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On the EAS muon number spectrum

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Abstract. We present new results on EAS muon flux characteristics which were obtained with the EAS MSU array. Of particular interest is the EAS muon number spectrum. The EAS muon number spectrum together with the EAS size spectrum gives an additional possibility for more accurate transformation to the primary cosmic ray energy spectrum.

1 Introduction

Study of the EAS muon component is of interest to get information on the energy spectrum and nuclear composition of the primary cosmic rays. Experimental data obtained with the EAS MSU array are used.

2 Experiment

The description of the EAS MSU array is given in Vernov et al. (1979). The array covers an area of approximately 0.5 km^2 and includes 77 detectors (Geiger counters) of particle density used for determination of EAS size N_e.

The underground muon detector is placed at 40 m.w.e. in the center of the array. It consists of 1104 Geiger counters of total area 36.4 m^2. The muon threshold energy is 10 GeV.

3 Determination of the average muon density

For determination of the total number of muons (N_μ) in a shower it is necessary to know the muon lateral distribution function (LDF) that, in its turn, assumes knowledge of the average muon density.

We determine the average muon density ρ using the method of maximum likelihood (Khristiansen, 1975) on the assumption that the muon numbers m hitting the muon detector of the area σ in a shower with given N_e and at given distance r from the shower core agrees the Poisson distribution and $\rho \sim N_e^\alpha$.

From the Bayes theorem

$$W(\rho_i, m_i) = \omega(\rho_i) L(m_i, \rho_i),$$

where W and ω are a posteriori and a priori probabilities of ρ correspondingly, L is the function of maximum likelihood. In our case

$$L = \prod_{i=1}^{n} (\rho_i \sigma_i \cos\theta_i)^{m_i} \exp(-\rho_i \sigma_i \cos\theta_i)/m_i!,$$

where n is the number of showers and θ is zenith angle. Using the relation

$$\rho_i = \rho_f (N_{ei}/N_{ef})^\alpha,$$

where ρ_f is the muon density in a shower with some fixed size N_{ef} we get

$$L = \prod_{i=1}^{n} [\rho_f k_i]^{m_i} \exp[-\rho_f k_i]/m_i!,$$

where

$$k_i = (N_{ei}/N_{ef})^\alpha \sigma_i \cos\theta_i.$$

The function ω is determined by the selection system with respect to the shower size and by the muon spectrum at a given r and N_e. The problem of finding a maximum of the function W was solved on the assumption that the maximum was determined by the function L (the function ω varies more slowly with its parameters when compared with L).

From condition

$$\frac{\partial W}{\partial \rho_f} = 0$$

we get

$$\rho_f = \sum m_i / \sum k_i.$$

According to our experimental data, $\alpha = 0.78$ (Khristiansen, 1971).

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4 Muon LDF

The muon size N_μ of a shower is determined by the relation $N_\mu = \rho_\mu / f_\mu(r, N_e, s)$, where f_μ is the muon lateral distribution function. Experimental data on muon LDFs were analysed in the wide range of size $N_e = 10^5$–5×10^7 in order to find the dependence of the average muon LDF on N_e and shower age s. Both dependencies are rather weak. The analysis showed that if we use, as usually, 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. As far as the dependence of f_μ on s is concerned, a noticeable deviation of the value of n from the average was observed only for young showers with $s < 0.9$ (for example, $n = 0.77 \pm 0.04$ at $N_e = (2$–$10) \times 10^5$). The contribution of those showers to the total is less than 10%.

Experimental data on muon LDFs obtained with increased statistics are shown in Fig. 1. A rather weak dependence of n on N_e follows also from our calculations based on the QGSJET model and the diffusion model of primary cosmic rays (PCR) propagation with normal composition before the knee (Kalmykov, 1997). As seen from Fig. 1, theoretical predictions are in a good agreement with experimental data.

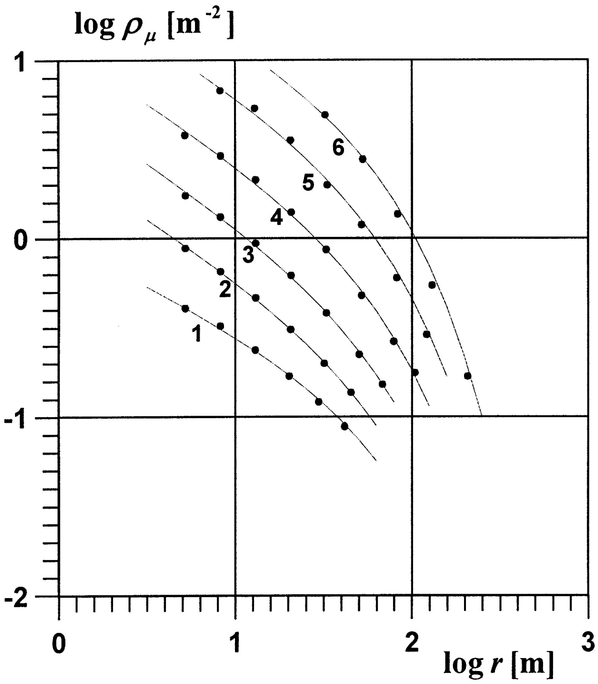

Fig. 1. Lateral distribution of muons. Full circles—experiment, curves—QGSJET model. $\log N_e$: 5.0–5.2 (1), 5.4–5.6 (2), 5.8–6.0 (3), 6.2–6.4 (4), 6.6–6.8 (5), 7.0–7.2 (6).

5 EAS muon number spectrum

Knowledge of the EAS muon number spectrum together with EAS size spectrum allows one to get additional information on the PCR energy spectrum. As calculations show, the transition from the EAS muon spectra to the PCR energy spectrum is more unambiguous compared the transition from the EAS size spectrum because charged particle flux fluctuations are significantly greater than those of the high energy muon flux.

The first data on the EAS muon spectra obtained with the EAS MSU array were published in (Khristiansen, 1965). Recently the EAS muon size spectrum was studied in the KASCADE experiment for muons of smaller energies (Glasstetter, 1999).

Here we present new results obtained with considerably greater statistics and improved methodical accuracy.

It should be noted that in constructing the EAS muon spectra special attention must be paid to correct determination of effective selection of showers with different N_μ. If the triggering system used selects showers with respect to electron component the effective area for showers with given $N\mu$ is determined by the condition that registration probability equals ~ 1 for all showers with such values of N_e and s in which given N_μ may occur.

The triggering system allows us to study effectively showers with $N_e \geq 10^5$. As follows from the distribution on N_μ at fixed $N_e = 10^5$ (see Fig. 2), the abundance of different N_μ is such that a part of showers with $N_\mu \geq 10^4$ is less 1%. So confining by showers with $N_e \geq 10^5$ we take into account practically all showers with $N_\mu \geq 10^4$ that gives us the possibility to construct accurately the EAS muon number spectrum.

The differential muon spectrum for showers with $N_\mu \geq 10^4$ is shown in Fig. 3. It can be described by a power law with slope $\kappa_\mu + 1 = 3.41 \pm 0.03$.

Using earlier measured dependence of N_μ on N_e in form

$$N_\mu = 3.24 \times 10^3 (N_e/10^5)^{0.78}$$

we get that for $N_\mu = 10^4$ the value of $N_e = 4 \times 10^5$. Hence the muon spectrum obtained refers to the area after the knee in the EAS size spectrum (Fomin, 1991). For comparison the muon spectrum transformed from the size spectrum (Fomin, 1991) according to foregoing relation of N_μ on N_e is also shown in Fig. 3. Both spectra are in a good agreement.

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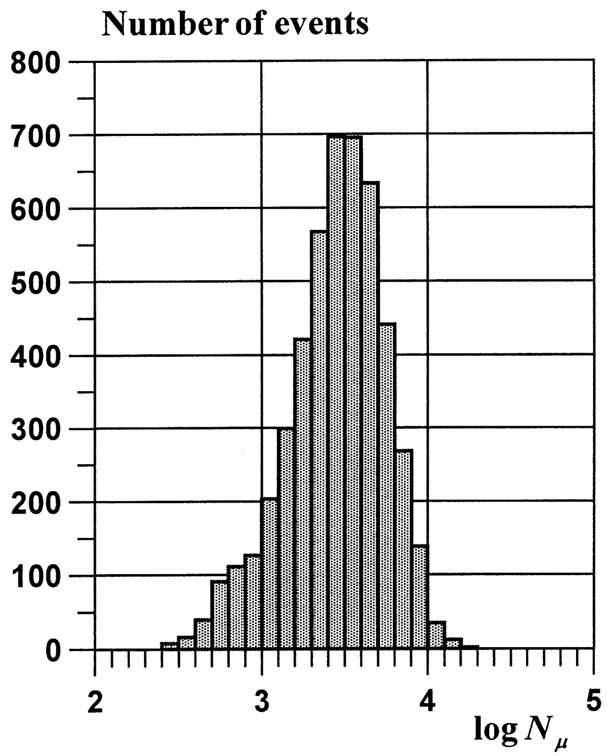

Fig. 2. Muon number distribution at fixed $N_e = 10^5$.

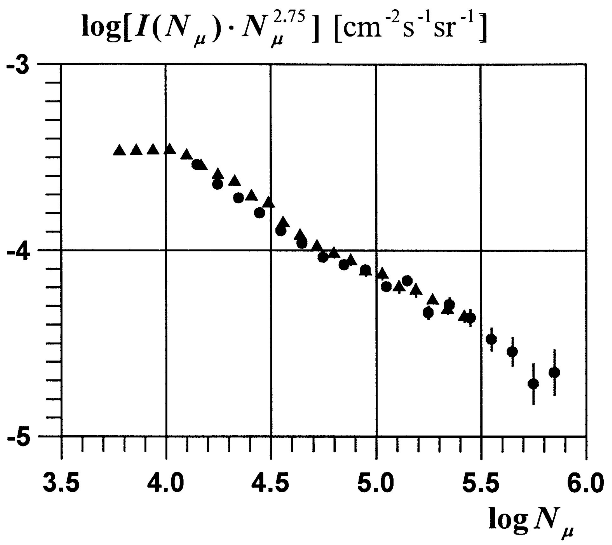

Fig. 3. Differential EAS muon number spectrum. Full circles—muon number spectrum, triangles—transformation from size spectrum.

References

Fomin Yu.A., et al., Energy spectrum of cosmic rays at energies of 5×10^{15}–5×10^{17} eV, Proc. 22nd ICRC, Dublin, **2**, 85–88, 1991.

Glasstetter R., et al., Analysis of electron and muon size spectra of EAS, Proc. 26th ICRC, Salt Lake Sity, **1**, 222–225, 1999.

Kalmykov N.N., et al., Quark-gluon string model and EAS simulation problems at ultra-high energies, Nucl.Phys.B (Proc.Suppl), **52**, 17–28, 1997.

Khristiansen G.B., et al., Energy spectrum, possible chemical composition and anisotropy of the ultra-high energy primary cosmic radiation, Proc. 9th ICRC, London, **2**, 799–801, 1965.

Khristiansen G.B., et al., The electron and muon structure functions in EAS of energies 10^{15}–10^{17} eV, Proc. 12th ICRC, Hobart, **6**, 2097–2108, 1971.

Khristiansen G.B., et al., Lateral structure of the EAS electron and muon components, Proc. 14th ICRC, Munich, **8**, 2801–2806, 1975.

Vernov S.N., et al., New EAS array at Moscow state university for studying the e.a.showers with energies up to 10^{18} eV, Proc. 16th ICRC, Kyoto, **8**, 129–134, 1979.