Lateral distribution function of high energy muons in EAS around the knee

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The lateral distribution function of high energy muons in EAS around the knee ($5.9 \leq \lg N_e < 7.1$) has been measured for near vertical showers ($\theta \leq 20^\circ$, effective muon threshold energy is 230 GeV). The measurements have been performed at the Baksan Underground Scintillation Telescope (BUST). The electromagnetic component is measured by the "Andyrchy" EAS array, located above the BUST. The knee in EAS size spectrum is found to be at $\lg N_e \approx 6.3$. The experimental results are compared with Monte Carlo simulations.

1. Introduction

Measuring the lateral distribution function of high energy muons and its dependence on the shower size provides additional information for studying the mass composition of the primary cosmic radiation as well as for choosing a model of high energy hadron interactions. In this work we present results of measurements of the muon lateral distribution functions in EAS for the following three regions around the knee: $5.9 \leq \lg N_e < 6.3$, $6.3 \leq \lg N_e < 6.5$ and $6.5 \leq \lg N_e \leq 7.1$ (the muon energy threshold is 230 GeV). The measurements have been performed using the facilities of the Baksan Neutrino Observatory: the BUST and the "Andyrchy" EAS array \cite{12}. The live data taking time is 24460.8 hours. The knee position in the EAS spectrum corresponding to the considered zenith angles $\theta \leq 10^\circ$ is found to be at $\lg N_e \approx 6.3$. We have also simulated the development of EAS in the Earth atmosphere by means of the CORSIKA package (version 6720). As the high and low energy hadronic interaction models we used QGSJET 01C and GHEISHA 2002d, respectively \cite{3}. The simulations have been carried out for primary protons and iron nuclei and the obtained muon lateral distribution function is compared with the experimental one.

2. Experiment

The "Andyrchy" EAS array is located on the slope of the mountain Andyrchy above the BUST and consists of 37 plastic scintillation detectors of 1 m$^2$ area each. The distance between the detectors is about 40 m in projection to the horizontal plane and the overall area of the installation is $4.5 \cdot 10^4$ m$^2$. The detectors are arranged in such a way that the central one is just above the BUST at a vertical distance of about 360 m which corresponds to 2060 m above the sea level. The shower trigger condition requires four detectors to fire within 3 microseconds. The trigger's rate is about 9 s$^{-1}$. The array and its characteristics are described in more details in \cite{4}.

The BUST is a four-floor building with $16.1 \times 16.1 \times 11.2$ dimensions located in a mine at the effective depth 850 kg/cm$^2$. The floors as well as the four vertical sides of the building are fully covered with 3150 liquid scintillation detectors. Each of the detectors has the dimensions $(0.7 \times 0.7 \times 0.3)$ m$^3$. The telescope allows to determine the number of the passing muons (1 - 200), their coordinates (with 0.7 m accuracy) and the arrival direction (with 1.5 degree accuracy). The coincidence trigger rate of the BUST and "Andyrchy" is about 0.1 s$^{-1}$.

The size, axis position and the EAS arrival di-
rection are determined using the "Andyrchy" array data; the BUST data are used to determine the number of muons crossing it. In the present analysis, only the showers with axes in central part of the installation (the distance from the center is not larger than 50 m) and with $5.9 \leq \lg N_e \leq 7.1$ were taken into account. The accuracy of the determination of $N_e$ for such showers is not worse than 12%. For more details on identification of EAS parameters at the "Andyrchy" detector array see, for example, [5,6,7].

3. The fraction of muons in the telescope

The underground telescope measures only a part of the total number of muons in EAS and the uncertainty in the determination of the EAS axis position at the observation level is comparable with the size of the BUST. In our experiment the fraction of muons in the telescope $\Delta(R)$ was measured as a function of the distance $R$ between the center of the telescope and the EAS axis for a set of showers with a given value of $N_e$ [5]. This fraction for a given range of $N_e$ is defined by

$$\Delta(R) = \frac{\bar{N}(R)}{\bar{N}_\mu(N_e)},$$  \hspace{1cm}(1)$$

where $\bar{N}(R)$ is the mean number of muons in the telescope at the distance $R$, $\bar{N}_\mu(N_e)$ is the mean number of muons in EAS. The mean number of muons in the BUST is determined as follows. Events within a given range of $N_e$ are grouped according to the distance to BUST center with step $\delta R = 10$ m. For each group, the number of muons is

$$M(R_i) = \sum_{j=1}^{K_i} m_{ij}$$  \hspace{1cm}(2)$$

where $K_i = K(R_i)$ is the number of EAS in the $i$-th group, and $m_{ij}$ is the total number of muons in the BUST in the $i$-th group for the $j$-th EAS.

Thus, the mean number of muons for a given range of $N_e$ can be written as

$$\bar{N}(R_i) = \frac{M(R_i)}{K_i} = \frac{1}{K_i} \sum_{j=1}^{K_i} m_{ij},$$  \hspace{1cm}(3)$$

The mean number of muons in a shower is then calculated as

$$\bar{N}_\mu = \frac{1}{S_t} \sum_i \bar{N}(R_i) \cdot S_r(R_i),$$  \hspace{1cm}(4)$$

where $S_t = 200$ m$^2$ is the effective area of the telescope, $S_r(R_i)$ is the area of the ring of radius $R_i$ with $\delta R = 10$ m.

We have mentioned above that the fraction of muons with $E_\mu \geq 230$ GeV in the telescope as a function of $R$ was obtained for the following three energy ranges about the knee in the EAS spectrum. For the first one, before the knee $5.9 \leq \lg N_e < 6.3$ (lg$\bar{N}_e = 6.1$), the mean number of muons in a shower is $\bar{N}_\mu = 100 \pm 2$; for $6.3 \leq \lg N_e < 6.5$ (lg$\bar{N}_e = 6.4$), this is $\bar{N}_\mu = 184 \pm 9$; and for $6.5 \leq \lg N_e \leq 7.1$ (lg$\bar{N}_e = 6.7$) $\bar{N}_\mu = 334 \pm 19$. The experimentally measured dependence $\Delta(R)$ for $5.9 \leq \lg N_e < 6.3$ is shown in Fig. 1 as black dots.

![Figure 1. The mean number of muons in the telescope as a function of the distance R between the center of the telescope and the shower axis for showers with $5.9 \leq \lg N_e < 6.3$. The experimental measurements are depicted by the dots. The curves correspond to the calculations with $r_0 = 4.6$ m using equation 3 and for $\sigma_R = 0$ m (curve 1) and $\sigma_R = 12$ m (curve 2).]
4. The muon lateral distribution function

The fraction of muons in the telescope $\Delta(R)$ depends only on the muon lateral distribution function $f(r)$ and the geometry of the installation. For distances much larger than the typical size of the installation ($R \gg \sqrt{S_t}$), the fraction of muons is $\Delta(R) \approx S_t \cdot f(R)$. In the analysis of the experimental data, the following form of the function was used

$$f(r) \sim \left( \frac{r}{r_0} \right)^{a + b \cdot \left( \frac{r}{r_0} \right)^c},$$

which, according to the BUST data on the muon groups, sufficiently reproduces the lateral distribution of high energy muons with the threshold energy-dependent parameter $r_0$, when $a = 0.58$, $b = 0.64$, $c = 0.47$ [10,11]. The same function fits the lateral distribution of muons with the threshold energy 230 GeV in the simulated showers as well. However, in order to keep the good agreement at the primary energies above $10^5$ GeV per nucleon, one has to change the values of the parameters to: $a = 0.65$, $b = 0.72$, $c = 0.4$, while $r_0$ depends only on the primary energy per nucleon.

The calculation of $\Delta(R)$ has been performed by the Monte Carlo method for a few values of $r_0$ with taking into account the uncertainty in determination of the shower axis which, at the BUST level, is $\sigma_R \approx 12$ m (the main contribution is from the determination of the EAS arrival direction due to the large distance between the installations).

In Fig. 1 we show the experimentally measured $\Delta(R)$ for $5.9 \leq \lg N_e < 6.3$ in comparison with the calculations at $r_0 = 4.6$ m for two values of $\sigma_R$: 0 m (no uncertainty in the determination of the arrival direction) and 12 m. This comparison gives the value of $r_0$ for each of the ranges of $N_e$ (Fig. 2): for $\lg N_e = 6.1$ $r_0 = 4.6 \pm 0.5$ m, for $\lg N_e = 6.4$ $r_0 = 4.0 \pm 0.8$ m and for $\lg N_e = 6.7$ $r_0 = 3.9 \pm 0.5$ m.

The dependence of the experimental values of $r_0$ on $\lg N_e$ in comparison with the corresponding calculations for protons and iron nuclei is displayed in Fig. 2. In this case the mean values of $N_e$ are taken as the means for every fixed primary energy, without taking fluctuations and the form of the primary spectrum into account.

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