Investigation of the energy deposit of inclined muon bundles in the Cherenkov water detector NEVOD

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Abstract. Results of investigations of the energy deposit 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 the wide range of zenith angles allows to explore the interval of primary particle energies from 10 PeV to 1 EeV. Measurement results are compared with CORSIKA based simulations of EAS muon component.

Introduction

In several cosmic ray experiments conducted at very- and ultra-high energies of primary particles, an excess of multi-muon events (the intensity of muon bundles - DECOR, muon content in EAS – Pierre Auger Observatory) in comparison with simulations performed with widely used hadron interaction models has been found. In principle, this excess may be caused as by cosmophysical (increasing abundance of heavy primary nuclei with the increase of energy) so by nuclear physical reasons (changes of characteristics of interaction of primary protons and nuclei with nuclei of air atoms). A key to the solution of this problem, often referred to as the "muon puzzle", may give investigations of the energy characteristics of the EAS muon component and of their change with the primary energy.

One of the possible approaches to such studies is the measurement of the energy deposit of muon bundles at their passage through the detector material. The specific energy loss of muons in matter almost linearly depends on the muon energy:

$$dE/dX \sim a + bE,$$

and the appearance of an excessive flux of high-energy muons in the bundles should lead to the change of the dependence of the average energy deposit ΔE_μ on the primary energy E_0 (Fig. 1).

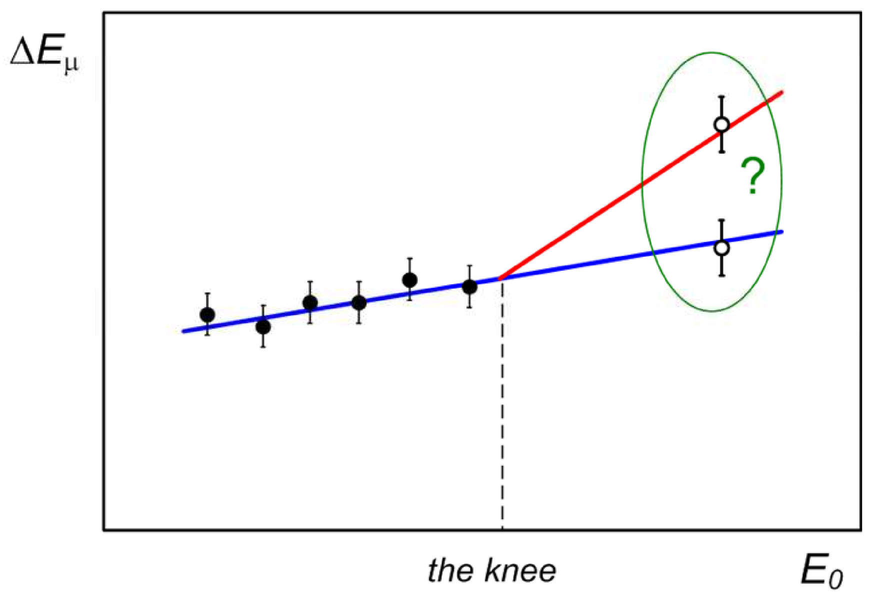

Fig. 1. Expected results of muon energy deposit measurements (a sketch).

Experimental complex NEVOD-DECOR

The experiment on the study of the energy deposit of the muon bundles was started at the Experimental complex NEVOD in 2012. The complex (Fig. 2) includes a large volume Cherenkov water calorimeter and the coordinate-tracking detector that provides a reliable identification of multi-muon events.

The measuring system of the Cherenkov water detector (CWD) NEVOD with the inner volume 9×9×26 m³ represents a spatial lattice of quasi-spherical modules (QSMs). Each QSM includes six FEU-200 PMTs with flat 15 cm diameter photocathodes directed along the axes of the orthogonal coordinate system. The measuring system contains 91 QSMs (546 PMTs) arranged in vertical strings (3 or 4 QSMs) with the distances 2.5 m along the water tank and 2.0 m across it and over the depth. After a recent modernization, the electronic system provides the measurements of PMT signals in a wide dynamic range (from 1 to 10^5 photoelectrons, ph.e.) for each PMT, thus ensuring possibilities of calorimetric studies of high energy cascade showers and muon bundles. The coordinate-tracking detector DECOR with a total area about 70 m² was specially designed for investigations of multi-particle events at large zenith angles. It 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 m². The supermodules consist of 8 vertical planes of plastic streamer tube chambers and ensure the spatial and angular accuracy of muon track localization better than 1 cm and 1°, respectively.

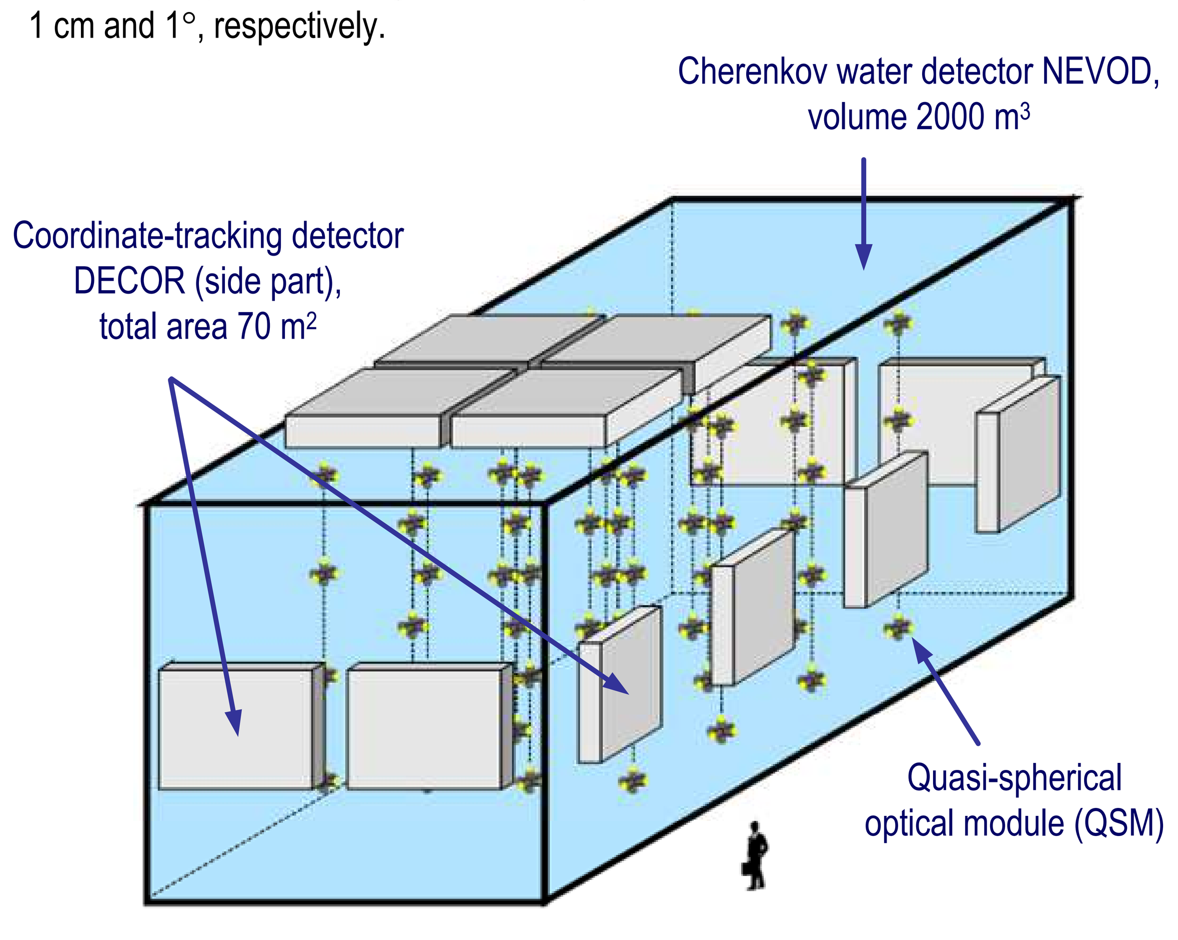

Fig. 2. General view of NEVOD-DECOR complex.

Experimental data

In the present analysis, data of two long-term measurement series are used: from May 2012 to March 2013 and from July 2013 to April 2015. Total live observation time is equal to 17439 h. In these data, 29335 events with muon bundles with muon multiplicity $m \geq 5$ and zenith angles $\theta \geq 55°$ were found. The events were selected in two 60°-wide sectors of azimuth angle where most of DECOR SMs (six of eight) were screened with the NEVOD water tank; data of these six shielded supermodules were used for muon track counting. Average threshold muon energy for such selection criteria is close to 2 GeV. Additionally, from the initial part of the experimental material (for 3253 h) muon bundles arriving at lower zenith angles were selected ($40° \leq \theta < 55°$, 15084 events).

An example of the event with the muon bundle detected in the NEVOD-DECOR setup is presented in Fig. 3. Detection of muon bundles of various multiplicities in a wide range of zenith angles gives the possibility to explore a wide interval of primary particle energies in frame of a single experiment.

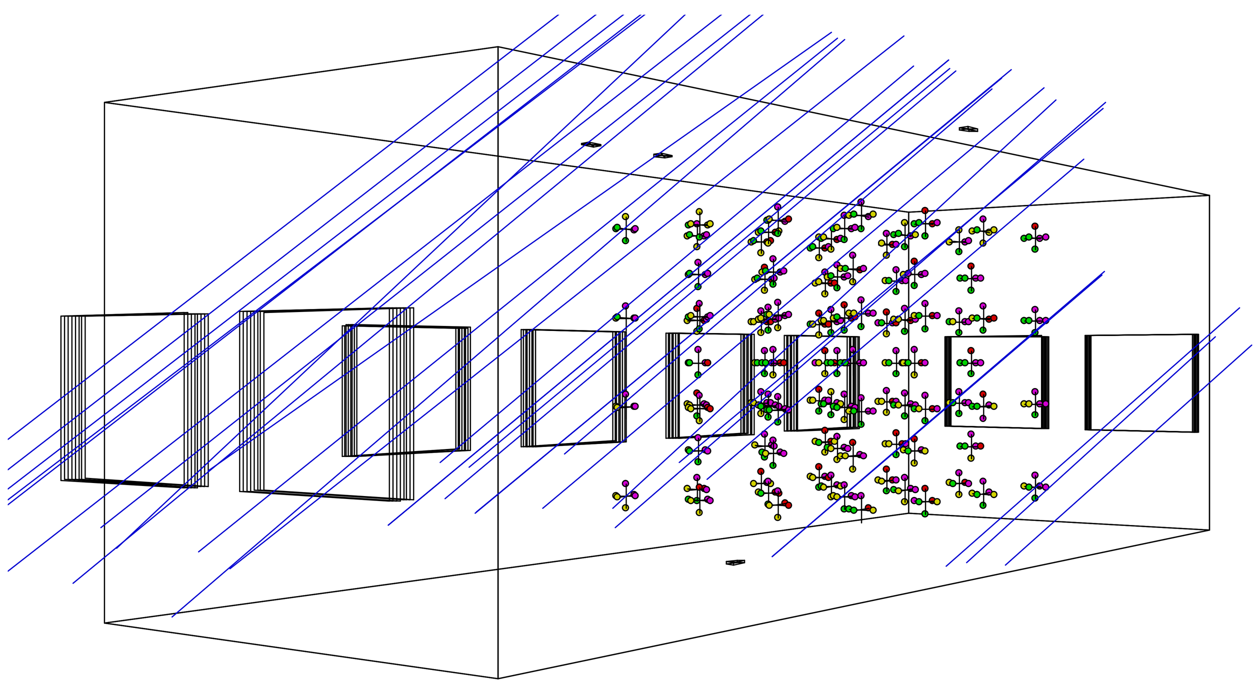

Fig. 3. An example of the event with the muon bundle in NEVOD-DECOR setup. Thin lines are reconstructed muon tracks. Small circles represent hit PMTs of the CWD (colors reflect the amplitudes); big rectangles around the CWD are supermodules of the coordinate detector; small rectangles at the top and the bottom: hit scintillation counters of the calibration telescope system.

As a measure of the energy deposit of the muon bundle, we use the total signal Σ of all hit PMTs of the water calorimeter (in units of photoelectrons, ph.e.). At that, an assumption is made that the total yield of Cherenkov photons is proportional to the total muon energy loss in the detector material (including secondary particles and cascades from them). The local muon density in the event was estimated from the muon multiplicity measured in the coordinate detector taking into account the effective area S_{det} of six DECOR SMs for a given direction of muon bundle arrival. It should be noted however that a straightforward estimate of the muon density as $D = m/S_{det}$ would be biased because of statistical fluctuations of the number of muons that hit the detector in conjunction with a steep spectrum of the events in the local muon density: $dF/dD = AD^{-(\beta+1)}$ where $\beta \approx 2.1$ is the index of the integral spectrum of muon density in the considered range. Assuming that the number of muons registered in the detector at a fixed density D obeys Poisson distribution with the mean value $\langle m \rangle = D \times S_{det}$, the average muon density in the events which give contribution to the formation of the events with a fixed measured multiplicity m may be found analytically:

$$\langle D \rangle = (m - \beta) / S_{det}.$$

In the further analysis, we use the estimate of muon density defined by this equation.

Results and discussion

Correlations of the measured energy deposit with the local muon density estimate for a sample of events with zenith angles $\theta \geq 60°$ are presented in Fig. 4. In the first approximation, the total energy deposit in the CWD is nearly proportional to the muon density, therefore further we analyze the specific energy deposit Σ/D, that is, the CWD response normalized to the muon density in the event.

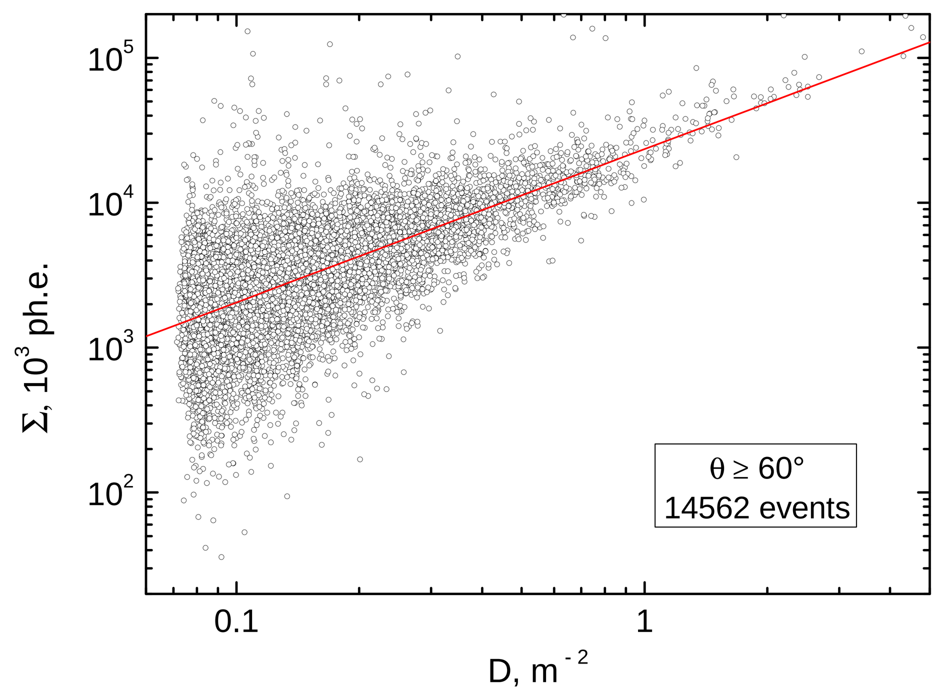

Fig. 4. Correlations of the measured energy deposit and muon density estimate.

The results of the measurements of the dependence of the average specific energy deposit on the zenith angle are presented by the points in Fig. 5. The arrows in the bottom part of the figure indicate typical energies (calculated mean-logarithmic values) of primary cosmic ray particles that contribute to the formation of muon bundles at different zenith angles.

At moderate zenith angles ($\theta < 55°$), a rapid decrease of the measured energy deposit with the zenith angle increase is seen. Such dependence may be explained as a decreasing residual contribution of electron-photon and hadronic components to the response of an unscreened detector deployed at the Earth surface. In this angular range, the measured dependence is well described by a negative exponent of the slant depth of the atmosphere X with the attenuation length $\Lambda = 134 \pm 15$ g/cm² (the dashed curve in the figure).

At detection of muon bundles with zenith angles more than 55°, practically only muon component remains. As seen from the figure, the data exhibit the increase of the average energy deposit in this angular range thus indicating an increase of the mean muon energy in the bundles. The solid curves in Fig. 5 represent the expected angular dependence of the muon bundle energy deposit obtained on the basis of simulations of the EAS muon component with the CORSIKA code for primary protons and iron nuclei. In simulations, we used the combination of hadron interaction models SIBYLL+FLUKA for hadrons with energies more than 80 GeV and below this value, respectively. The calculated value of the mean energy of muons detected in the bundles rapidly increases at large zenith angles and reaches about 500 GeV near the horizon.

The expected dependence of the average specific energy deposit of muon bundles in the CWD (the solid curves in the figure) was calculated in the following way. First, for every zenith angle the average specific energy loss of muons $\langle dE/dX \rangle$ was calculated using the energy loss tables. Then, as mentioned above, we assumed that the total Cherenkov light yield is directly proportional to the muon energy loss. Finally, the absolute calibration of the calculated dependence was obtained by means of normalizing data and calculations in 55° - 65° angular range.

As a whole, the measured dependence of the average specific energy deposit on the zenith angle confirms the increase of the mean muon energy in the bundles and is in a good agreement with expectation (with a possible exception of the point between 70° and 75°, which corresponds to effective energies of primary particles of the order of 10^{17} eV).

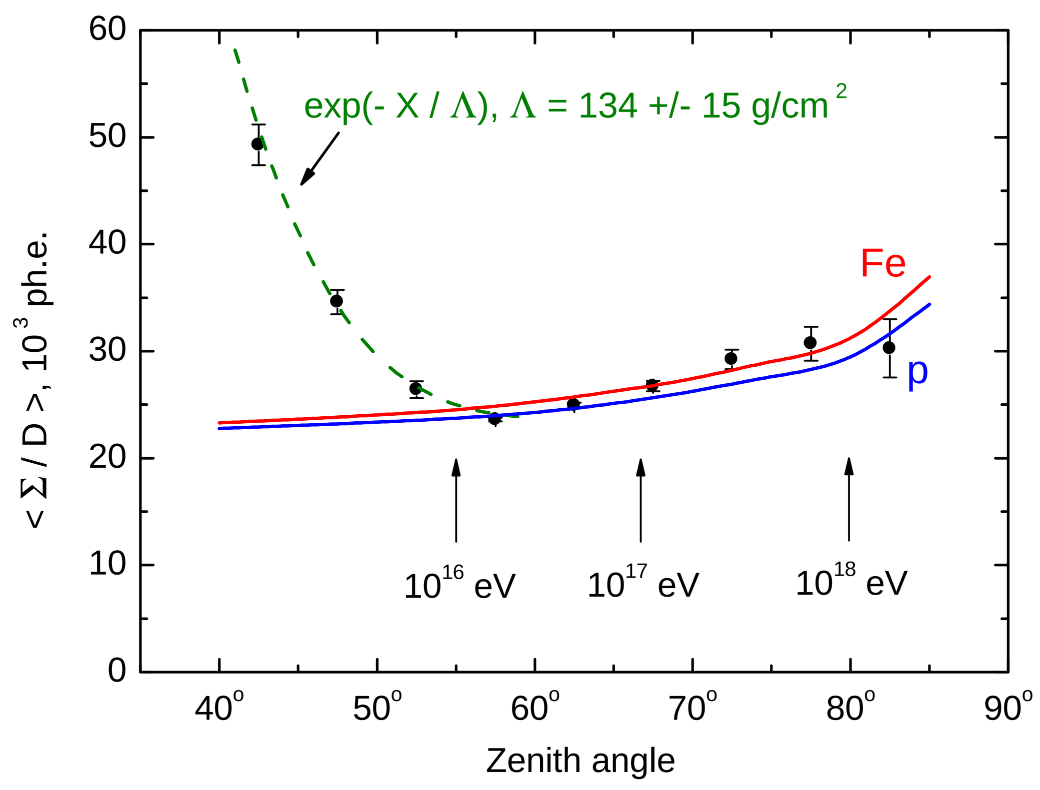

Fig. 5. Dependence of the average specific energy deposit of muon bundles in the Cherenkov water detector on zenith angle. Points: results of measurement; dashed curve is the exponential fit of the data in the range of zenith angles $\theta < 55°$; solid curves represent the expected dependence of muon bundle energy deposit for primary protons and iron nuclei, obtained on the basis of simulations with CORSIKA.

In Fig. 6, the experimental values of the average specific CWD response for muon bundles are presented as a function of the local muon density. Data include all selected events with zenith angles more than 55° where the residual contribution of electron-photon and hadron components is low. In fact, such an analysis for a fixed zenith angle interval allows to follow possible changes in the detector response (and correspondingly, in the mean muon energy in the bundles) for different primary energies. 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 Fig. 5 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 energy. Probably, this effect is related with a logarithmic shift of the maximum of the hadronic cascade to a deeper atmosphere, and hence a decrease of the probability of decays of high-energy parent mesons. On the contrary, the data exhibit some increase of the average specific energy deposit in the region of primary energies above 10^{17} eV. The value of the increase is greater than the difference of calculated results for two limiting assumptions about the mass composition of primary particles (pure protons and pure iron nuclei), therefore this increase cannot be explained in frame of a changing primary composition and a usual hadron interaction model.

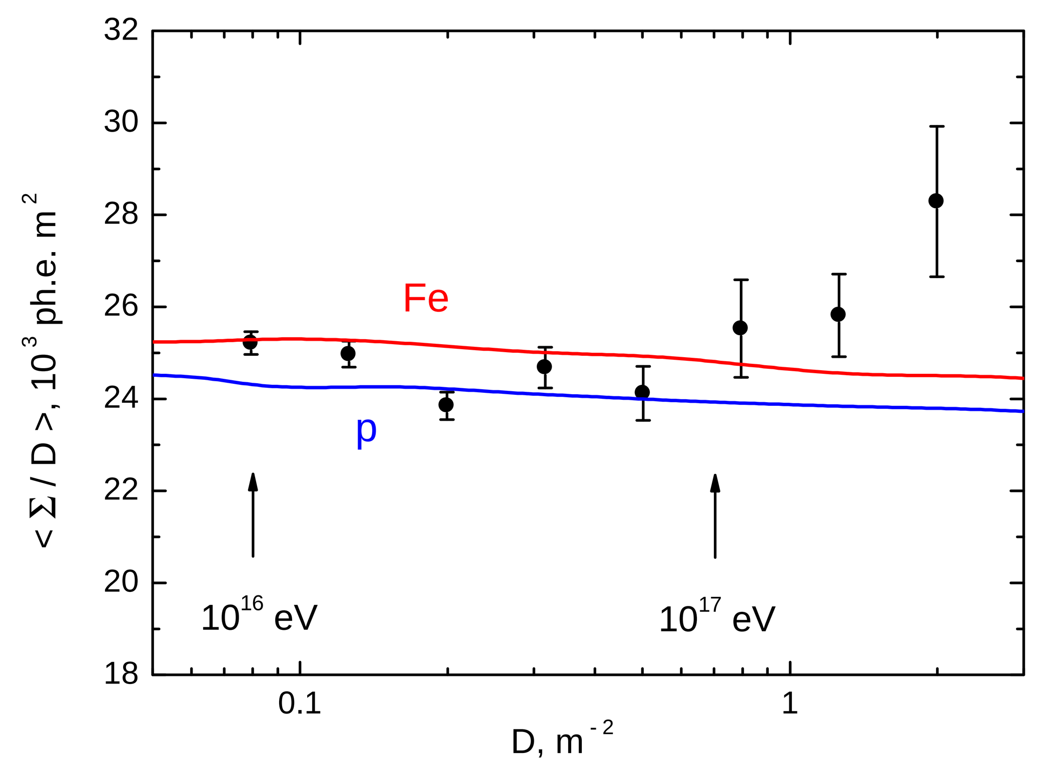

Fig. 6. Dependence of the average specific energy deposit on the local muon density. Curves: calculations on the basis of the CORSIKA code for primary protons and iron nuclei.

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 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. The first 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. If confirmed, this deviation will evidence for the inclusion of a new mechanism of generation of high-energy muons at ultra-high energies of primary particles.

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