ENERGY SPECTRUM OF CASCADE SHOWERS INDUCED BY COSMIC RAY MUONS IN THE RANGE FROM 50 GEV TO 5 TEV

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Abstract. Results of a new measurement of the energy spectrum of cascade showers induced by electromagnetic interactions of high energy muons of horizontal cosmic ray flux in iron absorber are presented. The total observation time exceeded 22,000 hours. Both the energy spectrum and angular distributions of cascade showers are fairly described in terms of the usual muon generation processes (i.e. through π- and K-decays in the atmosphere) with a single power index of the parent meson spectrum over the muon energy range from 150 GeV to 5 TeV.

1. Introduction. Recent magnetic spectrometer measurements of cosmic ray muon spectrum at large zenith angles [1,2] agree well with each other and are successfully interpreted within the frames of the conventional muon generation processes with a value of the differential parent particle spectrum index of about 2.7 up to several TeV muon energies. A similar result was obtained earlier in the ionization calorimeter measurements of the spectrum of cascade showers initiated by muons [3] and was confirmed by the MUTRON calorimeter data published recently [4]. However, a number of experiments [5-8] give appreciably more rigid shower spectrum around 1 TeV, what is claimed to be caused either by some additional flux of muons (or some other penetrating particles) or by an anomalous muon interaction increasing with energy. On the other hand, in the experiments [9,10] the steepening spectrum of cascade showers was observed.

Here we present the first results of a new measurement of the cascade shower spectrum using an ionization calorimeter. Compared to our old data [3], the energy range has been extended to lower energies. The exposure time and hence statistics of high energy events have been doubled.

2. Experimental. A schematic diagram of the experimental arrangement is given in Fig.1. The arrangement consists of the six-layer calorimeter and G.M. counter hodoscope detectors. Two trigger modes have been used in the operation. The first one required the coincidence of any three layers of ionization chambers (ionization $\geq$ 80 cascade particles) together with the total energy deposition exceeding 60 GeV. The second trigger was organized to study the low energy part of the spectrum and included a coincidence of two hodoscope detectors and triggering of any pair of adjacent layers of the calorimeter with the above ionization thresh-

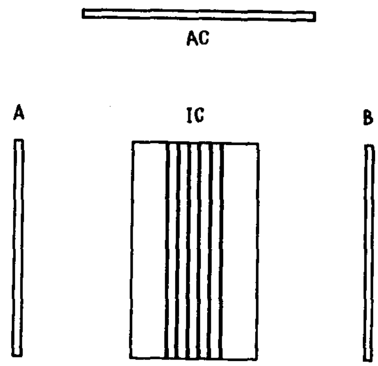

Fig.1

old. The cascade energy threshold in the latter case corresponded to approximately 20 GeV. A veto signal from an air shower shield was formed by a 4-fold coincidence in AC detector which consisted of 6 cells of 0.8 m^2 sensitive area each. A more detailed description of the experimental arrangement has been published in [11].

During five experimental runs in 1980 to 1984 with the total observation time of 8.0×10^7s of about 250000 events have been recorded and analysed. Only cascade showers initiated by muons crossing hodoscope detectors with zenith angles $\theta \geqslant 60°$ have been selected to study the shower energy spectrum and angular distribution. Edge events and a small amount of nuclear showers (which are very different from electromagnetic ones in longitudinal development) have been rejected. The total number of reconstructed events equals to 8.2×10^4 for trajectories traversing both A and B hodoscope detectors with $\Lambda \geqslant 2$ triggered layers of the calorimeter, and 3.8×10^4 for three-layer events ($\Lambda \geqslant 3$) with at least one hodoscope detector (A or B) discharged. The maximum detected shower energy was about 16 TeV.

3. Data analysis and results. To derive cascade shower generation spectrum from the observed distributions the accurate account for experimental conditions (arrangement geometry, trigger and selection criteria, hodoscope and reconstruction efficiency, the difference between the real shower energy $\mathcal{E}$ and its estimate $\tilde{\mathcal{E}}$, and so on) is necessary. We used the trial spectrum method to analyse our data. Calculations started from the expected (or "trial") spectrum of cascade shower generation in a unit target mass:

$$\mathcal{R}_o(\mathcal{E},\theta) = \int_{E_{min}}^{\infty} \mathcal{N}_\mu(E,\theta)\,\sigma(E,\mathcal{E})\,dE, \qquad (1)$$

where $\mathcal{N}_\mu(E,\theta)$ is the differential muon spectrum at the observation level (has been calculated after [12]), and $\sigma(E,\mathcal{E})$ is the sum of the cross sections of electromagnetic muon interaction processes [13-15]. A Monte Carlo technique was used to calculate the response of the experimental arrangement - the matrix of the numbers of events $N_o(\Delta\tilde{\mathcal{E}},\Delta\theta)$ expected in the energy estimate interval $\Delta\tilde{\mathcal{E}}$ and zenith angle interval $\Delta\theta$. The experimental values of the differential cascade shower generation spectrum were then derived from a comparison of the observed $\tilde{N}(\Delta\tilde{\mathcal{E}},\Delta\theta)$ and calculated $N_o(\Delta\tilde{\mathcal{E}},\Delta\theta)$ matrices using the following relation:

$$\tilde{\mathcal{R}}(\mathcal{E}^*,\theta^*) \simeq \mathcal{R}_o(\mathcal{E}^*,\theta^*)\times\tilde{N}(\Delta\tilde{\mathcal{E}},\Delta\theta)/N_o(\Delta\tilde{\mathcal{E}},\Delta\theta). \qquad (2)$$

Here θ^* is the average zenith angle in the $\Delta\theta$ interval, and

$\mathcal{E}^*$ is a logarithmically averaged value (i.e., $\mathcal{E}^* = \exp(\overline{\ln\mathcal{E}})$) of the cascade shower energy contributing to $\Delta\mathcal{E}$ interval. Such a choice of the reference energy minimizes the sensitivity of the derived spectrum to the slope of the trial one.

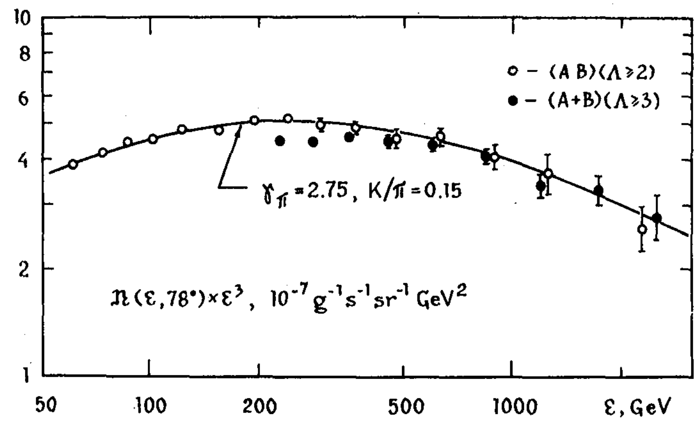

Fig.2

The experimental spectrum of cascade shower generation in iron is presented in Fig.2 for two selection criteria discussed in the previous section. Error bars indicated in the figure are statistical only. The systematic uncertainties may reach $\simeq$15%. The best-fit value of the pion generation spectrum index is 2.75+0.02 in the shower energy interval 50 GeV $\le \mathcal{E} \le$ 2 TeV for the events selected according to (AB)(Λ≥2) criterion, and 2.68+0.03 for (A+B)(Λ≥3)selection in the range 200 GeV$\le\mathcal{E}\le$3 TeV. Effective muon energy range covered by this experiment is approximately from 150 GeV to 5 TeV.

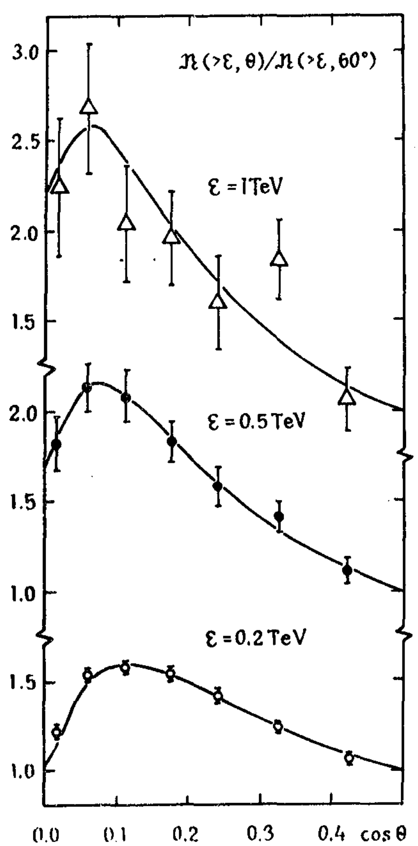

Fig.3

Angular distributions of cascade showers initiated by muons are given in Fig.3. The theoretical curves are calculated with γ_π= 2.70 and K/π = 0.15 and normalized to the experimental data. The agreement of the observed distributions with the theoretical prediction is excellent.

Cascade shower intesity above a certain energy $\mathcal{E}_o$ may be converted into absolute muon intensity above muon energy E_o. With an appropriate choice of the relation between $\mathcal{E}_o$ and E_o, the estimated muon intensity does not strongly depend on the spectrum model and relies mainly upon the electromagnetic interaction cross sections used in the conversion. Absolute muon intensities above 1 TeV at large zenith angles derived from the present experimental data are given in Fig.4 together with the recent magnetic spectrometer results. Errors quoted (except MUTRON point) are pure statistical. The systematic uncertainty of our data is of about 15% and is related mainly to the absolute normalization of shower energy measurements.

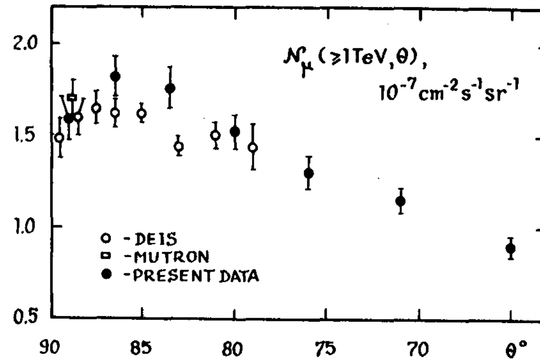

Fig.4

4. Conclusions. The energy spectrum of cascade showers initiated by cosmic ray muons and their angular distribution have been measured in a wide energy range with a good statistical accuracy. Both the spectrum and the angular distribution are fairly described by a conventional picture of muon generation in π- and K-decays with a single power index γ_π = 2.68 - 2.75 and K/π-ratio of 0.15 over the muon energy range from 150 GeV to 5 TeV. The absolute muon intensity at large zenith angles derived from the cascade shower intensity agrees with the recent magnetic spectrometer data and does not support the hypothesis of the additional muon interaction around 1 TeV muon energies.

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