Measurements of the energy deposit of inclined muon bundles in the CWD NEVOD

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Measurements of the energy deposit of inclined muon bundles in the CWD NEVOD

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Abstract. First results of investigations of the energy deposits of inclined muon bundles in the ground-based Cherenkov water detector NEVOD are presented. As a measure of the muon bundle energy deposit, the total number of photoelectrons detected by PMTs of the Cherenkov calorimeter is used. For each event, the local muon density at the observation point and the muon bundle arrival direction are estimated from the data of the coordinate-tracking detector DECOR. Registration of the bundles in a wide range of zenith angles allows to explore the interval of primary particle energies from ~ 10^{16} to ~ 10^{18} eV. Measurement results are compared with CORSIKA based simulations of EAS muon component. It is found that the mean energy of muons detected in the bundles rapidly increases with the zenith angle and reaches about 500 GeV near the horizon.

1. Introduction

In a number of cosmic ray experiments conducted at ultra-high energies of primary particles, an excess of multi-muon events (intensity of muon bundles, muon abundance in EAS) compared to simulations performed with widely used hadron interaction models is observed [1 – 4]. In principle, this excess may be caused by cosmo-physical (changes in the mass composition of primary cosmic rays with the increase of energy) or by nuclear-physical reasons (changes in characteristics of interactions of primary cosmic ray nuclei with the nuclei of air atoms). However, at energies of the order of 10^{18} eV and above, the excess of multi-muon events does not find its explanation in the frame of the existing interaction models even under the assumption of extremely heavy (iron nuclei) primary composition [3 – 5]. Therefore it seems that the contemporary models of the development of the nuclear cascade in the atmosphere have to be revised. The key to the solution of this problem, often referred to as 'the muon puzzle', may come from investigations of the energy characteristics of the EAS muon component and of their variations with primary energy [6].

One of the possible approaches to such investigations is the measurement of the energy deposit in the detector material at the passage of muon bundles. Average specific energy loss of muons almost linearly depends on their energy, and an appearance of an excessive flux of high-energy muons in the bundles has to be reflected in the dependence of the average energy deposit on the energy of primary particles. An experiment on the study of the energy deposit of muon bundles has been started at the NEVOD-DECOR complex in 2012. The complex includes a large-volume Cherenkov water calorimeter [7, 8] and coordinate-tracking detector [9] which ensures reliable identification of multi-muon events. The detection of muon bundles of different multiplicities at various zenith angles gives possibility to explore a very wide range of primary particle energies, from the knee region to few EeV, within a single experiment. The results of the measurements of the average energy deposit of inclined muon bundles obtained during first experimental series and their comparison with CORSIKA based simulations of muon energy characteristics are presented below.

2. Experimental data

The measuring system of the Cherenkov water detector (CWD) NEVOD with the inner volume 9×9×26 m^3 represents a spatial lattice of quasi-spherical optical modules (QSMs) [7]. Each QSM includes six FEU-200 PMTs with flat 15 cm diameter photocathodes directed along rectangular coordinate axes. In total, the measuring system contains 91 QSMs (546 PMTs) arranged in vertical strings with spacing of 2.5 m along the water tank, and 2.0 m across it and over the depth. After a recent modernization [8], the electronics system ensures measurements of PMT signals in a wide dynamic range (from 1 to 10^5 photoelectrons for each PMT) that provides the possibility of calorimetric studies of high-energy cascade showers and muon bundle energy deposits. The coordinate-tracking detector DECOR is specially designed for investigating multi-particle events at large zenith angles and includes 8 supermodules (SMs) deployed in the galleries of the NEVOD building from three sides of the water tank. The sensitive area of each SM is 8.4 m^2. SMs consist of 8 vertical planes of plastic streamer tube chambers and provide spatial and angular accuracies of the muon track localization better than 1 cm and 1° respectively. An example of the muon bundle event detected in the NEVOD-DECOR complex is shown in figure 1.

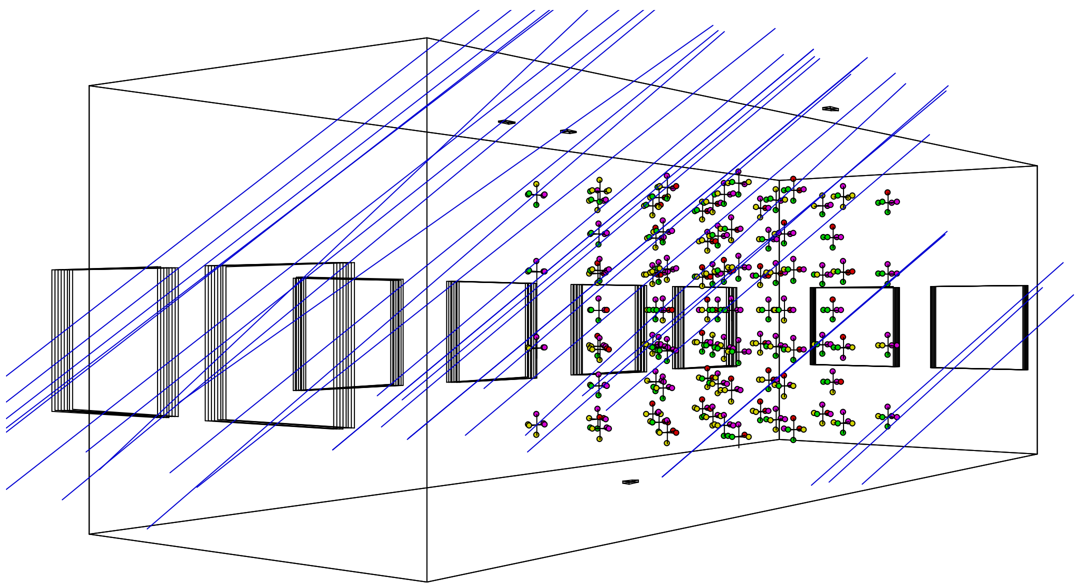

Figure 1. An example of the muon bundle event in the NEVOD-DECOR complex. Thin lines represent reconstructed muon tracks. Circles show hit PMTs of the CWD; big rectangles around CWD are DECOR supermodules; small rectangles on the top and on the bottom are triggered scintillation counters of the calibration telescope system.

In the present analysis, data of two first series of measurements – from May 2012 to March 2013 and from July 2013 to February 2014 – are used. Total 'live' observation time amounted to 9673 h. From these data, we selected 16416 muon bundle events with multiplicities $m \geq 5$, zenith angles $\theta \geq 55°$, in two 60º-wide sectors of azimuth angle where most of DECOR SMs (six of eight) were screened with the NEVOD water volume; data of these six shielded SMs being used for muon track counting. The average threshold muon energy for such selection criteria is about 2 GeV. In addition, from the initial part of the experimental material (for 3253 h observations) the bundles with lower zenith angles (40º ≤ θ < 55º, 15084 events) were selected. As a measure of the muon bundle energy deposit we use the sum Σ of all hit CWD PMT signals (in units of photoelectrons, ph.e.). The local muon density *D* in the event is estimated from the measured bundle multiplicity *m* with the allowance for the effective detector area S_{det} for the given arrival direction of the bundle. However, a straightforward calculation of the density as $D = m / S_{\text{det}}$ would lead to a bias, especially serious at moderate multiplicities, because of statistical fluctuations of the number of detected particles in combination with a rapidly decreasing spectrum of the events in the muon density: $dF / dD = A \times D^{-(\beta+1)}$, where $\beta \approx 2.1$ is the integral density spectrum slope in a considered range of densities and zenith angles [3]. Assuming that *at a fixed density* the number of particles that hit the detector obeys the Poisson distribution with the mean value $< m > = D \times S_{\text{det}}$, the mean value of density in the events contributing to the formation of muon bundles with *a fixed multiplicity* may be easily found analytically (see section 4 of [3]):

$$< D > = (m - \beta) / S_{\text{det}} . \qquad (1)$$

Further, we use the estimate of the muon density defined by this equation.

3. Results and discussion

The correlation of the measured energy deposit with the muon density estimate for a limited sample of the events with zenith angles θ ≥ 60º is shown in figure 2. As it might be expected, in a first approximation the total energy deposit in the CWD is nearly proportional to the muon density (the solid line in the figure), therefore further we analyze the specific energy deposit Σ / D, i.e. the CWD response normalized to the muon density in the event.

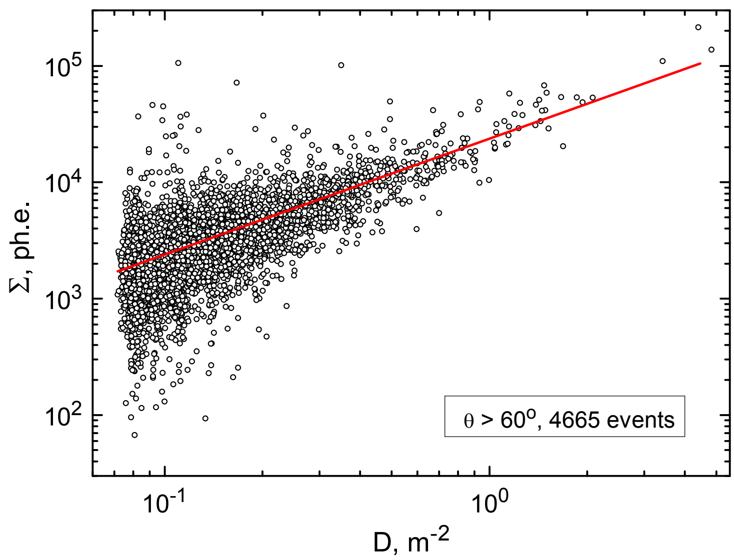

Figure 2. The correlation of the muon density estimate and the measured energy deposit.

Results of the measurements of the dependence of the average specific energy deposit on the zenith angle are presented by circles in figure 3. Arrows in the lower part of the figure indicate typical energies of primary particles (calculated mean-logarithmic values) that contribute to the formation of muon bundles at various angles. At moderate zenith angles (θ < 55º, open circles in the figure), a rapid decrease of the measured energy deposit with the increase of zenith angle is observed. It can be interpreted as a decreasing residual contribution of EAS electromagnetic and hadron components to the response of an unscreened detector located on the Earth's surface. In this angular range, the measured dependence is well approximated by the negative exponent of the atmosphere thickness (the dashed curve in the figure):

$$< \Sigma / D > \sim \exp(-X_0 \sec\theta / \Lambda) + \text{const}\,, \qquad (2)$$

where X_0 = 1014 g/cm^2 is the average vertical thickness of the atmosphere layer above the setup at the observation point, Λ = (134 ± 15) g/cm^2 is the attenuation length which is close to the known value of cosmic ray nucleon component absorption path in the atmosphere.

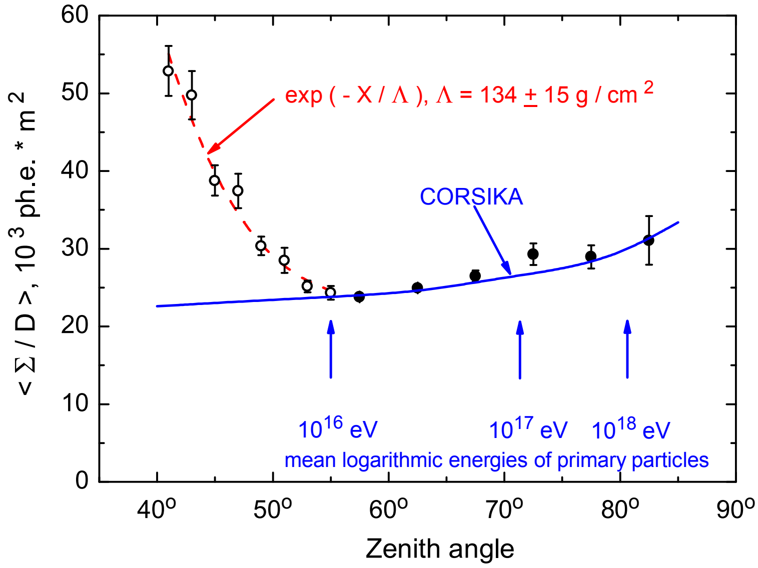

Figure 3. Dependence of the average specific energy deposit of muon bundles in the CWD on the zenith angle. Points are measurement results. Dashed curve is the exponential fit (2) of the data in the range of zenith angles less than 55º; solid curve represents the expected dependence obtained from CORSIKA-based simulations.

At detection of muon bundles with zenith angles more than 55º, practically pure muon component remains. As seen from the figure, the data (solid circles) show a growth of the average specific energy deposit in this angular range, thus indicating an increase of the average muon energy in the bundles. The solid curve in figure 3 represents the expected dependence of the energy deposit of muon bundles obtained on the basis of EAS muon component simulations for primary protons with the CORSIKA code [10]. We used the combination of hadron interaction models SIBYLL + FLUKA for hadron energies more than 80 GeV and below this value, respectively. Influence of the geomagnetic field at the setup location was taken into account. Simulations were performed for a set of fixed zenith angles from 40º to 85º and fixed primary energies E_0 from 10^{15} to 10^{19} eV. The number of simulated EAS varied from 1000 at moderate primary energies to 100 showers at maximal energies. The electron-photon component was not considered, that allowed simulating muon component using full Monte-Carlo (without thinning) with reasonable computer resources. Using the simulated showers, the average lateral distribution functions $\rho(E_0, \mathbf{r})$ for muons with energies more than 2 GeV were constructed. In calculating the mean muon energy in the events selected by muon density (that corresponds to the selection of muon bundles in an experiment with a small area detector), individual muons were taken with a weight proportional to $[\rho(E_0, \mathbf{r})]^{\beta-1}$. Physically, this weight allows taking into consideration that the higher particle density at a given point of the EAS cross section, the higher the frequency of the appearance of these muons in the selected events (for more details, see ref. [3]). The calculated value of the mean muon energy in the bundles rapidly increases at large zenith angles and reaches about 500 GeV near the horizon. The expected zenith-angular dependence of the average specific energy deposit of muon bundles in the CWD (the curve in the figure) was calculated in a following way. First, for each zenith angle the mean muon energy loss <*dE/dX*> was calculated using the energy loss tables [11]. Further, we made an assumption that the total Cherenkov light yield in the calorimeter is proportional to the muon energy loss. Finally, the absolute value of the proportionality coefficient was obtained from the normalization of calculated dependence to the experimental values near 60º zenith angle. The measured dependence of the average specific energy deposit on the zenith angle confirms the increase of the mean muon energy and is in a general agreement with CORSIKA-based expectation, with a possible exception of the point between 70 and 75º, which corresponds to effective energies of primary particles ~ 10^{17} eV.

In order to check whether the observed zenith angular dependence of the energy deposit might be imitated by the properties of the CWD detection system, we analyzed the measured average specific energy deposit as a function of the azimuth angle between the muon bundle arrival direction and the main axis of the NEVOD water tank (figure 4). As it is seen from the figure, the data exhibit a very good uniformity of the detector response for various azimuth angles; thus, a non-ideally isotropic structure of the CWD QSM lattice does not distort the results of measurements of the angular dependence of the energy deposit.

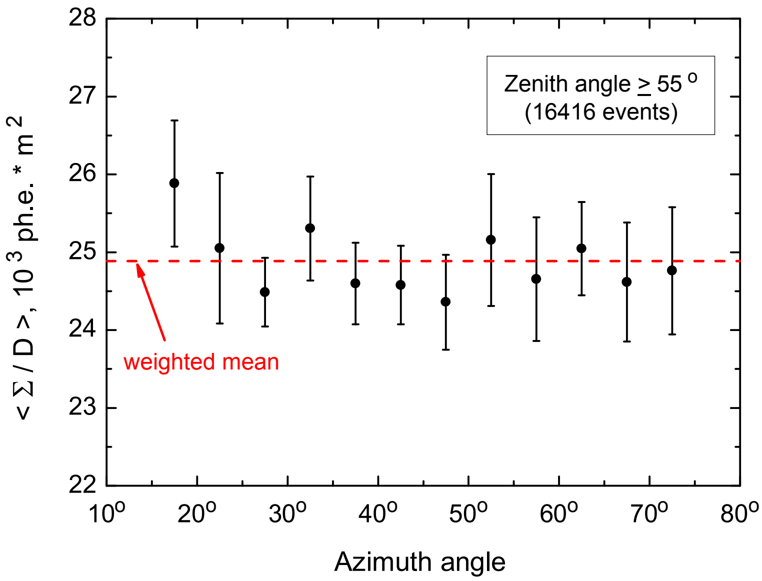

Figure 4. The dependence of the measured average specific energy deposit on the azimuth angle.

In figure 5, the experimental values of the average specific CWD response for muon bundles are presented as a function of the local muon density. All selected events with zenith angles $\theta \geq 55º$, where the residual contribution of electron-photon and hadron components is small, are included in these data. In fact, such an analysis for a fixed interval of zenith angles allows us to follow possible changes of the detector response (and correspondingly, of the average muon energy in the bundles) on the primary energy. Arrows in the bottom part of the figure indicate typical (mean-logarithmic) energies of primary particles contributing to the events with corresponding values of the muon density. The curve in the figure represents the expected dependence of the energy deposit on the local muon density obtained from our CORSIKA-based calculations for the zenith angle of 60º; the same coefficient for normalizing data and calculations as in figure 3 was applied. For the moment, taking into account the statistical uncertainties, it seems too early to speak about any clear dependence of the muon bundle energy deposit on the energy of primary particles, though some indication for its increase beyond the expectation at energies above 10^{17} eV is seen (two last points in figure 5). Higher statistics is necessary for a more detailed consideration, in particular, for the analysis of the behaviour of the average energy deposit in different zenith-angular ranges.

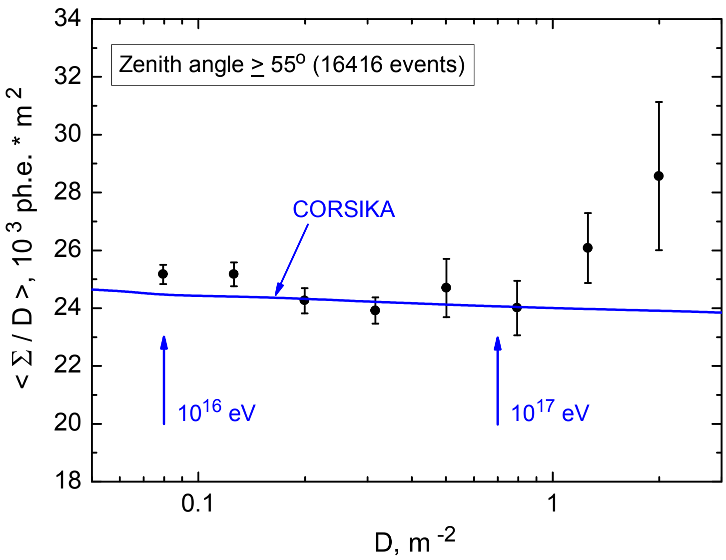

Figure 5. The dependence of the average specific energy deposit on the local muon density.

4. 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 NEVOD-DECOR complex. The aim of the experiment is the search of possible reasons of the appearance of the excessive flux of multi-muon events in ultra-high energy cosmic rays. First results of the measurements of the zenith-angular dependence of the average specific energy deposit of muon bundles in the Cherenkov water detector are in a reasonable agreement with CORSIKA-based simulations of EAS muon component and confirm the increase of the average energy of muons in the bundles from ~ 100 GeV at moderate zenith angles up to ~ 500 GeV near the horizon. A hint for an excess of the measured energy deposit compared to expectation at primary energies about 10^{17} eV is found; however, for the moment it is not statistically significant. If confirmed with a further increase of statistics, this deviation would be a good evidence for inclusion of a new mechanism of generation of high-energy muons at ultra-high energies of primary particles.

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