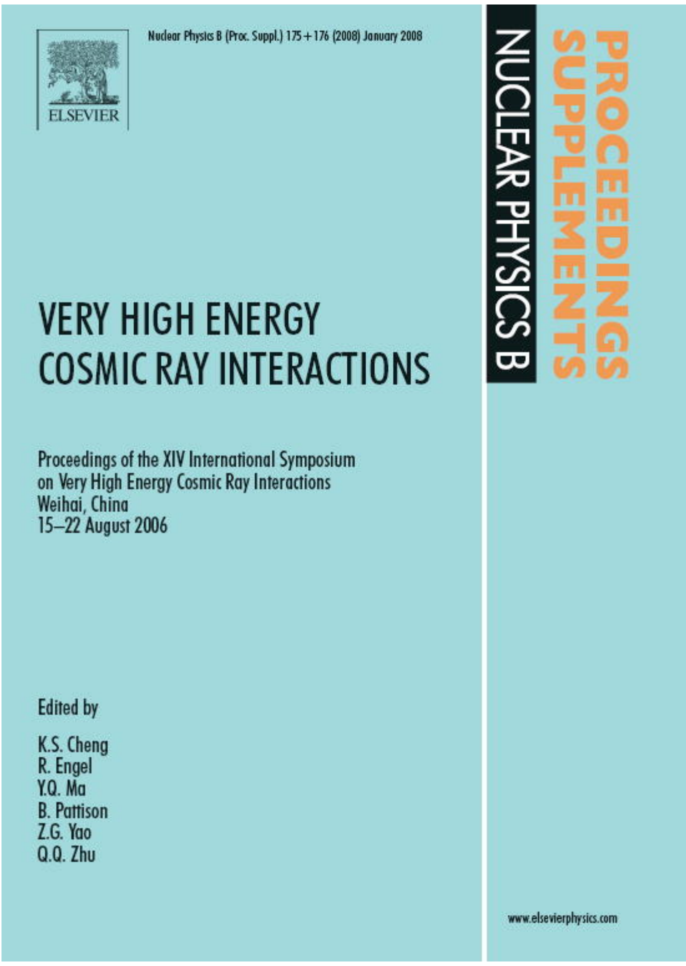
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Energy spectra and elemental composition of primary nuclei in the knee region: Recent results from the GAMMA experiment

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On the basis of the extensive air shower (EAS) data obtained by the GAMMA experiment, the energy spectra and elemental composition of the primary cosmic rays are derived in the $1-100$ PeV energy range. The reconstruction of the primary energy spectra is carried out using an EAS inverse approach with the hypothesis of power-law primary energy spectra with rigidity-dependent knees. The rigidity-dependent knee feature of the primary energy spectra is displayed at the rigidities $E_R \simeq 2.5 \pm 0.2$ PeV/Z and $E_R \simeq 3.1 - 4.2$ PeV/Z for the SIBYLL and QGSJET interaction models respectively.
Using the event-by-event method of the primary energy evaluation from the measured N_{ch}, N_μ and shower age (s) parameters, the all-particle energy spectrum is also obtained.

1. Introduction

The investigation of the energy spectra and elemental composition of primary cosmic rays in the knee region ($1-100$ PeV) remains one of the intriguing problems of modern high energy cosmic-ray physics. Despite the fact that these investigations have been carried out for more than half a century, the data on the elemental primary energy spectra at energies $E > 1$ PeV still need improvement.
Here, the main results of evaluations of primary energy spectra in the knee region on the basis of the GAMMA facility [1] EAS data [2,3] are presented. Preliminary results have already been presented in [2–4].

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2. GAMMA experiment

The GAMMA installation [1,2,5] is a ground-based array of 33 surface particle detection stations and 150 underground muon detectors, located on the south side of Mount Aragats in Armenia. The elevation of the GAMMA facility is 3200 m above sea level. A diagrammatic layout is shown in Fig. 1.

The surface stations of the EAS array are located on 5 concentric circles of radii ∼20, 28, 50, 70 and 100 m, and each station contains 3 square plastic scintillation detectors with the following dimensions: $1 \times 1 \times 0.05$ m^3 (Fig. 1). 150 underground muon detectors (muon carpet) are compactly arranged in the underground hall under 2.3 kg/cm^2 of concrete and rock. Detailed descriptions of the detector system, triggering, and method of reconstruction of EAS parameters

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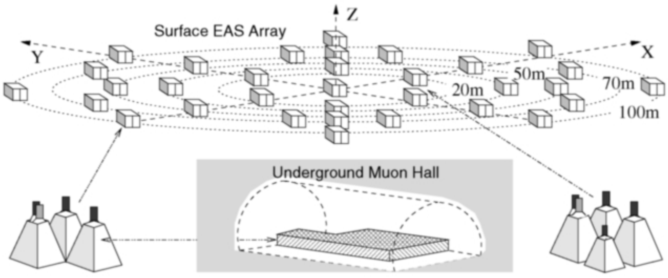

Figure 1. Diagrammatic layout of the GAMMA facility.

are presented in [1,2,5]. The detector response was computed [2,5] taking into account the EAS γ-quanta contribution using the CORSIKA 6.031 code [8].
Showers were selected for analysis with the following criteria: $N_{ch} > 5 \cdot 10^5$, $R < 25$ m, $\theta < 30°$, $0.3 < s < 1.6$, $\chi^2(N_{ch})/m < 3$ and $\chi^2(N_\mu)/m < 3$ (where m is the number of scintillators with non-zero signal). The selected measurement range provided 100% EAS detection efficiency and similar conditions for the reconstruction of the shower lateral distribution functions.

3. Elemental primary energy spectra

The observed spectra $F(\mathbf{q})$ in measured EAS parameters $\mathbf{q} = (N_{ch}, N_\mu, s)$ result from convolutions of the (a priori unknown) energy spectra $I_A(E)$ of primary nuclei ($A \equiv H, He, \ldots$ at least up to Ni) with the shower spectra $W_A(E, \mathbf{q})$ [6,7]:

$$F(\mathbf{q}) = \sum_A \int_E W_A(E, \mathbf{q}) I_A(E) dE \; . \qquad (1)$$

The functions $W_A(E, \mathbf{q})$ are derived using a model of the EAS development in the atmosphere and convolution of the resulting shower spectra at the observation level with the corresponding response functions [2,6].
The integral equation (1) defines the EAS inverse problem, namely the evaluation of the primary energy spectra $I_A(E)$ on the basis of the measured distributions $F(\mathbf{q}_i)$ and the known kernel functions $W_A(E, \mathbf{q}_i)$ [2,6].
In order to evaluate the primary energy spectra on the basis of the EAS data set we regularized the integral equation (1) using a parametrization method [7]. The solutions for the primary energy spectra in (1) were sought based on a broken power-law function with a "knee" at the rigidity-dependent energy $E_k(A) = E_R \cdot Z$, and the same spectral indices for all species of primary nuclei ($A \equiv p, He, O, Fe$), γ_1 below and γ_2 above the knee respectively:

$$\frac{dI_A}{dE} = \Phi_A \left(\frac{E_k}{1\,\mathrm{TeV}}\right)^{-\gamma_1} \left(\frac{E}{E_k}\right)^{-\gamma} , \qquad (2)$$

where $\gamma = \gamma_1$ for $E \leq E_k(A)$, $\gamma = \gamma_2$ for $E > E_k(A)$, E_R is the particle's rigidity and Z the charge of nucleus A.
The integral equation (1) is thereby transformed into a parametric equation with the unknown spectral parameters Φ_A, E_R, γ_1 and γ_2, which are evaluated by minimization of the corresponding χ^2 function [2,5].
EAS simulations for the evaluation of the primary energy spectra using the GAMMA facility EAS data were carried out for $\mathcal{N}_A \equiv 10^5$ primary H, $7.1 \cdot 10^4$ He, $4.6 \cdot 10^4$ O and $4.8 \cdot 10^4$ Fe nuclei using the CORSIKA NKG mode [8] and the SIBYLL [9] interaction model. The corresponding statistics for the QGSJET [10] interaction model were: 10^5, $6 \cdot 10^4$, $4.4 \cdot 10^4$ and $4 \cdot 10^4$.
The simulated energies were distributed following a weight function $I_0(A, E) \propto E^{-1.5}$ for the Monte-Carlo integration of parametric equation (1). The simulated showers had core coordinates distributed uniformly within a radius $R < 25$ m, and zenith angles $\theta < 30°$.
Using the aforementioned formalism, the $U = 6$ examined functions: $F(\mathbf{q}) \equiv dF(\theta)/dN_e$, $dF(\theta)/dN_\mu$, $dF(N_\mu)/dN_e$, $dF(N_e)/dN_\mu$, $\overline{s}(N_e)$, $\overline{N_\mu}(N_e)$; and the corresponding EAS data set, the unknown spectral parameters Φ_A, E_R, γ_1 and γ_2 of parametrization (2) were derived by minimization of the χ^2 [2,5] and forward folding (1), with a number of degrees of freedom $n_{d.f.} = \sum_1^6 V_u - p - 1 \simeq 350$, where $p = 7$ is the number of adjustable parameters.
The values of the spectral parameters (2) derived

from the solution of the parameterized equation (1) are presented in Table 1 for the SIBYLL and QGSJET interaction models. The primary energy spectra obtained for p, He, O, and Fe nuclei, along with the all-particle energy spectra, are shown in Fig. 2 (lines and shaded areas) for the SIBYLL (left panel) and QGSJET (right panel) interaction models. The symbols in Fig. 2 show the all-particle spectra obtained by KASCADE [6] from a 2-dimensional (N_e, N_μ) unfolding using an iterative method, and from GAMMA [4] using an event-by-event method. Also shown as error bars in the left panel of Fig. 2 are extrapolations of the balloon and satellite data to the energy $E \simeq 10^6$ GeV, computed using power-law approximations to the available direct measurement data [11]. In this extrapolation, the O-like group was assumed to include the elements $Z = 3$–16, and the Fe-like group the elements $Z = 17$–26.

Table 1
Parameters of the primary energy spectra (2) from combined approximations to the EAS data. The scale factors Φ_A and particle rigidity E_R respectively have units of $(\mathrm{m}^2 \cdot \mathrm{s} \cdot \mathrm{sr} \cdot \mathrm{TeV})^{-1}$ and TV.

Parameters	SIBYLL	QGSJET
Φ_H	0.095 ± 0.008	0.165 ± 0.005
Φ_{He}	0.100 ± 0.012	0.020 ± 0.008
Φ_O	0.034 ± 0.007	0.008 ± 0.004
Φ_{Fe}	0.024 ± 0.004	0.013 ± 0.005
E_R	2500 ± 200	3200 ± 150
γ_1	2.68 ± 0.015	2.66 ± 0.010
γ_2	3.19 ± 0.03	3.11 ± 0.02
$\chi^2/n_{d.f.}$	2.0	1.5

As can be seen from Fig. 2 and Table 1, the derived primary energy spectra depend significantly on the interaction model.

The energy spectra of primary H, He, O-like and Fe-like nuclei obtained with the SIBYLL interaction model agree with corresponding extrapolations of the balloon and satellite data to $\sim 10^3$ TeV energies. The energy spectra obtained from the QGSJET model show a predominantly proton composition in the knee region.

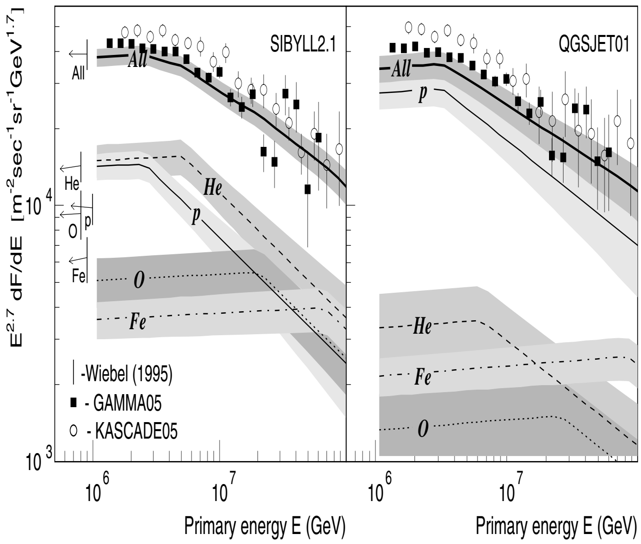

Figure 2. Energy spectra and abundances of the primary nuclei groups (lines and shaded areas) for the SIBYLL (left panel) and QGSJET (right panel) interaction models. All-particle spectra from GAMMA [4] and KASCADE [6] are shown as symbols. Vertical bars show the extrapolations of balloon and satellite data [11].

4. All-particle energy spectrum

The mountain location of the GAMMA experiment and the agreements of observed and simulated data in the measurement range $5 \cdot 10^5 < N_{ch} < 5 \cdot 10^7$ allowed, apart from above, to obtain the all-particle energy spectra with high reliability. The method is based on an event-by-event evaluation of the primary energy using reconstructed parameters N_{ch}, N_μ, s, θ of detected EAS [2,4].

Using the simulated database, $J = 1.5 \cdot 10^4$ EAS events were taken for each of $k = 1, \ldots, 4$ kinds (H, He, O, Fe) of primary nuclei and each interaction model (SIBYLL, QGSJET). The reconstructed N_{ch}, N_μ, s shower parameters, known

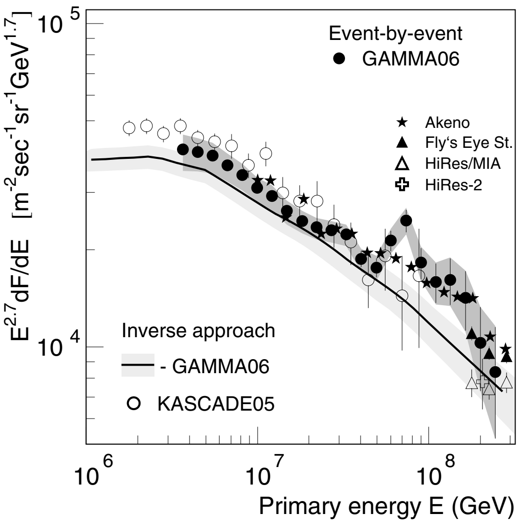

Figure 3. All particle primary energy spectra obtained by event-by-event analysis (filled symbols) and EAS inverse problem solutions (solid and dashed lines) on the bases of GAMMA 2004-2006 database for $R < 50$m and $\theta < 45^0$.

zenith angle θ and primary energy E_0 were used at minimization $\chi^2(a_1,\dots,a_6,\sigma_E|\ln E_1,\ln E_0)$, where $E_1 = f(a_1,\dots,a_6|N_{ch},N_\mu,s,\theta)$ is the investigated parametric function with $a_1,...,a_6$ parameters.

The best estimates were found to fit:

$$\ln E_1 = a_1 x + \frac{a_2\sqrt{s}}{c} + a_3 + a_4 c + \frac{a_5}{(x - a_6 y)}, \quad (3)$$

where $x = \ln N_{ch}$, $y = \ln N_\mu(R < 50m)$, $c = \cos\theta$. The values of the $a_1,\dots,a_6$ parameters for both interaction models are presented in [2,4] at corresponding $\chi^2_{\min}/n_{d.f.} \simeq 1$, where the number of degree of freedom ($n_{d.f.}$) was equal to 6×10^4, and $\sigma_E = 0.15$.

The all-particle energy spectrum derived by the fit above, at the SIBYLL (filled circle symbols) interaction models taking into account statistical and methodical errors (dark shaded area) are shown in Fig. 3.

5. Conclusion

A rigidity-dependent primary energy spectra (2) describes the EAS data of the GAMMA experiment at particle magnetic rigidities $E_R \simeq 2.5 \pm 0.2$ PV (SIBYLL) and $E_R \simeq 3.1 - 4.2$ PV (QGSJET). The corresponding spectral power-law indices are $\gamma_1 = 2.68 \pm 0.02$ and $\gamma_2 = 3.10 - 3.23$ below and above the knee respectively, and the element group scale factors Φ_A are given in Table 1. The abundances and energy spectra obtained for primary p, He, O-like and Fe-like nuclei depend on the interaction model. The SIBYLL interaction model is preferable in terms of consistency of the extrapolations of the derived primary spectra (Fig. 2) with direct measurements in the energy range of satellite and balloon experiments [11]. The obtained energy spectra for primary P, He, Fe nuclei (Fig. 2) strong disagree with the same KASCADE data from [6]. The observed anomaly of the all-particle energy spectrum in the 50-150 PeV energy range (Fig. 3) unaccounted for at present and will require subsequent investigations.

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