Energy Spectrum of Cosmic Rays in the Knee Region and Studies of Different Components of Extensive Air Showers

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Abstract

The energy spectrum of the primary cosmic rays is presented. The spectrum was derived from the electron and muon (with energies above 10 GeV) size spectra obtained with the MSU EAS array and using the contemporary QGSJET model for hadron interactions. The existence of the knee at energy $\sim 3 \times 10^{15}$ eV in the primary energy spectrum is confirmed. The change of the spectral index before and after the knee amounts $\sim$ 0.4–0.5.

Study of the EAS electron and muon components is being continued with the MSU array. In parallel with the traditional study of the EAS size spectrum considerable attention was paid to investigation of the EAS muon number spectrum.

The description of the MSU EAS array is given in [9]. The array covers an area of approximately 0.5 km^2 and includes 77 detectors (Geiger counters) of particle density ρ used for determination of the EAS size N_e.

For determination of the total number of charged particles in a shower at the observation level it is necessary to know in detail their lateral distribution function (LDF). Our analysis showed that experimental data are described rather well by the function proposed by Greisen [3] and having the form

$$\rho \sim x^{s-2}(1+x)^{s-4.5}(1+\beta x),$$

where s is an age parameter, $x = r/r_0$, $r_0 = 80$ m at sea level and $\beta \sim 0.2$–0.4.

However the best agreement can be achieved for the empirical LDF having more complex form

$$\rho \sim x^{s-2}(1+x)^{s-4.5}\left[x(1+x)\right]^{\alpha},$$

where a parameter α depends on the shower axis distance (Fig. 1). Further we used namely this LDF for determining of the particle number N_e.

To construct the EAS size spectrum all showers were divided on narrow intervals on N_e ($\Delta \lg N_e = 0.1$). In each interval the effective collecting area

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pp. 119–122

corresponding 0.95 probability of shower registration was determined by minimum value of N_e in the interval.

The differential size spectrum is presented in Fig. 2. The spectrum is not described by unique power law and has a knee near $\lg N_e \sim 5.6$ confirming our previous results. For comparison in Fig. 2 the size spectrum obtained in the KASCADE experiment [8] is also shown. The KASCADE spectrum is normalized to the intensity of our spectrum at $N_e \sim 10^5$. Both spectra were obtained for near-vertical zenith angles $\theta < 18^\circ$. As follows from Fig. 2, both spectra are in close agreement in form and exhibit a knee approximately at the same value of N_e. Change of the power index before and after the knee amounts 0.42 ± 0.03.

Experimental data on the EAS muon component were obtained with the underground detector (40 m.w.e.) consisting of 1104 Geiger counters of total area 36.4 m^2. The threshold muon energy is 10 GeV.

The muon size N_μ of a shower is determined by the relation

$$N_\mu = \rho_\mu / f_\mu(r, N_e, s),$$

where ρ_μ is muon density, f_μ is the muon lateral distribution function depending rather weakly on N_e and s [7]. If we use as usual our muon LDF approximation

$$f_\mu \sim r^{-n} \exp(-r/R)$$

with $R = 80$ m, the value of n changes from 0.6 to 0.7 at $N_e = 10^5$–5×10^7 [6]. A rather weak dependence of n on N_e follows also from our calculations based on the QGSJET model [4].

The first data on the EAS muon spectrum were obtained with the MSU EAS array as early as 1965 [5]. Here we present new results obtained with significantly greater statistics and improved methodical accuracy.

The differential muon number spectrum is presented in Fig. 3. To increase statistics we used showers with zenith angles $\theta < 30^\circ$ for spectrum construction. For comparison the muon number spectrum transformed from the size spectrum using the relation $N_\mu \sim N_e^{0.78}$ is also shown in Fig. 3.

As can be seen from Fig. 3, the experimental muon number spectrum is practically assigned to the interval N_μ which corresponds to the spectrum after the knee in the EAS size spectrum. This circumstance is due to the used triggering system which effectively selects showers beginning from $N_e > 10^5$. That allows us to take into account all showers with $N_\mu > 10^4$, but limits our possibilities to study showers with $N_\mu < 10^4$. Both spectra in Fig. 3 are in a good agreement. The value of spectral index after the knee equals 3.41 ± 0.03.

We used experimental EAS spectra on N_e and N_μ to derive an information about the primary energy spectrum and mass composition in the frame of QGSJET model [4].

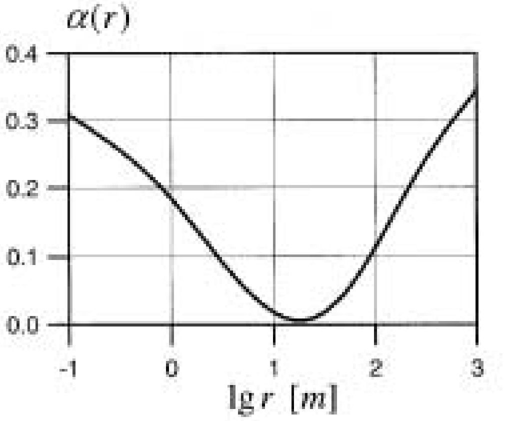

Fig. 1. Dependence of $\alpha(r)$ on the distance from the shower axis.

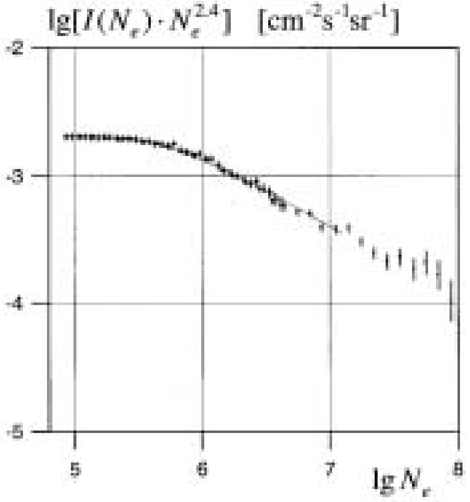

Fig. 2. The EAS electron number spectrum. Points are our data, crosses are KASCADE data [8], curve presents results of calculations.

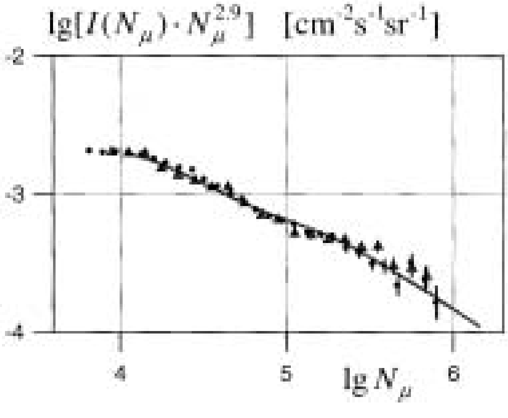

Fig. 3. The EAS muon number spectrum. Triangles are our data, points are recalculations from the EAS size spectra. Curve presents results of calculations.

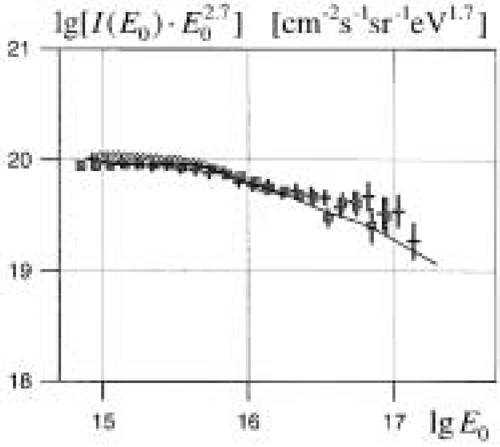

Fig. 4. The primary energy spectrum. Crosses, diamonds, and squares are the KASCADE [8], EAS TOP [1], and Tunka [2] data respectively. Curve presents results of calculations.

The following formula relates the number of showers in a given interval $\Delta N = N_{\max} - N_{\min}$ to primary energy spectrum $I(E_0, A)$:

$$J(\Delta N) = \sum_{k=1}^{k_{\max}} P_k \int_{-\infty}^{\infty} I(E_0, A)\, dE_0 \int_{N_{\min}}^{N_{\max}} W(N(E_0, A))\, dN,$$

were k is the group number, P_k is the abundance of a given nucleus group, $W(N(E_0, A))\, dN$ is the probability of the event that the number of particles in a shower generated by a primary of energy E_0, and mass number A belongs to the interval $(N, N + dN)$; $k_{\max}$ is the maximum number of nucleus groups. Function $W(N(E_0, A))$ is calculated for different nucleus groups and the results of these calculations may be presented as Gaussians (in variable $\ln N$).

Adopting power law spectra with a knee at energy $E_{0Z}(\bar{Z}(A))$ for different nuclei and setting P_k, one can calculate theoretical size spectrum for any prescribed combination of P_k and spectral indices γ_1 and γ_2 before and after the knee. After that an “optimal” combination (in the sense of χ^2-criterion) can be found which defines the primary energy spectrum and mass composition.

The primary energy spectrum derived using MSU data is shown in Fig. 4. The uncertainty in abundances of individual groups are rather large and so we present only the total energy spectrum. The primary energy spectra obtained in the experiments Tunka [2], EAS TOP [1], and KASCADE [8] are also presented in Fig. 4. All spectra exhibit a knee near $E_0 \approx (3–5) \times 10^{15}$ eV although spectral indices before and after a knee slightly differ from each other.

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