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Primary composition and energy spectra obtained with the GAMMA facility

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On the basis of the Extensive Air Shower (EAS) data observed by the GAMMA experiment, the energy spectra and elemental composition of the primary cosmic rays have been derived in the $10^3 \div 10^5$ TeV energy range. Reconstruction of the primary energy spectra are carried out in the framework of the SIBYLL and QGSJET interaction models and the hypothesis of the power-law steepening primary energy spectra. All presented results are derived taking into account the detector response, reconstruction uncertainties of EAS parameters and fluctuation of EAS development.

1. Introduction

The investigation of the energy spectra and elemental composition of primary cosmic rays in the knee region ($10^3 \div 10^5$ TeV) 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 of $E > 10^3$ TeV need improvement.
High statistical accuracies of recent EAS experiments already allowed us to infer that the rigidity-dependent steepening energy spectra of primary nuclei can approximately describe the observed EAS size spectra in the knee region in the framework of conventional interaction models. However, the accuracies of the obtained elemental primary energy spectra are still insufficient due to both the uncertainty of interaction model and the accuracy of the solutions of the EAS inverse problem.

2. GAMMA experiment

The GAMMA installation is a ground based array of 33 surface particle detection stations and 150 underground muon detectors located on the south side of Mount Aragats, Armenia. Elevation of the GAMMA facility is 3200 m above sea level, which corresponds to 700 g/cm^2 of atmospheric depth [1, 2]. The surface stations of the EAS array are located on 5 concentric circles of radii: 20, 28, 50, 70, 100 m and each station contains 3 square plastic scintillation detectors with the following dimensions: 1x1x0.05 m^3. 150 underground muon detectors (muon carpet) are compactly arranged in the underground hall under 2.3 Kg/cm^2 of rock. Unbiased ($< 5\%$) estimations of N_{ch}, s, x_0, y_0 shower parameters are obtained at $N_{ch} > 5 \cdot 10^5$, $\theta < 30^0$, and $R < 25$ m from the shower core to the center of the EAS array distances. Corresponding accuracies are derived from MC simulations by the CORSIKA(EGS) [3] and are equal to: $\Delta N_{ch}/N_{ch} \simeq 0.1$, $\Delta s \simeq 0.05$, $\Delta x, \Delta y \simeq 0.5 \div 1$ m. The reconstruction accuracy of EAS muon truncated ($R_\mu < 50$m) size is equal to $\Delta N_\mu / N_\mu \simeq 0.2 \div 0.35$ at $N_\mu \simeq 10^5 \div 10^3$ respectively [2].

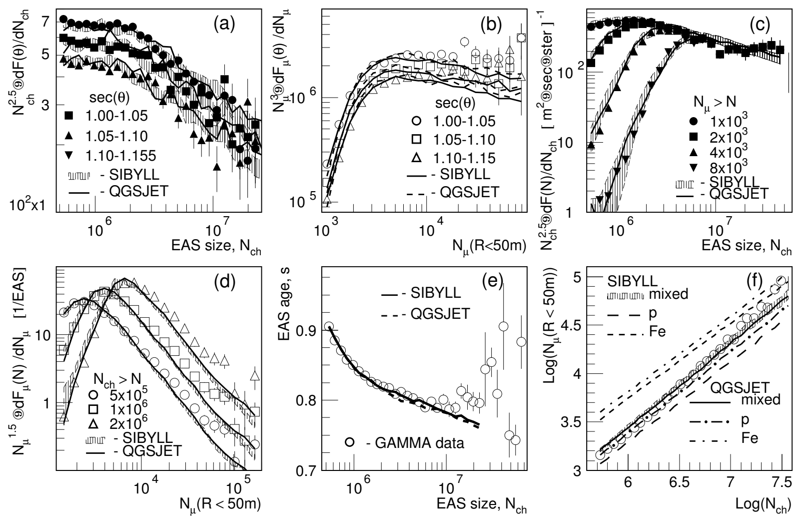

Figure 1. EAS data of the GAMMA experiment (symbols) and corresponding predictions in the framework of the SIBYLL (shaded areas and solid lines) and QGSJET (dashed lines) model.

3. EAS data

The EAS data of the GAMMA experiment are shown in Fig.1a-f (symbols). The EAS size spectra (1a) in units of $(m^2 \cdot sec \cdot ster)^{-1}$ and normalized (1/EAS) EAS muon truncated size spectra (1b) at 3 zenith angular intervals are shown in Fig.1a,b. The EAS size spectra at different muon size thresholds (c) and normalized EAS muon truncated size spectra (d) at different EAS size thresholds are shown in Fig.1c,d. The average EAS age parameter (s) versus EAS size is shown in Fig.1e. The (N_{ch}, N_μ)-correlation plot is shown in Fig.1f. These results were obtained at the $6.19 \cdot 10^7$ sec operation time (2002-2004). All the shaded areas and solid lines (dashed lines) in Fig.1a-f are the corresponding predictions obtained in the framework of the SIBYLL2.1 [4] (QGSJET01 [5]) interaction model (next section).

4. EAS inverse problem

Combined 1,2-D approach: All observed quantities $(\Delta F/\Delta\tilde{q}_u)$ in the high energy EAS physics are obtained via convolutions of the energy spectra dI_A/dE of primary nuclei $(A \equiv H, He, \dots)$ with the differential spectra $W_A(E, q_u)$ of the EAS parameters $q_u \equiv N_{ch}, N_\mu, s$ at the observation level and EAS array response $\partial\mathcal{R}_A(E, q_u, \theta)/\partial\tilde{q}_u$ [2]:

$$\frac{\Delta F_u}{\Delta\tilde{q}_u} = \sum_A \int_E \frac{dI_A}{dE} \int_D \int_{Q_u} W_A(E, q_u) \frac{\partial\mathcal{R}_A}{\partial\tilde{q}_u} dE dD dq_u \ , \tag{1}$$

where the EAS parameter $\tilde{q}_u$ is a reconstructed value of q_u, $dD \equiv \cos\theta dx dy d\Omega$ is an element of the multi-dimensional phase space (D) of the EAS detection taking into account the EAS selection criteria and trigger conditions, $W_A(E, q_u, \theta)$ are the corresponding differential spectra of the EAS parameters (q_u) at the primary energy E, zenith angle of incidence θ and a given kind of primary nucleus (A).

The unambiguous way to interpret the experimental data above is to unfold the integral expression (1) using

Table 1. Parameters of primary energy spectra (2) at 1,2-D and 4-D analysis of EAS data. Scale factors Φ_A and particle's rigidity E_R have units of $(m^2 \cdot sec \cdot ster \cdot TeV)^{-1}$ and (TV) respectively.

Parameters	(1,2D)SIBYLL	(4D)SIBYLL	(1,2D)QGSJET	(4D)QGSJET
Φ_H	0.081 ± 0.004	0.089 ± 0.003	0.164 ± 0.004	0.14 ± 0.004
Φ_{He}	0.072 ± 0.008	0.053 ± 0.005	0.005 ± 0.008	0.034 ± 0.004
Φ_O	0.028 ± 0.008	0.049 ± 0.004	0.005 ± 0.006	0.016 ± 0.003
Φ_{Fe}	0.028 ± 0.003	0.029 ± 0.003	0.018 ± 0.003	0.015 ± 0.002
E_R	2560 ± 200	3000 ± 300	3400 ± 150	3300 ± 200
γ_2	3.21 ± 0.04	3.16 ± 0.08	3.10 ± 0.03	3.10 ± 0.03
$\chi^2/d.f.$	2.5	1.2	2.6	1.1

parametrization of the unknown functions dI_A/dE at a given interaction model [6]. As a criterion of the validity of the solutions, the χ^2 test of the detected and expected data may be performed. Evidently, the accuracies of the unfolding of expression (1) depend not only on number of measurement points (bins) and different measured spectra but also on the wealth of information about the primary energy spectra and the interaction model folded in the given measured EAS spectra.

The primary energy spectra in (1) were used based on the theoretically suggested power-law function [7] with the "knee" at the rigidity-dependent energies $E_k(A) = E_R \cdot Z$ and the same indices $(-\gamma_1)$ and $(-\gamma_2)$ before and after the knee respectively, for all kinds of primary nuclei (A):

$$\frac{dI_A}{dE} = \Phi_A E_k^{-\gamma_1} \left(\frac{E}{E_k}\right)^{-\gamma} \tag{2}$$

where $\gamma = \gamma_1 \equiv 2.65$ at $E \leq E_k(A)$, $\gamma = \gamma_2$ at $E > E_k(A)$ and Z is a charge of A nucleus.

The shower spectra $dW_A(E, q_u, \theta)$, $(q_u \equiv N_{ch}, N_\mu, s \dots)$ on the observation level of the GAMMA facility we have computed using the CORSIKA6031(NKG,EGS) EAS simulation code [3] with the QGSJET01 [5] and SIBYLL2.1 [4] interaction models for 4 groups $(A \equiv H, He, O, Fe)$ of primary nuclei at the power-law energy spectra $(\sim E^{-1.5})$ in the $5 \cdot 10^2 \div 5 \cdot 10^5$ TeV energy range. The EGS mode of the CORSIKA was used for computations of the response functions of the GAMMA detectors taking into account the EAS gamma-quanta contributions and choice of the corresponding input parameters of the adequate NKG mode. All EAS muons with energies of $E_\mu > 4$ GeV on the GAMMA observation level have passed through 2.3 Kg/cm^2 of rock to the muon scintillation carpet. Fluctuations of the muon ionization losses and electron (positron) accompaniment due to the muon bremsstrahlung, direct pair production, knock on and photo-nuclear interactions are taken into account [2].

Using the aforementioned formalism and $(U = 6)$ 2-dimensional examined functions from Fig.1a-d (symbols) and 1-dimensional functions from Fig.1e,f, the unknown spectral parameters $\Phi(A), E_k(A), \gamma_2$ were derived by the minimization of χ^2 at $\gamma_1 = 2.65$ and the degree of freedom $\sum_1^6 V_u \simeq 350$. The values of spectral parameters (2) obtained by the solution of the parameterized equation (1) are presented in Table 1 at corresponding interaction models. The derived primary energy spectra for p, He, O, Fe nuclei are shown in Fig.2 (shaded areas) in comparison with the KASCADE data (symbols) from [8]. The expected spectra conforming the examined data set according to the solutions above are shown in Fig.1a-f (lines and shaded area) for the QGSJET and SIBYLL interaction models.

4-D approach: The combination of 1,2-dimensional approximations of EAS data above does not take into account all the information about primary energy spectra folded in the detected EAS data. In general, the EAS inverse problem can be formulated in the multidimensional space of EAS parameters. In case of the

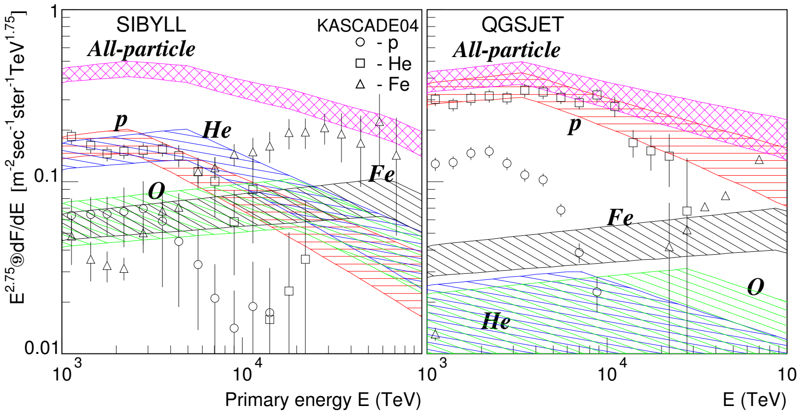

Figure 2. Energy spectra and abundance of the primary nuclei (shaded areas) at the SIBYLL (left panel) and QGSJET (right panel) interaction models. The symbols are the KASCADE data from [8].

4-parametric $(N_{ch}, N_\mu, s, \theta)$ analysis, the expression (1) is written as [2]:

$$\frac{\Delta F}{\Delta \tilde{N}_{ch} \Delta \tilde{N}_\mu \Delta \tilde{s} \Delta \Omega} = \sum_A \int_E \frac{dI_A}{dE} \int_Q \int_D \mathcal{G}_A(E,\theta) \mathcal{R}(\theta) dE dD dN_{ch} dN_\mu ds \;, \tag{3}$$

where $\mathcal{G}_A(E,\theta) \equiv \partial^3 W_A(E,\theta)/\partial N_{ch} \partial N_\mu \partial s$, are the multidimensional differential EAS spectra at given A, E, θ parameters of the primary nucleus, $\mathcal{R}(\theta) \equiv \partial^3 R(\theta)/\partial \tilde{N}_{ch} \partial \tilde{N}_\mu \partial \tilde{s}$ are the error functions of the experiment. Evidently, the amount of information about primary energy spectra contained in the detected multidimensional spectrum ΔF is always greater than the cumulative amount of information contained in the 1,2-dimensional spectra $\Delta F_u / \Delta \tilde{q}_u$ of the expression (1). The difference is determined by the inter-correlations of EAS parameters that are taken into account in the expression (3).

On the basis of the EAS data set of the GAMMA experiment, the simulated EAS database and parameterization (2), the equations (3) were resolved by the χ^2-minimization method. The total number of the degree of freedom at 4-dimensional χ^2-minimization was equal to 1560. The values of spectral parameters (2) obtained by the solution of the parameterized equation (3) are presented in Table 1 at the QGSJET and SIBYLL interaction models.

The obtained energy spectra of primary nuclei disagree (Fig.2) with the same KASCADE data [8] obtained by iterative method [9].

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