Primary Cosmic-Ray Spectra in the Knee Region

Samvel Ter-Antonyan\textsuperscript{1} and Peter Biermann\textsuperscript{2}
(1) Yerevan Physics Institute, Yerevan 375036, Armenia
(2) Max-Planck Institut für Radioastronomie, Bonn, Germany

Abstract

Using EAS inverse approach and KASCADE EAS data the primary energy spectra for different primary nuclei at energies $10^{15} - 10^{17}$ eV are obtained in the framework of multi-component model of primary cosmic ray origin and QGSJET and SIBYLL interaction models. The rigidity-dependent behavior of spectra is the same for two interaction models. The extrapolation of the obtained primary spectra in a $10^{17} - 10^{18}$ eV energy range displays a presence of the extragalactic component of primary cosmic rays.

1. Introduction

The solution of the EAS inverse problem - reconstruction of energy spectra ($f_A \equiv \partial \Im / \partial E_A$) of primary nuclei ($A \equiv 1, 4, 16, 56$) using measured EAS size spectra ($I_\theta \equiv \partial I(\theta) / \partial N_e$) at different zenith angles ($\theta$) on the observation level KASCADE [1] and ANI [2] has been done in [3] on the basis of parameterization of the set of integral equations

$$\sum_A K_{f_A} = I_\theta ,$$

where $K$ is Fredholm’s integral operator. As an object function ($f_A$) in [3] we considered the expected primary energy spectra according to multi-component model prediction [4]. Here, in addition to the last KASCADE EAS size spectra in a right-hand part of the set of equations above, we included the EAS “truncated” muon size spectra ($\partial I_\theta / \partial N_\mu$) from [5]. The kernel functions of equations (1) were calculated by CORSIKA6016(NKG) EAS simulation code [6] on KASCADE observation level (1020 g/cm$^2$) at QGSJET01 [7] and SIBYLL2.1 [8] interaction models taking into account the measurement errors ($N_{e,\mu}; N_{e,\mu}^*$). The details of calculations are presented in [9].
2. Primary energy spectra and spectral parameters

Energy spectra of primary nuclei according to the multi-component model of primary cosmic ray origin [4] at energies $10^{12} - 10^{18}$ eV are considered here in a 3-component form:

$$\frac{\partial \mathcal{I}}{\partial E_A} = \beta \Phi_A \left( \delta_{A,1} \frac{d\mathcal{I}_1}{dE_A} + \delta_{A,2} \frac{d\mathcal{I}_2}{dE_A} \right) + \Phi_{EG} \frac{d\mathcal{I}_3}{dE_A}$$  \hspace{1cm} (2)

where the $\beta$ is a dimensionless normalization parameter, $\Phi_A$ are scale spectral factors and model parameters $\delta_{A,i}, i=1,2$ are the fractions of each component ($\delta_{A,1} + \delta_{A,2} = 1$) in a primary flux of nuclei (A). All spectra have a rigidity-dependent power law shapes:

1) $\frac{d\mathcal{I}_1}{dE_A} = E_A^{-\gamma_1}$ at $E_A < E_{cut}$, where the model parameter $E_{cut}$ is a cut-off energy of at Z nuclear charge;

2) $\frac{d\mathcal{I}_2}{dE_A} = E_A^{-\gamma_2}$ at $E_A < E_k$ and $\frac{d\mathcal{I}_2}{dE_A} = E_k^{-\gamma_2}(E_A/E_k)^{-\gamma_3}$ at $E_A > E_k$, where the model parameter $E_k$ is a knee energy of component;

3) $\frac{d\mathcal{I}_3}{dE_A} = E_{ank}^{-2.75}(E_A/E_{ank})^{-2}$ at $E_A < E_{ank}$ and $\frac{d\mathcal{I}_3}{dE_A} = E_A^{-2.75}$ at $E_A > E_{ank}$, $E_{ank} \approx 6.5 \cdot 10^5$ TV, $\Phi_{EG} \approx 0.032$ ($\text{m}^2\cdot\text{sec}\cdot\text{ster}\cdot\text{TeV})^{-1}$.

In [3] we have already obtained the evaluations of spectral indices $\gamma_1 = 2.78 \pm 0.03$, $\gamma_2 = 2.65 \pm 0.03$ as solutions of parametric equations (1) using KASCADE [1] and ANI [2] EAS size spectra at 5 zenith angular intervals. Since these values agreed with the model predictions here we set them fixed.

3. Results

The set of the parametric equations (1) is resolved by minimization of $\chi^2(I, P)$-functional with a measurement vector $I \equiv \{\Delta I/\Delta N_{e,i,k}, \Delta I/\Delta N_{\mu,j,k}\}$ and corresponding prediction vector $P$ from a left-hand part of equations (1) at $i = 1, \ldots, 42$ energy intervals of EAS electron size spectra, $j = 1, \ldots, 26$ energy intervals of EAS truncated muon size spectra and $k = 1, 2, 3$ zenith angular bins from KASCADE data [5]. However, the combined analysis of electron and muon size spectra at $\chi^2$-minimization requires to include in the expected shower spectra 2 additional unknown dimensionless parameters $\eta_e$ and $\eta_\mu$ which define a constant bias of each spectrum due to peculiarities of interaction model and systematic measurement errors [9]. The dimensionless parameter $\beta$ in expression (2) was determined by normalization of the obtained all-particle spectrum $\sum(\partial \mathcal{I}/\partial E_A)$ with JACEE data at 100 TeV energy. Table 1 contains the values of all spectral parameters which were obtained by the method above. The normalization factors in Table 1 are: $\beta = 1.13 \pm 0.05$ at QGSJET model and $\beta = 1.0 \pm 0.05$ SIBYLL model. Obtained energy spectra of different nuclei and corresponding all-particle spectrum up to energy $3 \cdot 10^{18}$ eV are presented in Fig. 1. The thick line corresponds to expected energy spectra of extragalactic component [4]. The corresponding
value of $\chi^2 \simeq 1$ with 2% uncertainty of expected data (and 4% uncertainty at SIBYLL model). For biases of shower spectra we obtained the values: $\eta_e = 1.23 \pm 0.04$, $\eta_\mu = 1.12$ at QGSJET model and $\eta_e = 1.0 \pm 0.01$, $\eta_\mu = 1.3 \pm 0.02$ at SIBYLL model. These values point out possible existence of systematic biases both at EAS measurements and in interaction models.

On the basis of obtained values of spectral parameters (Table 1) we also calculated the expected EAS muon lateral distribution functions for KASCADE experiment and expected all-hadron energy spectrum at mountain level (3200m a.s.l.) for PION experiment [11]. These results are presented in [9] in a well agreement with corresponding experimental data [11,12].

4. Conclusion

Predictions of the multi-component model of the cosmic ray origin [4] explain the measured KASCADE EAS data in the knee region ($E_0 \simeq 10^{14} - 10^{17}$ eV) with accuracy 10-15% in the framework of QGSJET and SIBYLL interaction models respectively.
The rigidity-dependent behavior of spectra for different primary nuclei is the same for two interaction models.
The agreement of the expected all particle spectrum and world data in $E_0 \simeq 10^{17} - 10^{18}$ eV primary energy range displays a presence of the extragalactic component of primary cosmic rays according to 3-component model predictions.

<table>
<thead>
<tr>
<th>Spectral Parameters</th>
<th>QGSJET01</th>
<th>SIBYLL2.1</th>
<th>3-component predictions</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_1$</td>
<td>2.78±0.03</td>
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<td>$\gamma_2$</td>
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<td>$\gamma_3$</td>
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<td>3.25±0.04</td>
<td>3.07±0.1 3.28±0.07 [3]</td>
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<td>$E_{\text{cut}}$</td>
<td>200±100</td>
<td>200±100</td>
<td>120-250 210±60 $TV$ [3]</td>
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<tr>
<td>$E_k$</td>
<td>2100±140</td>
<td>1910±150</td>
<td>700-1400 1900±100 $TV$ [3]</td>
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<td>$\delta_{A=1,2}$</td>
<td>0.47±0.04</td>
<td>0.5±0.04</td>
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<td>$\delta_{A&gt;1,2}$</td>
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<td>0.9</td>
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<td>$\beta\Phi_P$</td>
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<td>$\beta\Phi_{Fe}$</td>
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<td>0.035±0.005</td>
<td>($m^2 \cdot s \cdot sr \cdot TeV)^{-1}$</td>
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5. References