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Absorption Curves of Muons and Muon Cascades in Air

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Abstract

Experimental data on muons (with threshold energy of 1 GeV) in extensive air showers with energies above 10^{17} eV obtained at the Yakutsk EAS array from 1974 to 1998 are presented. Zenith-angular dependencies of muon component have been obtained. These dependencies are shown to be considerably different for different energy ranges.

1 Introduction:

The experiment and treatment of extensive air showers (EAS) muon component data have been described in (Glushkov et al, 1994) and (Glushkov et al, 1995). In this work the periods of reliable stable operation of the muon detectors have been selected more precise. In addition, unlike (Glushkov et al, 1994) and (Glushkov et al, 1995) the showers with cores beyond the array have not been considered. The readings of those counters of any detector which deflected from the average value more then 5σ have also been excluded from the treatment. We have considered 149747 showers with $E_0 > 10^{17}$ eV at the zenith angle $\vartheta \le 60°$, selected according to these criteria.

2 Experimental Results:

Mean lateral distribution functions (LDF) were approximated by the functions of the following form

$$\rho_\mu(R) = f(R)\cdot(1+R/2000)^{-g} \qquad (1)$$

with $f(R)$ given by the Greisen distribution

$$f(R) = N_\mu (C_\mu / R_0{}^2) r^{-0.75}(1+r)^{0.75-b_\mu}\,, \qquad (2)$$

where $g=3$, $r = R/R_0\,(R_0 = 280m), C_\mu$ is a normalizing constant, N_μ is total number of muons in a shower at the observation level, b_μ is a structural parameter.

The parameter b_μ characterizing the LDF form versus E_0 is shown in Fig.1 for five angular intervals with a step of $\Delta\cos\vartheta=0.1$. For clearly demonstration of the graphs, two versions of data treatment with a step of $\Delta\log E_0=0.2$ have been carried out. The second version is shifted in respect to the first one by a half step, that is $\Delta\log E_0=0.1$. The straight lines in Fig.2 correspond the dependence

$$b_\mu = b_0 - b_1(\sec\theta - 1) + b_2(\sec\theta-1)(\log E_0 - 18), \qquad (3)$$

where $b_0 = 3.27 \pm 0.05$, $b_1 = 1.47 \pm 0.06$, $b_2 = 0.52 \pm 0.05$ are found by the standard least squares method and are in agreement with (Nikiforova, 1998). Here the problem on the observed irregularities in E_0-dependence of b_μ is not considered.

For the angular interval with $\langle\cos\vartheta\rangle=0.95$ the parameter b_μ depending on the energy E_0 changes with a rate $\delta b_\mu/\delta\log E_0=0.03\pm0.01$. At first sight, it is in contradiction with (Glushkov et al, 1994) and (Glushkov et al, 1995). However, in the mentioned papers in the same angular interval of $\langle\cos\vartheta\rangle=0.95$ at $E_0<5\cdot10^{18}$ eV the linear approximation gives $\delta b_\mu/\delta\log E_0=0.04\pm0.01$. Note that the muon LDF for the Akeno array (Hayashida et al, 1995) doesn't depend on the energy.

The rise of b_μ in dependence on the energy with the growth of zenith angle θ is of interest. In (Glushkov et al, 1994) and (Glushkov et al, 1995) in the angular interval $\langle\cos\vartheta\rangle=0.55$ at the energies $E_0<3\cdot10^{19}$ eV b_μ also takes the values essentially smaller than at $E_0>3\cdot10^{19}$ eV.

The muon density $\rho_{\mu,600}$ at a distance of 600 m from the core is a well measured parameter and characterizes LDF by the absolute value. The dependence of $\rho_{\mu,600}$ on the energy E_0 for those five angular

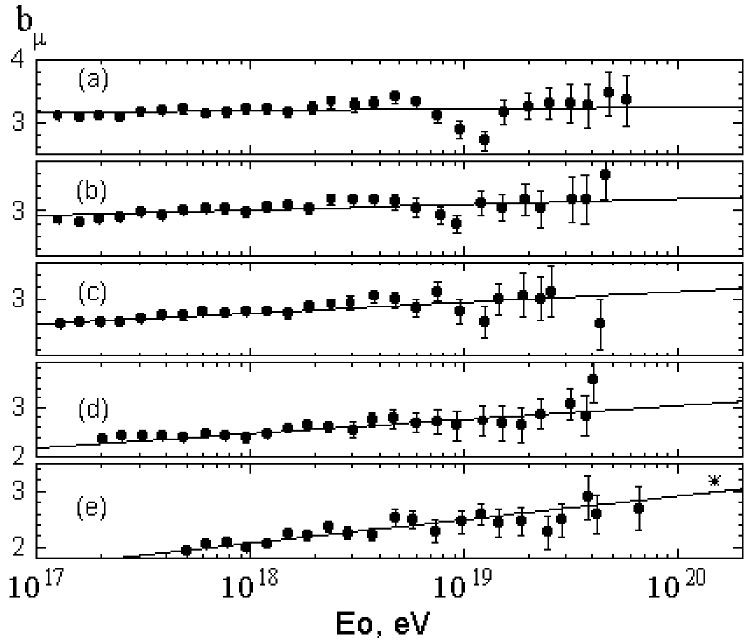

Fig.1 The dependence of b_μ on E_0 : a - <cosϑ> = 0.95, b - <cosϑ> = 0.85, c -<cosϑ> = 0.75, d - < cosϑ> = 0.65, e - < cosϑ> = 0.55. ∗ is a shower with $E_0 \approx 1.5 \cdot 10^{20}$ eV and ϑ=58.7°. The straight lines are the relationship (3)

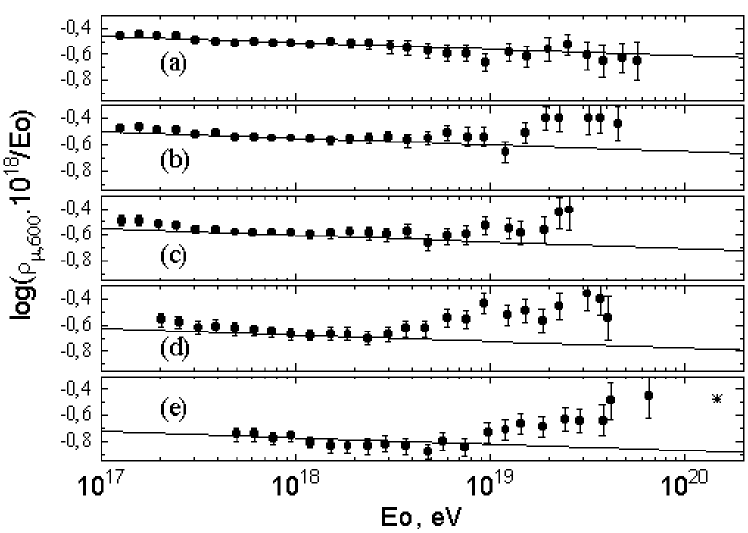

Fig.2 The dependence of $\rho_{\mu,600} \cdot (10^{18}/E_0)$ on E_0 : a - <cosϑ> = 0.95, b - <cosϑ> = 0.85, c - <cosϑ> = 0.75, d - < cosϑ> = 0.65, e - <cosϑ> = 0.55. ∗ is a shower with $E_0 \approx 1.5 \cdot 10^{20}$ eV and ϑ=58.7°. The straight lines correspond to (Glushkov et al, 1994) and (Glushkov et al, 1995)

intervals is shown in Fig.2. The densities are normalized by E_0 to 10^{18} eV. This dependence is in complete agreement with previous results in (Glushkov et al, 1994) and (Glushkov et al, 1995). For the angular interval of <cosϑ>=0.55 the essential growth of $\rho_{\mu,600}$ is observed as the energy increases. At the Akeno array the growth of the muon portion from the total number of the charged particles $\rho_{\mu,600}/\rho_{s,600}$ as a function of $\rho_{s,600}$ in the same interval has not been revealed.

The shower “Arian”(Glushkov et al, 1991) registered on May 7, 1989 with the energy $E_0 \approx 1.5 \cdot 10^{20}$ eV and a zenith angle ϑ=58.7° is nearly entirely consisting of muons and it is in agreement with the obtained average values of b_μ and $\rho_{\mu,600}$ and contradicts to the Akeno array data. Possible, it is caused by the fact that the Akeno array is located on hills and the inclined showers at the angle of ~60° are registered unreliably.

It is worth noting that the shower energy E_0 at the Yakutsk array is determined by a calorimetric method worked out for the angles to 45°. For more inclined showers in the present work the extrapolation have been used. The shower “Arian” energy at the calorimetric method extrapolation with different absorption paths have been varied from $1.0 \cdot 10^{20}$ eV to $1.5 \cdot 10^{20}$ eV. On the assumption that the inclined shower with $E_0 \geq 10^{19}$ eV are of lower energy than it was obtained by extrapolation then it will lead to the increase of abnormal behaviour of b_μ and $\rho_{\mu,600}$.

For the purpose of studying the stability of the parameter b_μ for various distances, the behaviour of

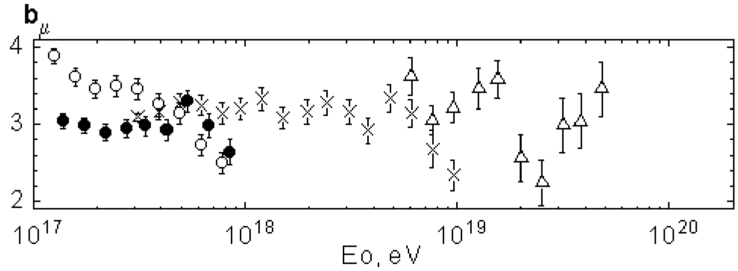

Fig.3. The dependence b_μ on E_0 at <ϑ>=18° for different distance ranges: O - 30-200 m, × - 200-700 m, Δ - 700-2000 m, • - the result of modelling

this parameter for three ranges: 30-200, 200-700, 700-2000 m has been considered. Fig.3 shows the obtained b_μ for <cosϑ>=0.95. On the whole the value of the parameter b_μ for different distance range are in agreement with each other, and in this case the scattering of b_μ increases. However, for the distance range of 30-200 m b_μ decreases. Such a behaviour of b_μ might be initiated by the saturation of the muon detectors. But there is no saturation in this case.

For the distance range of 30-200 m the errors for the determination of the core coordinates might be essential. The total mathematic modelling of the registration process and the experimental data treatment of the Yakutsk EAS array was carried out. The showers were simulated beginning from the energy $5 \cdot 10^{16}$ eV in the circle of 1500 m radius for a zenith angle uniformly distributed by cosϑ. The errors of shower arrival direction determination with the array have been imitated by a simulation of the accidental deviation from the true direction by the normal distribution with a root-mean-square deviation σ=8.6°. By a simulated energy value the mean values of the parameters b and b_μ have been determined for LDFs of charged particles and muons. The true values of b and b_μ were simulated around the mean values according to the normal low with a root-mean-square deviation σ=0.25. For simulated values of b and b_μ the expected particle density for every station were determined and around this value the registered particle density were simulated. The selection and treatment of artificial showers were made by the same programs as the experimental ones. Fig.3 shows the obtained b_μ as a result of modelling for the range of 30-200 m at <cosϑ>=0.95. The scattering of this parameter value is seen, yet the decrease is not observed. The decrease of the parameter b_μ for the experimental showers is probably associated with the energy spectrum change for the high-energy muons or with the growth of their transverse impulse.

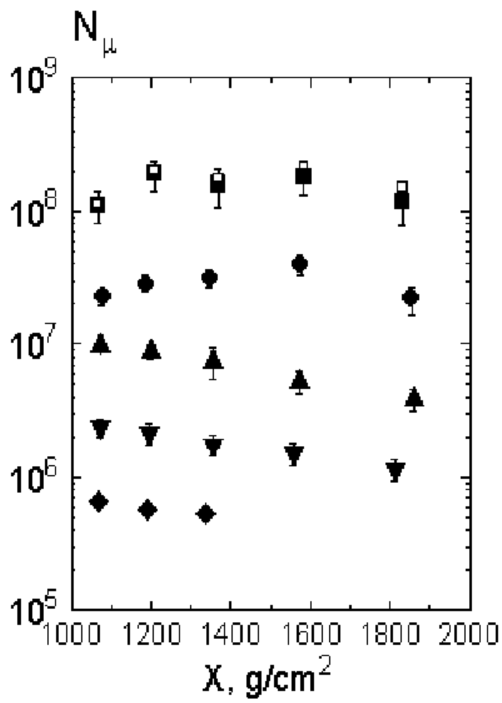

Fig.4 Zenith-angular dependence of muon N_μ on depth of atmosphere X for different energies : ◆ - <logE_0> = 17.2, ▼ - <logE_0> = 17.79, , ▲ - <logE_0> = 18.38, , ● - <logE_0> = 18.98, , ■ - <logE_0> = 19.58. □ - cascade curve for <logE_0> = 19.58

Zenith-angular dependence of muon N_μ on depth of atmosphere X for different energies are shown in Fig.4. These dependencies are considerably different for different energy ranges. At E_0 approximately greater 10^{19} eV the dependencies possibly have maximum at 1500 g/cm^2. An absorption length of cascade curve of muon at $E_0=10^{18}$ eV, ϑ=50° equal 2470 g/cm^2 for hydro-dynamic model (Ivanov, 1987) and corresponding absorption length of zenith-angular dependence of muon in the angle range of 0-50° equal 1400 g/cm^2. Using these absorption lengths we can transform zenith-angular dependence to cascade curve, as it is shown in Fig.4.

3 Discussion:

The structural parameter b_μ depends on the height of the muon generation. From the expression (3) it follows that the change rate of the parameter b_μ with the increase of energy E_0 $\delta b_\mu/\delta \log E_0$ is proportional to (secϑ-1). From (3) also it follows that at the fixed energy the parameter b_μ depends on the zenith angle ϑ as a function of secϑ. Probably, it is caused by the atmosphere density change for the inclined showers. However, on the basis of geometry it is impossible to explain the change of rate of the parameter b_μ $\delta b_\mu/\delta \log E_0$ as proportional to (secϑ-1).It is also impossible to explain the growth of b_μ for the inclined showers by the increase of a portion of high-energetic muons with the shower energy increase because it doesn't explain the constancy of this parameter b_μ for the vertical showers. On the assumption of the constancy of the energy muon spectrum in EAS the behaviour of the parameter b_μ means the constancy of the muon production height for the vertical showers and the decrease of the height with the energy growth for the inclined showers.

One can explain the observed behaviour of b_μ , $\rho_{\mu,600}$ and N_μ by the fact that the cascade curve of muons has a maximum at the depth more than 1000 g/cm^2.

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References

Glushkov, A.V. et al. 1991, Izvestia AN SSSR 55, 717

Glushkov, A.V. et al. 1994, Izvestia RAN 58, 87

Glushkov, A.V. et al. 1995, Astrop. Phys. 4, 15

Hayashida, N et al. 1995, J. Phys. G: Nucl. Part. Phys. 21, 1101

Ivanov, A.A. 1987, Sbornik nauchnykh trudov. Shirokiye atmosfernye livni s energiei vyshe 10^{17} eV, Yakutsk, 74

Nikiforova, E.S. 1998, Nauka i obrazovanie, Yakutsk 4, 34