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Study of the energy deposit of muon bundles in the NEVOD detector

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Abstract. In several cosmic ray experiments, an excess of multi-muon events in comparison with calculations 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. The results of the analysis of the first experimental data are discussed. It has been found that the average specific energy deposit in the Cherenkov calorimeter appreciably increases with zenith angle, thus reflecting the increase of the mean muon energy in the bundles. A possible evidence for an increase of the energy deposit at primary energies above 10^{17} eV is observed.

1. Introduction

In several cosmic ray experiments at very- and ultra-high energies of primary cosmic ray particles [1–5] an excess of muons in comparison with simulation performed within the framework of commonly used hadron interaction models has been revealed. This excess may appear due to the changing behavior of hadronic interactions and may indicate the appearance of new physical processes, production of new state of matter in interactions of primary cosmic ray particles with air nuclei, etc. [6].

In order to clarify the nature of the muon puzzle, investigations of the energy characteristics of EAS muon component are necessary. A possible approach to the solution of this task is the measurement of the muon energy deposit in the detector material. The total muon energy loss may be expressed as a function of the muon energy as:

$$dE/dX \sim a + bE, \tag{1}$$

where a represents the ionization loss and b is the fractional energy loss for radiation processes (both coefficients are slowly varying functions of the energy). If the excess of high-energy muons appears in the bundles, it should be reflected in the dependence of the energy deposit ΔE on the primary particle energy (see Fig. 1) [7]. Such experiment has been started at the NEVOD-DECOR complex (MEPhI, Russia) in 2012.

2. Experimental setup

Experimental complex NEVOD-DECOR includes two main detectors: Cherenkov water calorimeter NEVOD and coordinate-tracking detector DECOR.

The detecting system of the Cherenkov water detector (CWD) NEVOD [8,9] with a volume 2000 m^3 is a spatial lattice of quasi-spherical optical modules (QSMs). Each QSM consists of 6 low-noise 12-dynode photomultipliers FEU-200 with flat 15 cm diameter photocathodes directed along rectangular coordinate axes. Such a system allows recording of Cherenkov radiation of charged particles arriving from any direction with almost identical efficiency. A wide dynamic range ($1 - 10^5$ photoelectrons) is provided due to 2-dynode signal readout and allows to measure both high-energy cascades and energy deposit of muon bundles in the calorimeter. In total, there are 91 QSMs (546 PMTs) arranged into an array of 25 vertical strings. The distance between the modules in the string is 2 m; the string planes (consisting of 16 or 9 QSMs alternately) are located with spacing 1.25 m along the water tank and 1 m across it. NEVOD is equipped with a system of calibration telescopes (SCT): 40 scintillation counters ($20 \times 40\,\text{cm}^2$) are placed on the top of the water tank, and 40 ones on the bottom.

Eight vertical supermodules (SMs) of the coordinate detector DECOR [10] are deployed in the galleries of the NEVOD building, from three sides of the water tank. Each SM has an effective area 8.4 m^2 and consists of 8 planes of streamer tube chambers with resistive cathode coating. The length of the chambers is 3.5 m, inner tube cross section is $9 \times 9\,\text{mm}^2$. The planes of the chambers are equipped with a two-dimensional system of external readout strips. Spatial and angular accuracy of the muon track location in the supermodule is better than 1 cm and 1°, respectively.

An example of a muon bundle event detected in NEVOD-DECOR and the main parts of the experimental complex are shown in Fig. 2.

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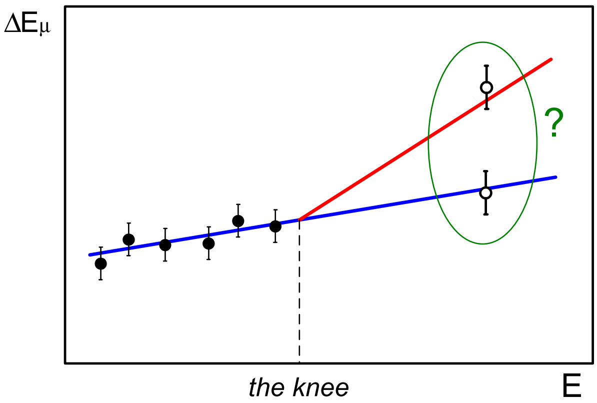

Figure 1. Expected results of muon energy deposit measurements (a sketch) [7].

3. Relation between the local muon density and energy of primary particles

At large zenith angles, hadron and electron-photon components of EAS are almost completely absorbed in the atmosphere, and practically only the muon component is detected on the ground level. Due to the large distance from the shower generation point to the observation level, transverse dimensions of EAS in muons rapidly increase with zenith angle, the effect being additionally enhanced by the particle deflection in the geomagnetic field. Therefore, a muon detector with sizes of the order of tens meters may be considered as a point-like probe. In an individual event, the local density of EAS muons (at the observation point) may be estimated as the ratio of the muon bundle multiplicity, m, to the detector area for a given direction: $D = m/S_{\text{det}}$. Distribution of events in muon density D forms the local muon density spectrum (LMDS). A detailed description of the phenomenology of the LMDS technique, a novel approach to the analysis of the data on muon bundles, was published in [11].

Contribution to the events with a certain muon density D gives showers with different energies of primary particles, detected at random distances from the axis. However, due to a fast decrease of the primary cosmic ray intensity with the increase of energy, the effective range of the energies of primary particles appears relatively narrow (see Fig. 3). It is important to note that at different zenith angles the events with a fixed muon density are formed by primary particles with substantially different energies. At that, the event collection area is determined by transverse dimensions of the showers in muon component (up to several square kilometers). These circumstances allow one to explore a very wide range of energies of primary cosmic rays in a single experiment with a relatively small detector.

It is important to emphasize that, due to selection of the events by the local density, the LMDS are formed mainly by the central part of the EAS (where the muon density is maximal) and are determined by the most energetic muons and the most energetic parent hadrons propagating near the shower axis; hence, they carry additional information about the forward kinematical region of hadron interactions.

4. Experimental data

The selection of muon bundles from DECOR data is based on the fact that the tracks of muons generated in the atmosphere (far from the setup) are nearly parallel. The selection procedure includes several stages: at a trigger level, 3-fold coincidence of signals from the DECOR SMs within the time gate of 250 ns; program reconstruction and selection of muon bundle candidates containing quasi-parallel tracks (within a 5°-cone) in at least 3 different SMs; final event classification and track counting by the operators.

In the present work, characteristics of inclined muon bundles detected by the experimental complex NEVOD-DECOR during two long series of measurements (03.05.2012 – 20.03.2013 and 16.07.2013 – 24.02.2014) have been analyzed. The total live time of the setup operation amounted to 9673 h. In total, 16416 events with muon multiplicity $m \geq 5$ and zenith angles $\theta \geq 55^\circ$ were found. In order to suppress the background of accompanying soft particles, the 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 the local muon density. On the average, the minimal muon energy for such selection conditions is about 2 GeV. Additionally, from the part of the experimental material (3253 h live time) 15084 muon bundles with smaller zenith angles in the range from 40° to 55° were selected.

5. Results of data analysis

As a measure of the muon bundle energy deposit in the CWD, the sum of the signals of all PMTs (ΣN_{pe}, in photoelectrons) of the NEVOD detector was used. The number of Cherenkov photons, which are generated as a result of the passage of the muon through the water calorimeter, is approximately proportional to the total muon energy loss, and the average loss is almost linearly related to the energy (1). Therefore, in principle, by measuring the number of muons and their total energy deposit, it is possible to estimate mean energy of muons in the bundle.

The local density of muons D in the events was estimated from the DECOR detector data. Taking into account the bias due to a steep muon density spectrum and Poisson fluctuations of the number of muons that hit the setup, it was calculated as:

$$D = (m - \beta)/S_{\text{det}}, \tag{2}$$

where S_{det} 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 [11].

As might be expected, the energy deposit is nearly proportional to the local density of muons. Therefore in the further analysis we use the specific energy deposit $\Sigma N_{\text{pe}}/D$ (i.e., the CWD response normalized to the muon density estimate).

The measured dependence of the average specific CWD response on the zenith angle is presented by the

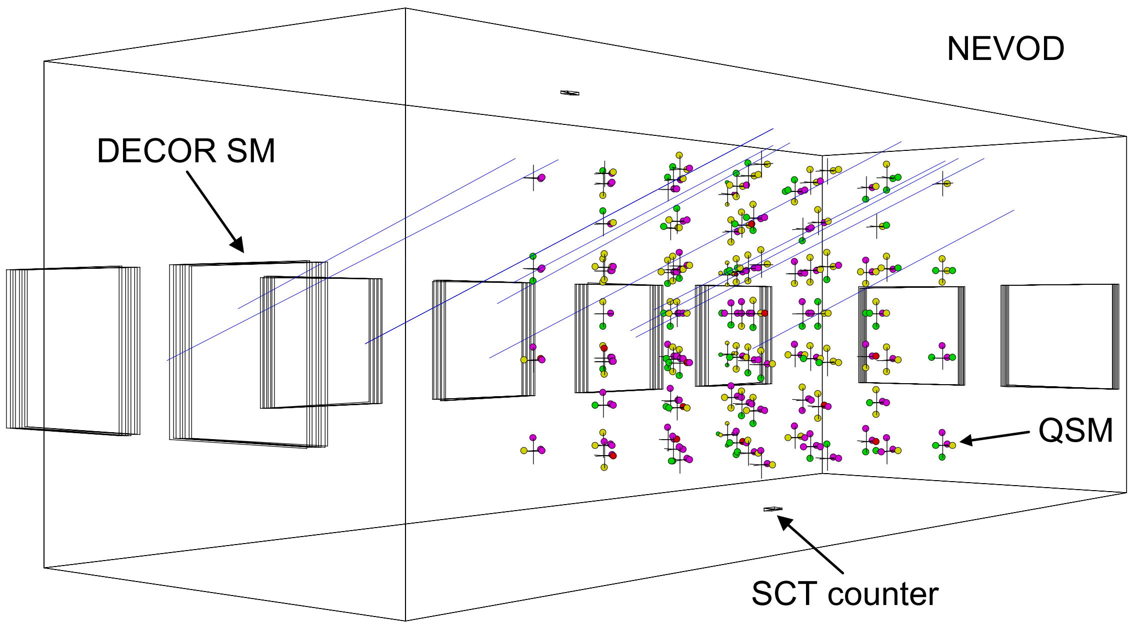

Figure 2. An example of a muon bundle event detected in the NEVOD-DECOR complex. Thin lines: reconstruction of muon tracks from DECOR data; small circles: hit phototubes in the Cherenkov water detector (colors reflect signal amplitudes); big rectangles on the side: supermodules of the DECOR setup; small rectangles on the top and the bottom: triggered scintillation counters of the system of calibration telescopes.

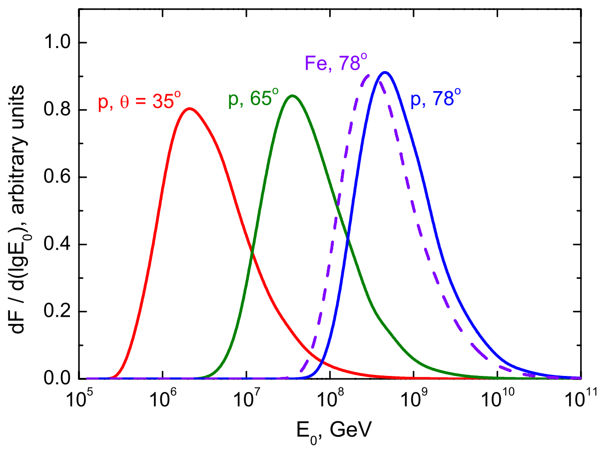

Figure 3. Distribution of primary cosmic ray particle energies contributing to events with a fixed muon density ($D \approx 0.2\,\mathrm{muons/m^2}$) at different zenith angles. CORSIKA-based simulation for primary protons and iron nuclei [11].

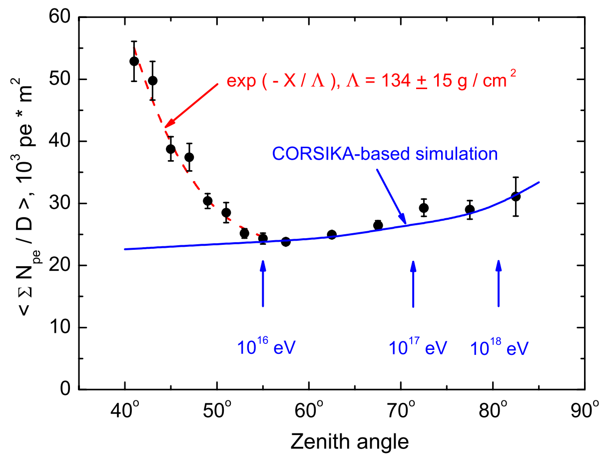

Figure 4. Zenith-angular dependence of the average specific energy deposit for muon bundles. Arrows in the bottom part of the figure indicate typical (mean logarithmic) energies of primary particles.

points in Fig. 4. At moderate zenith angles ($40^\circ - 55^\circ$), the average response falls off rapidly which can be explained as an atmospheric suppression of the residual contribution of electromagnetic and hadron EAS components. The zenith-angular dependence in this range is well fitted by the exponential decay (the dashed curve in Fig. 4): $\exp(X/\Lambda)$, where $X = X_0/\sec\theta$ is the inclined depth of the atmosphere, $X_0 = 1014\,\mathrm{g/cm^2}$ is the average vertical depth at the setup position. The estimated value $\Lambda = 134 \pm 15\,\mathrm{g/cm^2}$ is close to the characteristic absorption length of the nucleon component of cosmic rays in the atmosphere. At larger zenith angles ($\theta > 60^\circ$), the average specific energy deposit increases with the zenith angle, thus reflecting the increase of the mean muon energy in the bundles.

The solid curve in Fig. 4 represents the results of calculations of the expected dependence of the specific energy deposit for muon bundles, obtained by simulating the EAS muon component with the CORSIKA program (v.7.40) [12]. In the simulations, the combination of SIBYLL-2.1 and FLUKA2011 hadron interaction models was used for high ($E_\mathrm{h} > 80\,\mathrm{GeV}$) and low hadron energies, respectively. The simulation of air showers was performed taking into account the influence of the Earths magnetic field. The procedure of calculation of the energy deposit of muon bundles in the CWD was the following. The mean local density over all analyzed events with muon

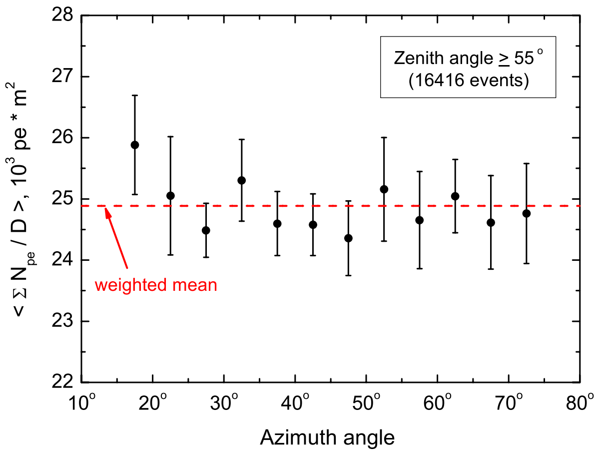

Figure 5. Dependence of the average specific Cherenkov water detector response on the azimuth angle.

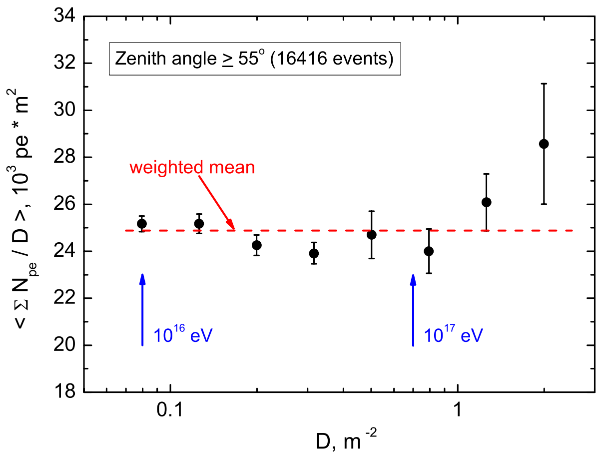

Figure 6. Average specific NEVOD response as a function of muon density.

bundles was found ($D \approx 0.13$ particles/m^2), and then the appropriate effective energies of primary particles for different of zenith angles ($\theta = 40^\circ - 85^\circ$) ranging from $E_0 = 3 \times 10^{15}$ to 3×10^{18} eV were estimated [11]. EAS initiated by primary protons with such energies and arrival directions were simulated. 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, were found to vary from ≈ 90 GeV for $\theta = 40^\circ$ to ≈ 500 GeV for $\theta = 85^\circ$. 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 [13]. It was found that in the considered range of zenith angles it increases by about 1.5 times: from 2.97 MeV/(g/cm^2) for $\theta = 40^\circ$ to 4.39 MeV/(g/cm^2) for $\theta = 85^\circ$. Finally, the calculated dependence was normalized to the experimental data on the number of photoelectrons at the zenith angle of 60°. As seen from Fig. 4, the experimental dependence is in satisfactory agreement with the expected one in the zenith angle range $\theta = 55^\circ - 85^\circ$.

In order to check whether the measured angular dependence could be imitated by a not ideally isotropic structure of the NEVOD QSM lattice, we 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 (Fig. 5); horizontal dashed line shows the weighted mean value. The data exhibit a good uniformity. Thus, the structure of the NEVOD measuring system does not distort the results of angular dependence measurements.

In Fig. 6, 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, see Fig. 4) 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 $\Sigma N_{pe}/D$ on the energy of primary particles. At present, within the measurement errors, no clear dependence of the response normalized to the muon density is seen, at least for the bulk data in a whole range of large zenith angles. One can notice a hint on an increase of the energy deposit at densities of muons greater than 1 particles/m^2 (effective primary energies of 10^{17} eV and above); however, it may be related with both systematical and physical effects. A more refined analysis will be possible as more reach experimental statistics will be accumulated.

6. Conclusion

An experiment on the measurements of the energy deposit of inclined muon bundles in the Cherenkov water detector is being conducted with the NEVOD-DECOR complex. As a result of the analysis of the data accumulated during the first series of measurements (9673 h), a significant dependence of the average specific energy deposit (normalized to the density of muons) on the zenith angle has been revealed. This dependence is explained by an increase of the mean energy of muons in the bundles at large zenith angles and is in a good agreement with expectation based on CORSIKA-based simulations. A possible evidence for an increase of the specific energy deposit at primary energies above 10^{17} eV is observed. Accumulation of data and their further analysis are in progress.

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References

[1] V. Avati *et al.*, Astropart. Phys., **19**, 513 (2003)
[2] J. Abdallah *et al.*, Astropar. Phys., **28**, 273 (2007)
[3] R.P. Kokoulin *et al.*, Nucl. Phys. B (Proc. Suppl.) **196**, 106 (2009)
[4] O. Saavedra *et al.*, Journ. of Phys.: Conf. Ser., **409**, 012009 (2013)
[5] G. Rodriguez, EPJ Web of Conf. **53**, 07003 (2013)

[6] A.A. Petrukhin *et al.*, Journ. of Phys.: Conf. Ser., **409**, 012103 (2013)
[7] A.A.Petrukhin, Nucl. Instr. and Meth. in Phys. Research A, **742**, 228 (2014)
[8] V.M. Aynutdinov *et al.*, Astrophys. Space Sci., **258**, 105 (1998)
[9] S.S. Khokhlov *et al.*, Astrophys. Space Sci. Trans., **7**, 271 (2011)
[10] N.S. Barbashina *et al.*, Instrum. Experim. Techniques, **43**, 743 (2000)
[11] A.G. Bogdanov *et al.*, Phys. Atom. Nucl., **73**, 1852 (2010)
[12] D. Heck *et al.*, Forschungszentrum Karlsruhe Report FZKA 6019 (1998)
[13] D.E. Groom *et al.*, Atomic Data and Nuclear Data Tables, **78**, 2 (2001)