Primary Cosmic-Ray Spectra in the Knee Region

Samvel Ter-Antonyan[1] and Peter Biermann[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 (θ) 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

$$\sum_A \mathsf{K} f_A = I_\theta \ , \tag{1}$$

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].

pp. 235–238

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:

$$\frac{\partial \Im}{\partial E_A} = \beta \Phi_A \Big(\delta_{A,1} \frac{d\Im_1}{dE_A} + \delta_{A,2} \frac{d\Im_2}{dE_A} \Big) + \Phi_A^{EG} \frac{d\Im_3}{dE_A} \tag{2}$$

where the β is a dimensionless normalization parameter, Φ_A are scale spectral factors and model parameters $\delta_{A,i=1,2}$ 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) $d\Im_1/dE_A = E_A^{-\gamma_1}$ at $E_A < E_{cut}Z$, where the model parameter $E_{cut}Z$ is a cut-off energy of at Z nuclear charge;

2) $d\Im_2/dE_A = E_A^{-\gamma_2}$ at $E_A < E_k Z$ and $d\Im_2/dE_A = E_k^{-\gamma_2}(E_A/E_k)^{-\gamma_3}$ at $E_A > E_k Z$, where the model parameter $E_k Z$ is a knee energy of component;

3) $d\Im_3/dE_A = E_{ank}^{-2.75}(E_A/E_{ank})^{-2}$ at $E_A < E_{ank}Z$ and $d\Im_3/dE_A = E_A^{-2.75}$ at $E_A > E_{ank}Z$, $E_{ank} \simeq 6.5 \cdot 10^5$ TV, $\Phi_{A=1}^{EG} \simeq 0.032$ (m^2·sec·ster·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 $\chi^2(\mathbf{I}, \mathbf{P})$-functional with a measurement vector $\mathbf{I} \equiv \{\Delta I/\Delta N^*_{e,i,k}, \Delta I/\Delta N^*_{\mu,j,k}\}$ and corresponding prediction vector $\mathbf{P}$ 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 χ^2-minimization requires to include in the expected shower spectra 2 additional unknown dimensionless parameters η_e and η_μ which define a constant bias of each spectrum due to peculiarities of interaction model and systematic measurement errors [9]. The dimensionless parameter β in expression (2) was determined by normalization of the obtained all-particle spectrum $\sum(\partial \Im/\partial E_A)$ 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

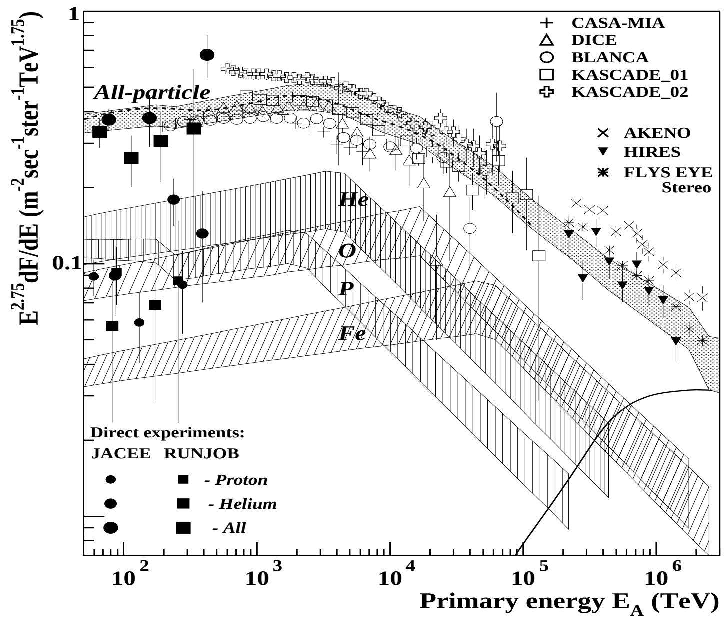

Fig. 1. Expected all-particle energy spectrum and energy spectra of different nuclei (shaded areas) according to 3-component model of primary cosmic rays. The solid line is expected (third) extragalactic component and dashed line are expected all-particle spectrum from [3]. The JACEE, RUNJOB, CASA, DICE, BLANCA, KASCADE02 data is taken from review [10], KASCADE01 - from [5].

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 1. Spectral parameters of reconstructed primary energy spectra.

Spectral Parameters	QGSJET01	SIBYLL2.1	3-component predictions	Comments
γ_1	2.78±0.03	-	2.75±0.04	[3]
γ_2	2.65±0.03	-	2.67±0.03	[3]
γ_3	3.25±0.04	3.25±0.04	3.07±0.1	3.28±0.07 [3]
E_{cut}	200±100	200±100	120-250	210±60 TV [3]
E_k	2100±140	1910±150	700-1400	1900±100 TV [3]
$\delta_{A=1,2}$	0.47±0.04	0.5±0.04	-	0.5-0.8 [3]
$\delta_{A>1,2}$	0.9	0.9	-	0.85-1 [3]
$\beta\Phi_P$	0.120±0.007	0.106±0.006		$(m^2 \cdot s \cdot sr \cdot TeV)^{-1}$
$\beta\Phi_{He}$	0.089±0.011	0.084±0.010		$(m^2 \cdot s \cdot sr \cdot TeV)^{-1}$
$\beta\Phi_O$	0.058±0.007	0.064±0.006		$(m^2 \cdot s \cdot sr \cdot TeV)^{-1}$
$\beta\Phi_{Fe}$	0.026±0.005	0.035±0.005		$(m^2 \cdot s \cdot sr \cdot TeV)^{-1}$

5. References

1. Glasstetter R. et al., Nucl.Phys. B (Proc.Suppl) 75A (1999) 238.
2. Chilingaryan A.A. et al., Proc. 26th ICRC, **1** (1999) 240.
3. Ter-Antonyan S.V. and Biermann P.L. Proc. 27th ICRC Hamburg, HE225 (2001) 1051// Preprint, astro-ph/0106076 (2001).
4. Biermann P.L., Astron. Astrophys. **271** (1993) 649.
5. Kampert K.-H. et al. (KASCADE collaboration), Highlight Paper, Proc. 27th ICRC, Hamburg (2001)// astro-ph/0204205 (2002).
6. Heck D. et al., Forschungszentrum Karlsruhe Rep., FZKA 6019 (1998) 90p.
7. Kalmykov N.N., Ostapchenko S.S., Yad. Fiz. **56** 1993, 105.
8. Engel R. et al., Proc. 26th ICRS (Salt Lake City), **1** (1999) 415.
9. Biermann P.L. et al., astro-ph/0302201 (2003).
10. Swordy S.P. et al., Astropart. Phys. **18** (2002) 129.
11. Ter-Antonyan S.V. and Haroyan L.S., Workshop ANI98, Forschungszentrum Karlsruhe Rep., FZKA 6216 (1998) 115.
12. Antoni T. et al., Astropart.Phys. **14** (2001) 245.