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Status of the NEVOD–DECOR Experiment on the Study of Muon Bundles Energy Deposit

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Abstract—The existence of an excessive number of multimuon events observed in many experiments at ultrahigh EAS energies (above 10^{17} eV) relative to calculations cannot be explained using modern models of hadronic interactions. One way of solving the problem of muon excess is to study the energy characteristics of the EAS muon component. Results are presented from measurements of muon bundle energy characteristics over 7 years of observations. The experimental dependences are compared to results from simulation done with the CORSIKA software package.

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INTRODUCTION

An important problem in the physics of ultrahigh energy cosmic rays (so-called "muon puzzle") is the excess of multimuon events, relative to calculations. The excess of muons is observed in the region of extensive air shower (EAS) energies above 10^{17} eV. An international working group has combined the results from investigating the muon excess. These include data from different experiments [1, 2], particularly the NEVOD–DECOR experiment, in which the dependence of the muon excess on the energy primary particles (10^{15} to 10^{18} eV and higher) was measured for the first time [3, 4]. It was shown that the muon excess cannot be described above 10^{17} eV in the context of existing ideas about nuclear interactions, not even for the ultimately heavy composition (iron nuclei) of primary cosmic rays.

Since different mechanisms of the emergence of excess of multimuon events (of cosmophysical or nuclear-physical nature) must affect the muon energy differently, one possible way of solving the problem is to study the energy characteristics of the EAS muon component [5]. The average energy loss of muons in a matter depend almost linearly on the muon energy. If there is an excess of ultrahigh energy muons, it must affect the dependence of the average muon energy on the energy of primary particles. Such experiment can be performed nowadays only at the NEVOD–DECOR complex, and have been under way since 2012. Earlier results were presented in [6, 7], where the energy deposited by muon bundles was measured. An increased deposit of energy was revealed for primary particle energies above 10^{17} eV in the dependence of the average specific deposit of energy by bundles on the local muon density for fixed intervals of zenith angles. The aim of this work was to estimate the average muon energy in bundles and its change with an increase in the local muon density and, correspondingly, in the energy of primary particles.

EXPERIMENTAL SETUP AND DATA

The setup included the NEVOD Cherenkov water calorimeter (CWC) [8, 9] with a volume of 2000 m^3 and the DECOR coordinate-tracking detector [10] with an area of 70 m^2. The measuring system of the NEVOD CWC is a spatial array of 91 quasi-spherical modules (QSMs), each of which contains six FEU-200 photomultiplier tubes with a 15-cm-diameter flat photocathode. The tubes are directed along the axes of an orthogonal coordinate system. The dynamic range of detected signals is 1 to 10^5 photoelectrons (ph. e.) for each PMT. The DECOR coordinate-tracking detector consists of eight supermodules (SMs) located in building galleries on three sides of the water volume of the NEVOD detector. The angular and spatial accuracies of reconstructing muon tracks that intersected the SMs is better than 1° and 1 cm, respectively.

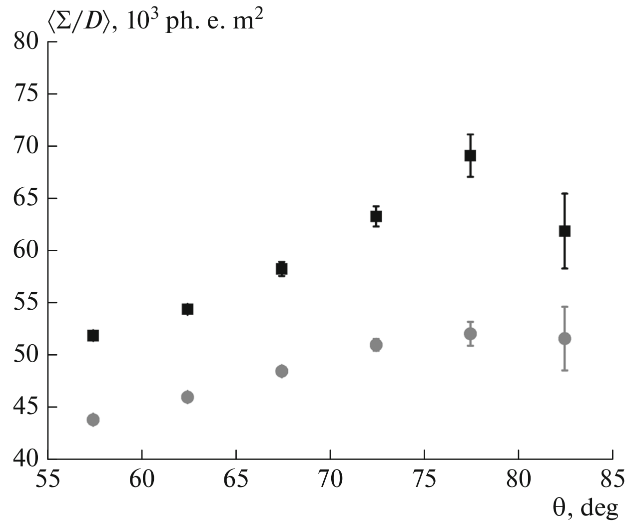

Fig. 1. Average specific energy deposit of muon bundles as a function of the zenith angle. The black squares are experimental data; the gray dots are results from simulation with a fixed muon energy of 100 GeV.

Results are presented that are based on data from three series of measurements made at the NEVOD–DECOR complex over 46901 h of live observations in the period July 2013 to May 2020. We selected 80078 events with muon bundles having multiplicities of at least five particles and zenith angles of more than 55°. Due to the observed residual contribution from the electromagnetic and hadron EAS components in the response of the calorimeter located on the Earth's surface at moderate zenith angles ($\theta < 55°$) [11], the energy deposited by bundles was analyzed only with events that had zenith angles exceeding 55°, where almost pure muons remained. The coordinate-tracking detector allowed determination of the local muon density in bundles and the direction of their arrival (and thus estimates of the energies of primary particles from these data). The deposit of energy by muon bundles was reconstructed using the response of the NEVOD Cherenkov calorimeter (as sum Σ of signals from all PMTs in ph. e.).

The muon density in events was estimated from number m of tracks in the DECOR, with allowance for effective area S_{det} of the supermodules for the measured direction of bundle arrival and the slope of local muon density spectra, $\beta \approx 2.1$ [3]:

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

Since the total deposit of energy in the first approximation is proportional to the muon density in an event, in the subsequent analysis the specific deposit of energy (the total photon number divided by the estimate for the muon density in an event) was used.

We simulated the deposit of energy by muon bundles with fixed muon energies of 100 GeV at the NEVOD–DECOR facilities. Events with bundles were distributed according to the local muon density spectra with a slope close to experimental one. Our simulation allowed for physical features of the facilities and conditions of the hardware, software, and operator selection of events with muon bundles. The Geant4 package was used to calculate the response of the NEVOD Cherenkov water calorimeter for events satisfying the conditions of selection [12, 13]. The NEVOD CWC model was tested and calibrated using the response to single near-horizontal muons.

ANALYSIS OF EXPERIMENTAL DATA

Figure 1 presents the dependence of the average specific energy deposit on the zenith angle. The black squares are experimental data and the gray dots are the simulated specific energy deposit of muon bundles with fixed muon energies of 100 GeV. An increase is observed for both experimental and simulation results in the average specific energy deposit upon a rise in the zenith angle. However, the experimental dots are notably higher than the simulation results, due to the contribution from different muon energies in bundles (the average muon energy in bundles is above 100 GeV).

We moved from average specific energy deposit in water to the muon energy in bundles. The ratio of the experimental values of average specific energy deposit to those modeled for fixed muon energies of 100 GeV was calculated. Average muon energies in the calorimeter and statistical errors were calculated by interpolating the obtained values according to tabulated data of average specific muon losses [14], normalized to losses at energy of 100 GeV. Figure 2a presents the dependence of the average energy of muons in bundles on the zenith angle, which was obtained for the first time. The arrows denote the calculated logarithmic mean energies of primary particles. The solid and dashed curves were obtained through EAS simulation in the CORSIKA software [15] with protons and iron nuclei as primary particles. Hadron interactions were simulated using the QGSJET-II-04 model [16, 17]. The obtained data are in excess over those expected for zenith angles $\theta = 55°$–$65°$, due probably to the residual contribution the accompanying electron–photon and hadron EAS components. Good agreement with expectations is observed at large zenith angles.

Figure 2b presents the dependence obtained for the average muon energy on the local muon density for zenith angle interval $65° \le \theta < 75°$. The notations for curves and arrows is the same as in Fig. 2a. The curves in the figure were obtained through EAS simulation for primary protons and iron nuclei at fixed zenith angle $\theta = 69°$. The data indicate an increase in the

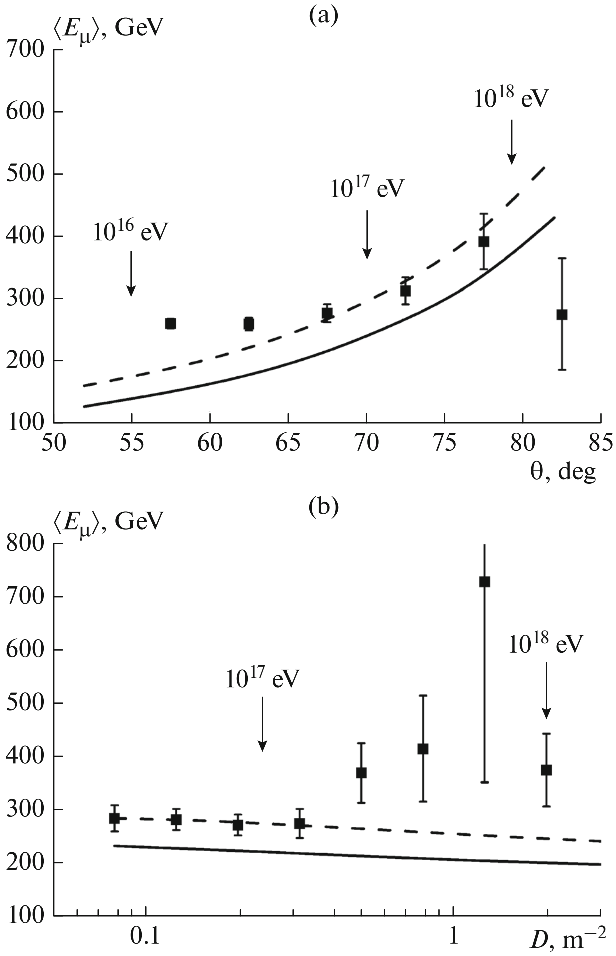

Fig. 2. Average muon energy in muon bundles as a function of (a) zenith angle and (b) local muon density for zenith angles θ = 65°–75°. The dots are experimental data and the curves are the expected dependences for EAS muon bundles formed by primary protons (solid line) and iron nuclei (dashed line). The arrows show the characteristic energies of cosmic ray primary particles.

average muon energy in bundles at high muon densities, which corresponds to primary particle energies above 10^{17} eV.

CONCLUSIONS

Estimates for the average muon energy in bundles were obtained for the first time in the NEVOD–DECOR experiment at different zenith angles and local densities. The estimates corresponded to primary particle energies of 10^{16}–10^{18} eV. An increase in the average muon energy in bundles was observed for primary energies above 10^{17} eV.

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