Investigation of the energy characteristics of EAS muon component with the NEVOD-DECOR setup

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Abstract. Investigations of the energy characteristics of muon component with the increase of the primary cosmic rays energy can be a key to solving 'muon puzzle' – the problem of excess of EAS muons (observed in several experiments at high – ALEPH, DELPHI – and ultrahigh energies – DECOR, Pierre Auger Observatory) in comparison with the expected flux. The measurements results of the energy deposit of inclined muon bundles in water depending on the zenith angle and the local density of muons are presented. As a measure of the energy deposit, the total number of photoelectrons registered by PMTs of the Cherenkov water calorimeter NEVOD was used. The local density of muons, which gives an estimate of the energy of primary particles was obtained from the data of coordinate-tracking detector DECOR. The experimental data are compared with the results of calculations based on simulations of the muon component of EAS by means of the CORSIKA code.

1. Introduction

The studies of the muon component of extensive air showers (EAS) are of particular interest because its characteristics are closely associated with both the energy spectrum, mass composition of primary cosmic rays (on the one hand) and the properties of nucleus-nucleus interactions (on the other hand). If the increase of the EAS muons number with the rise of the primary particles energy is usually explained in terms of the heavier mass composition of primary cosmic rays, the appearance of very high energy muons should testify in favor of the inclusion of new physical processes (new state of matter). One of the possible approaches to search very high energy muons (and to validate the existing hadron interaction models) is the measurement of the muon component energy deposit in the detector material depending on the primary particle energy [1], since total muon energy loss almost linearly depends on muon energy: $dE_{\mu}/dX \sim a + bE_{\mu}$.

Such studies are currently being conducted in the NEVOD-DECOR experiment on registration of inclined muon bundles. Cherenkov water detector (CWD) NEVOD measures the energy deposit of muons, and coordinate-tracking detector DECOR measures the number of muons and their direction. It is important to note that the earlier developed new method of EAS investigations by local muon density spectra (LMDS) [2] allows to estimate the energy of the primary particles according to the DECOR data. The point is that, though the contribution the events with a fixed local density is given by the showers with different primary energies detected at different (random) distances from the shower axis, due to a fast decrease in the cosmic ray flux with the increase in energy the effective interval of primary particle energies is relatively narrow.

2. Experimental complex (setup)

Experimental complex NEVOD-DECOR includes Cherenkov water detector NEVOD [3,4] with volume 2000 m^3 and coordinate-tracking detector DECOR [5] with total area 70 m^2.

The detecting system of the NEVOD detector is formed by a spatial lattice, in the knots of which 91 quasi-spherical optical modules (QSMs) registering the Cherenkov radiation from any direction with practically the same efficiency are located. The distances between the modules are 2.5 m along the detector and 2 m across it and over the depth. Each QSM consists of 6 low-noise FEU-200 photomultipliers with flat 15 cm diameter photocathodes directed along rectangular coordinate axes. The use of 2-dynode signal readout from PMT provides a wide dynamic range of the measurements ($1 - 10^5$ photoelectrons) and allows to carry out calorimetric studies, in particular, to investigate the energy characteristics of EAS muon component.

The DECOR setup represents a modular multilayer system of plastic streamer tube chambers – 8 vertical assemblies (supermodules, SMs) arranged in the galleries of the building from three sides of the water calorimeter NEVOD. Each SM has an effective area 8.4 m^2 and consists of 8 planes of streamer tube chambers with resistive cathode coating, the planes are equipped with a two-coordinate external strip readout system. Spatial and angular accuracy of the muon track location in the supermodule is better than 1 cm and 1°, respectively.

Selection of events by the triggering system is based on coincidences between the signals from DECOR supermodules. An example of a muon bundle event registered in the NEVOD-DECOR setup and the main parts of the experimental complex are shown in figure 1.

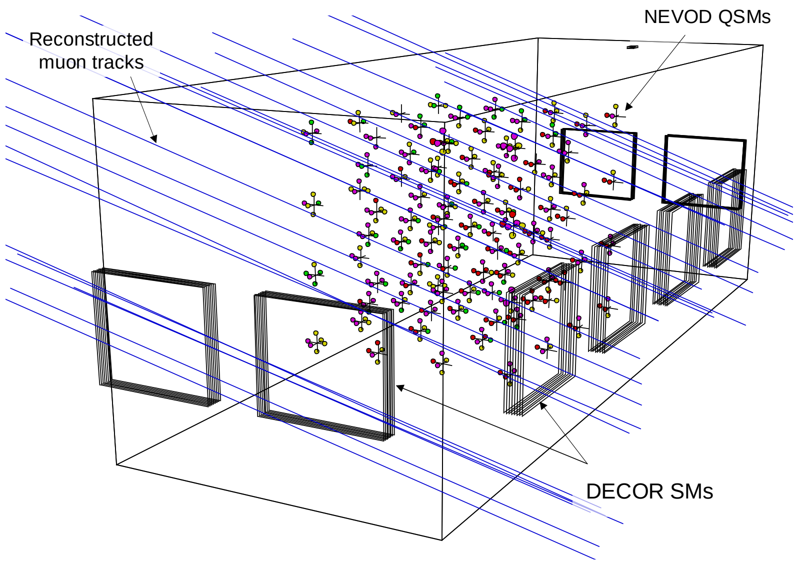

Figure 1. An example of the muon bundle event in the NEVOD-DECOR complex.

3. Experimental data

In the present work, data of two long series of measurements: from May 2012 to March 2013 and from July 2013 to April 2015 with inclined muon bundles detected by the experimental complex NEVOD-DECOR have been analyzed. Total live observation time is equal to 17439 h. In these data, 29335 events with muon multiplicity $m \geq 5$ and zenith angles $\theta \geq 55^{\circ}$ were found. Additionally, from the first part of the experimental material (for 3253 h) muon bundles arriving at lower zenith angles were selected ($40^{\circ} \leq \theta < 55^{\circ}$, 15084 events). Multi-muon events were selected in two 60°-wide sectors of azimuth angle, where most of DECOR SMs (six of eight) were screened with the CWD volume. Average threshold muon energy for such selection criteria is close to 2 GeV.

The local density of muons D in the events was estimated from the DECOR detector data. Taking into account the spectrum slope and Poisson fluctuations of the number of muons that hit the setup, it was calculated as: $D = (m - \beta)/S$, where m is muon multiplicity, S is the total area of six DECOR SMs for a given direction, and $\beta \approx 2.1$ is the integral slope of the LMDS in the considered muon density and zenith angle region [2].

As a measure of the muon bundle energy deposit in the CWD, the sum of the all PMTs signals (ΣN_{pe}, in photoelectrons) of the NEVOD detector was used. It was assumed that the number of Cherenkov photons, which are generated as a result of the muons passage through water calorimeter, is approximately proportional to the total muon energy loss in the detector material. In the first approximation, the total energy deposit in the CWD is nearly proportional to the local muon density, therefore in the further analysis we use the specific energy deposit $\Sigma N_{pe}/D$ (i.e., the CWD response normalized to the muon density in the event).

4. Results of data analysis

The measured dependence of the average specific energy deposit on the zenith angle is presented by the points in figure 2. At moderate zenith angles (40 − 55°), rapid decrease of the measured energy deposit can be explained as an atmospheric suppression of the residual contribution of electromagnetic and hadron EAS components. At large zenith angles ($\theta > 60^{\circ}$) practically only the muon component is detected on the ground level and the average specific energy deposit increases with the zenith angle, thus reflecting the increase of the mean muon energy in the bundles: from 150 GeV at $\theta = 60^{\circ}$ to 500 GeV at $\theta = 85^{\circ}$. The solid curves in the figure represent the results of calculations of the expected dependence of the specific energy deposit for muon bundles, obtained by simulating the EAS muon component by means of the CORSIKA code (v.7.40) [6] for primary protons and iron nuclei; the combination of SIBYLL-2.1 and FLUKA2011 hadron interaction models was used. On the basis of the modeled showers, two-dimensional lateral distribution functions (LDF) of muons were constructed, and the mean energies of muons in the bundles, taking into account the features of the LMDS technique [2], were found. The specific energy loss was calculated for the mean energy of muons in the bundles as the sum of ionization and radiation loss (bremsstrahlung, pair production and photonuclear interactions) by means of interpolation of tabulated data [7]. Finally, the calculated dependence was normalized to the experimental data on the number of photoelectrons at the zenith angle of 60°. As seen from the figure, the experimental dependence is in satisfactory agreement with the expectation.

In figure 3, the experimental values of the average specific CWD response for muon bundles detected at zenith angles $\theta \geq 55^{\circ}$ (where the residual contribution of EAS components is small) are presented as a function of the muon density. In fact (for a fixed range of zenith angles), this is a measurement of the dependence of the energy deposit on the energy of primary particles. Arrows in the bottom part of the figure indicate typical (mean logarithmic) energies of primary particles which give the contribution to the formation of the events with corresponding values of muon density. The curves in the figure represent the expected dependence of the energy deposit on the local muon density, calculated on the basis of simulations with CORSIKA for 60° zenith angle. The same calibration coefficient as in figure 2 was applied in order to normalize calculated results to the data. Results of simulations demonstrate a trend to a decrease of the mean muon energy in the bundles with the increase of the primary particle energy. On the contrary, the data exhibit a hint to some increase of the energy deposit at densities of muons greater than 1 particle/m^2 (effective primary energies of 10^{17} eV and above). The reasons for these deviations may be both of physical and methodical origin, therefore, a detailed analysis of experimental procedure and calculation results as well as the increase in the statistics will be continued.

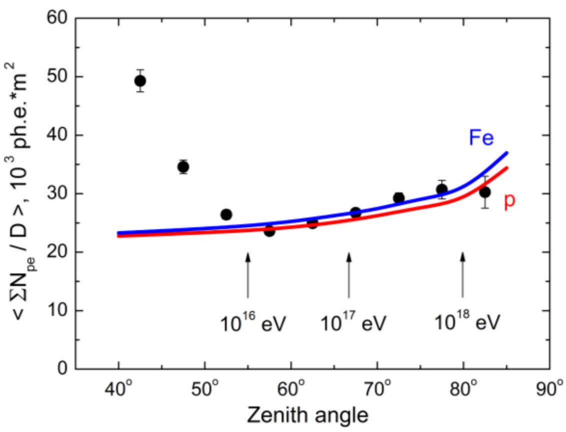

Figure 2. Dependence of the average specific energy deposit of muon bundles in the Cherenkov water detector on zenith angle. Points are measurement results, curves represent the expected dependencies obtained from CORSIKA-based simulations.

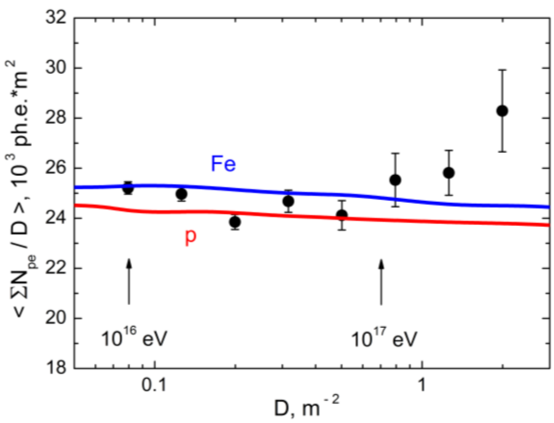

Figure 3. Dependence of the average specific energy deposit on the local muon density. Arrows indicate typical energies of primary particles. Points are measurement results, curves represent the expected dependencies obtained from CORSIKA-based simulations.

5. Conclusion

The experiment on the investigation of the energy characteristics of inclined muon bundles formed as a result of interactions of primary cosmic ray particles with energies 10^{16} – 10^{18} eV is being conducted at the Experimental Complex NEVOD. The results of the measurements of zenith-angular dependence of the average specific energy deposit in the Cherenkov water detector are in a reasonable agreement with CORSIKA-based simulations of the EAS muon component and confirm the increase of the mean energy of muons in the bundles at large zenith angles. An indication for an increase of the average specific energy deposit compared to the expectation at primary energies above 10^{17} eV has been found. However, further increase of experimental statistics and a careful analysis of possible systematic effects are necessary.

Acknowledgments

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