Energy spectrum of muons in air showers at large zenith angles

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(Submitted July 1, 1976)
Pis'ma Zh. Eksp. Teor. Fiz. **24**, No. 7, 443–446 (5 October 1976)

We obtain the integrated muon spectrum at large zenith angles in the energy interval 0.28 TeV $\le E_\mu \le 35$ TeV. The results are compared with data by others.

PACS numbers: 92.50.+a, 92.60.+f, 92.80.+r

The study of the energy spectrum of muons of ultrahigh energies in cosmic rays should make it possible to estimate the contribution made to the formation of this spectrum by the muons produced, for example, in "direct" processes[1] or due to the decay of superheavy particles.[2] The largest-luminosity method for the investigation of the energy spectrum of muons at ultrahigh energies is to measure the spectrum of the horizontal air showers (HAS).[3] The recalculation from the spectrum of an HAS with respect to the number of particles N to the energy spectrum of the muons can be carried out by assuming normal or anomalous interactions of the muons in the atmosphere. A comparison of the energy spectrum of the muons, obtained as a result of a recalculation from the HAS spectrum, with the "true" energy spectrum makes it possible to assess the role of the anomalous interactions of muons[4,5] in the formation of the HAS.

Measurement of the particle-number spectrum of HAS was carried out with a specialized installation of the Khar'kov University, containing eight scintillation detectors with area 1 m^2, intended for the selection of the HAS and for the measurement of the position of the shower axis in space. The size of the shower was determined with the aid of 12 hodoscopic detectors, each consisting of ~200 Geiger—Mueller counters of type MS-9, operating in the regime of pulsed high-voltage supply. The luminosity of the installation for HAS with $N = 5\times10^3$ amounts to 2.4×10^2 m^2-sr, and for HAS with $N = 3\times10^4$ it amounts to 3.55×10^3 m^2-sr.

After 900 hours of continuous operation, we observed 8 showers of size $3.8\cdot10^3 \le N \le 4\cdot10^4$ in the region of zenith angles $70 \le \theta \le 90°$ at an average age parameter $\bar{s} = 1$.

The integrated particle-number spectrum of the HAS for the entire aggregate of the showers (including the data of[6]) can be described by a power function with a single exponent γ_1:

$$J\,(> N > 70°) = K\left(\frac{N}{2\cdot10^2}\right)^{-\gamma_1} \ \mathrm{cm^{-2}\ sec^{-1}\ sr^{-1}}\ , \qquad (1)$$

where $K = (4.13 \pm 0.67)\cdot10^{-9}$, $\gamma_1 = 2.65 \pm 0.1$. This form of the integrated spectrum agrees with the measurements of the HAS spectrum in[7,8].

Assuming that the HAS is formed by bremsstrahlung photons of the muons,

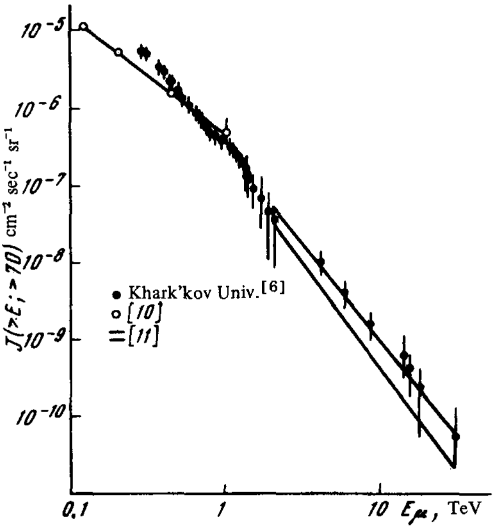

FIG. 1.

we obtain that the integrated particle-number spectrum of the HAS is connected with the energy spectrum $P_\mu(E',\theta)$ of the muons[9] by the following expressions:

$$J(> N > \theta) = \frac{N_0 t_0}{A} \int_0^\infty P_\mu(E', \theta) W(E', E) dE' dE \int_0^\infty \left[\frac{N}{E_N(t)}\right]^\gamma dt, \quad (2)$$

Here N_0 is the Avogadro number, $t_0 = 37.1$ g cm^2 is the radiation unit length of air, A is the atomic weight of air, $P_\mu(E',\theta)dE'$ is the differential energy spectrum of the muons, $W(E',E)dE$ is the probability of production of a photon of energy E by a muon of energy E', $E_N(t)$ is the energy of a photon producing a shower of size N at a distance t, and γ is the exponent of the integrated energy spectrum of the muons.

The figure shows the integrated energy spectrum of the muons obtained as a result of recalculation from the integrated HAS spectrum (1) with the aid of expression (2). For comparison Fig. 1 shows the muon spectra measured at an angle $\theta \approx 83°$ by the magnetic-spectrometer method[10] and by a calorimeter with x-ray films.[11]

The energy spectrum of the muons can be represented in the form

$$J(> E > 70°) = (1.73 \pm 0.28) \cdot 10^{-5} \left(\frac{E}{0.2}\right)^{-2.53 \pm 0.10} \text{cm}^{-2}\,\text{sec}^{-1}\,\text{sr}^{-1}$$

in the energy interval E from 0.28 to 35 TeV and

$$J(> E > 70°) = (3.15 \pm 1.00) \cdot 10^{-7} E^{-2.59 \pm 0.20} \text{cm}^{-2}\,\text{sec}^{-1}\,\text{sr}^{-1}$$

in the energy interval E from unity to 35 TeV.

Analysis shows that within the limits of experimental errors the energy spectrum of the muons obtained in the present paper agrees with the data of[11]. The discrepancy between the absolute values of the intensity of the muons in the energy region $0.28 \leq E \leq 0.4$ TeV, obtained in[6] and in[10], can be eliminated by recalculating the effective registration area of[6] with account taken of the individual values of the age parameters of the small-size showers.

The results of the present study leads to the following conclusions: the HAS spectra agree in form with the horizontal flux of the muons up to muon energies ~35 TeV, and there is good agreement between the absolute values of the integrated intensities of the HAS and the muons. We can therefore conclude that there are apparently no significant changes either in the mechanism of generation of muons with such energies, or in the mechanism of their interaction with air-atom nuclei up to energies ~35 TeV.

At much higher energies, the production and interaction of the muons can be investigated only by registering the HAS. To this end it is necessary to produce a large specialized comprehensive setup having a luminosity 10 times larger than that of the present setup. Such a project obviously can be realized only in a mountain area or by using out of town high-altitude structures.

The authors are grateful to V. I. Kartasheva for reducing the primary shower information.

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