First results of the study of the energy deposit of inclined muon bundles in the Cherenkov water detector

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Abstract: In several UHECR experiments, an excess of muons in comparison with simulations performed in frame of the widely used hadron interaction models was found. In order to solve this puzzle, investigations of muon energy characteristics in EAS are required. An experiment on the measurement of the energy deposit of muon bundles in water has been started with the NEVOD-DECOR experimental complex. Experimental results based on about 20,000 muon bundles detected during first 3,250 h of the experiment are presented. It has been found that the average specific energy deposit in the Cherenkov calorimeter (normalized to the local muon density estimated from the coordinate detector data) only slightly depends on the muon density; however, an appreciable dependence on the zenith angle has been revealed.

Keywords: inclined EAS, muon component, energy deposit, Cherenkov water detector.

1 Introduction

In several UHECR experiments [1, 2, 3, 4], an excess of multi-muon events or single very-high-energy muons in comparison with simulations performed in frame of the widely used hadron interaction models was found, even under assumption of a heavy (pure iron) primary composition. In order to solve this puzzle, investigations of muon energy characteristics in EAS are required. An experiment on the measurement of the energy deposit of muon bundles in water has been started with the experimental complex NEVOD-DECOR. The complex includes the Cherenkov water calorimeter (2000 m^3 volume) equipped with a spatial lattice of quasi-spherical optical modules [5] and the large area (70 m^2) precise coordinate-tracking detector [6] composed of streamer tube chambers. First experimental results based on more than 20,000 muon bundle events with multiplicity ≥ 5 particles and zenith angles greater than 40° detected during about 3,250 h of the experiment are presented. Estimates show that such events correspond to effective primary energies in the range $10^{16} - 10^{18}$ eV. Dependences of the average energy deposit of the bundles in the calorimeter on the local muon density and zenith angle have been obtained and compared to preliminary Monte-Carlo simulations.

2 Experimental data

The detecting system of the Cherenkov water detector (CWD) NEVOD is formed by a spatial lattice of quasi-spherical optical modules (QSMs), each of them including 6 photomultipliers with flat 15 cm diameter cathodes directed along rectangular coordinate axes. In total, there are 91 QSMs (546 PMTs) arranged with distances 2.5 m along the water tank, and 2.0 m across it and over the depth. Recently, electronic system of the NEVOD was modernized [7], and now it provides a wide dynamic range (from 1 to $\sim 10^5$ ph.e. for each PMT), thus allowing the measurements of high-energy cascades and energy deposit of muon bundles in the CWD. Eight super-modules (SMs) of the coordinate detector DECOR are deployed in the galleries of the NEVOD building, from three sides of the water tank. The sensitive area of each SM is about 8.4 m^2; the structure of the SM consisting of 8 layers of streamer tube chambers with two-dimensional system of external readout strips provides the spatial and angular accuracy of muon track location about 1 cm and better than 1°, respectively. An example of a muon bundle event detected in NEVOD-DECOR is shown in figure 1.

An experiment on investigation of muon bundle energy deposit in Cherenkov water detector was started in 2012. During May – November 2012, data corresponding to 3250 h live measurement time were accumulated. Multi-muon events were selected in two sectors of azimuth angle, where most of DECOR SMs (six of eight) were screened with the CWD volume, data of these shielded SMs being used to reconstruct the geometry and to estimate local muon density. More details concerning the procedure of muon bundle selection from coordinate detector data may be found in [8]. In total, 20467 events with muon multiplicities $m \geq 5$ and zenith angles $\theta \geq 40°$ were selected.

As a measure of the muon energy deposit in the CWD, the sum of the signals Σ of all PMTs of the NEVOD detector (in photoelectrons, ph.e.) was used. The estimate of the muon density in the event, taking into account the bias due to a steep muon density spectrum [8], was obtained as

$$(m-\beta)/S_{\text{det}},$$

where S_{det} is the total area of six SMs for a given direction, and $\beta \approx 2.1$ is the integral slope of the local muon density distribution. Correlation of the total CWD response with the local muon density for a sample of the events with zenith angles $\theta \geq 60°$ is shown in figure 2.

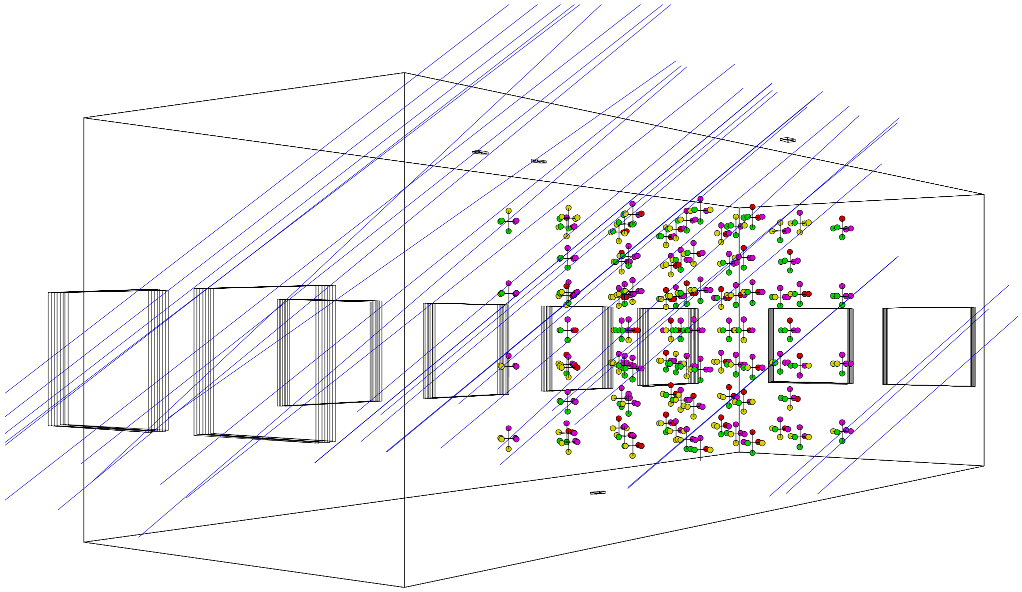

Figure 1: Example of muon bundle event detected in the NEVOD-DECOR complex. Thin lines: reconstruction of muon tracks from DECOR data; small circles: hit phototubes in Cherenkov water detector (colors reflect signal amplitudes).

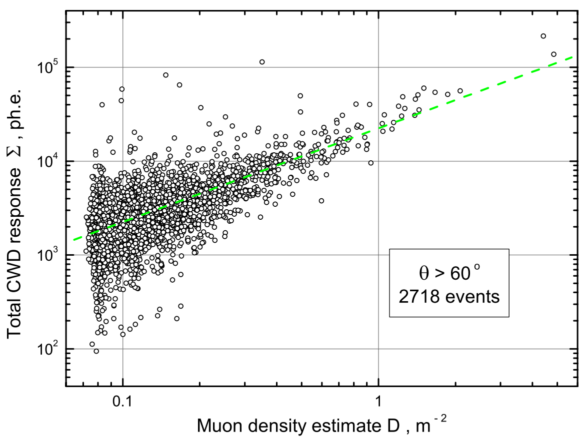

Figure 2: Correlation of the total CWD response with the local muon density estimate.

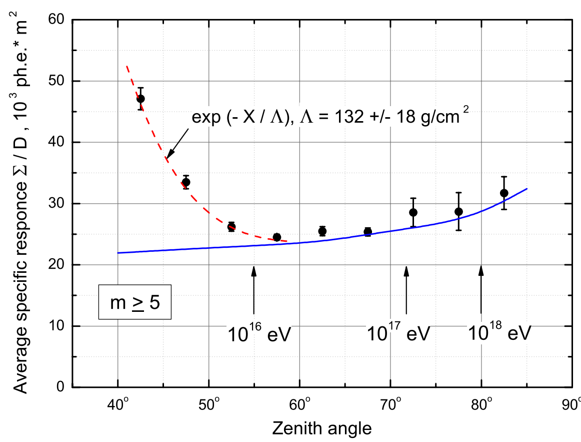

Figure 3: Zenith-angular dependence of the average specific CWD response for muon bundles.

In general, as it might be expected, the CWD response is nearly proportional to the local density of muons (the dashed line in the figure). Therefore in the further analysis we use the average specific CWD response $< \Sigma/D >$, i.e., the response normalized to the muon density estimate.

3 Average CWD response

The measured dependence of the average specific CWD response on the zenith angle is presented in figure 3. Arrows in the bottom part of the figure indicate typical (mean logarithmic) energies of primary particles. At moderate zenith angles $(40-55^\circ)$, the average response falls off rapidly which can be explained as an atmospheric suppression of the residual contribution of electromagnetic and hadron EAS components detected in the unscreened CWD along with the muons of the bundles. The zenith-angular dependence in this range is well fitted by the exponential decay with the attenuation length $\Lambda = 132 \pm 18$ g/cm^2 (the dashed curve in the figure).

At larger angles $(\theta > 55^\circ)$, the average specific CWD response increases with θ, thus reflecting the increase of the average muon energy in the bundles at large zenith angles. The solid curve in the figure represents the results of preliminary calculations of the expected dependence for the muon bundles, obtained on the basis of the CORSIKA code [9]. Simulations were performed for combination of SIBYLL+FLUKA hadron interaction models and primary protons. The procedure of absolute mutual calibration of the calculated and measured CWD response is rather delicate; for the moment, we chose to simply normalize this curve to the data near 60°. Nevertheless, the relative increase of the response with the zenith angle is in a quite reasonable agreement with the expectation.

In order to check whether the measured angular dependence could be imitated by a not ideally isotropic structure of the NEVOD QSM lattice, we have analyzed the dependence of the specific CWD response on the azimuth angle between the muon bundle arrival direction and the longitudinal axis of the water tank (figure 4). Horizontal dashed

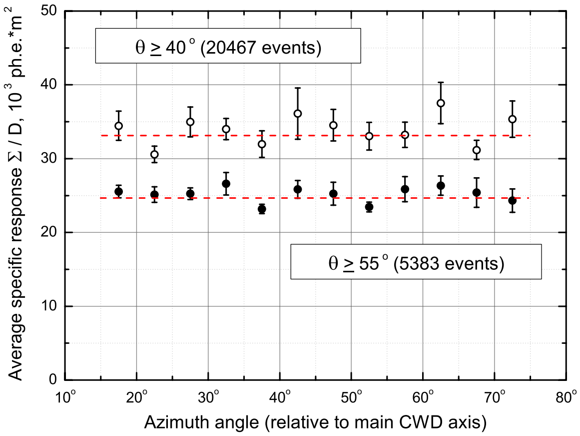

Figure 4: Dependence of the average specific CWD response on the azimuth angle.

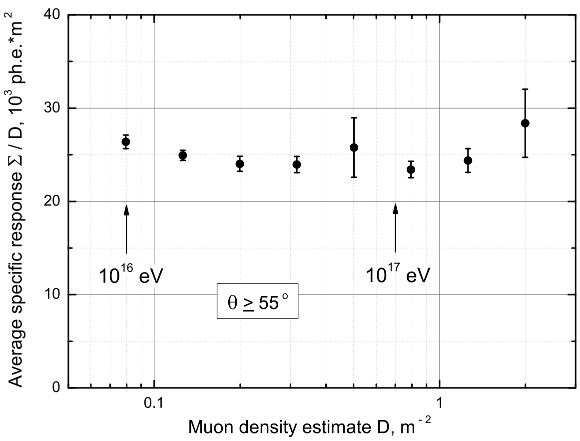

Figure 5: Average specific CWD response as a function of muon density (zenith angle range $\theta \geq 55^\circ$)

lines show weighted average values for two intervals of zenith angle. The data for two analyzed samples exhibit a good uniformity; thus, the structure of the measuring system does not distort the results of the angular dependence measurements.

In figure 5, 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 electromagnetic and hadron EAS components is small, see figure 3) are presented as a function of muon density. At present, within the measurement errors, no clear dependence of the response normalized to muon density is seen, at least for bulk data in a wide range of large zenith angles. A more refined analysis will be possible as higher experimental statistics will be accumulated.

4 Conclusion

An experiment on the measurements of inclined muon bundle energy deposit in the Cherenkov water detector has been started with the NEVOD-DECOR complex. A preliminary analysis of the first data accumulated during 3,250 h has been conducted. It has been found that the specific energy deposit (normalized to the local muon density measured with the coordinate detector) only slightly depends on the muon density; however, an appreciable dependence on the zenith angle has been revealed. This dependence is explained by the increase of the average energy of muons in the bundles at large zenith angles and is in a good agreement with expectation based on MC simulations. Accumulation of data and their further analysis are in progress.

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