic and pulsar) component model of the primary cosmic ray origin.

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