ISSN 1062-8738, Bulletin of the Russian Academy of Sciences: Physics, 2023, Vol. 87, No. 7, pp. 915–917. © Allerton Press, Inc., 2023.
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Average Muon Energies in Inclined Bundles, According to NEVOD-DECOR Data

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Received December 25, 2022; revised February 12, 2023; accepted March 29, 2023

Abstract—Results are presented from measuring the energy characteristics of muon bundles in inclined extensive air showers in the NEVOD-DECOR experiment. Estimates of the average energy of muons in the bundles are obtained in the 10 to 1000 PeV range of primary particle energies and compared to values calculated under different assumptions about the composition of cosmic radiation and models of hadronic interactions. An excess of experimental values of the average muon energy relative to calculations is found for high local densities corresponding to primary particle energies above 100 PeV.

DOI: 10.3103/S1062873823702696

INTRODUCTION

An important problem in cosmic ray physics is the so-called muon puzzle—the excess of multi-muon events that grows with the energy of primary particles, relative to results from calculations within modern models of hadronic interactions. An excess of muons has been found in many experiments, and a combined result of such research was presented by the Working Group on Hadronic Interactions and Shower Physics (WHISP) [1, 2]. The observed excess could be due to many factors (e.g., the generation of new particles or states of matter in nucleus–nucleus interactions) not considered in models of hadronic interactions. One way of solving the muon puzzle is to study the energy characteristics of muon bundles in extensive air showers (EASes) and how they change with the energy of primary particles. A possible approach to studying the energy characteristics of the EAS muon component is to measure the energy deposit of muon bundles in the matter of the detector. The average losses of muons in matter depend almost linearly on their energy: $dE/dX = a + bE$. The specific energy deposit (normalized to the muon density) gives information about the average energy of muons in bundles. Signs of an excess of high-energy muons could indicate the introduction of new physical processes [3]. Results from studying the energy deposit of muon bundles in the NEVOD Cherenkov water calorimeter were presented in [4], and preliminary results on the average energies of muons in bundles were given in [5, 6]. The aim of this work was to obtain experimental estimates of the average energies of muons in bundles, depending on the zenith angle and local muon density in a wide range of primary energies (10–1000 PeV) with more experimental statistics reflecting the main systematic effects that affect measuring results.

EXPERIMENTAL SETUP AND DATA

The setup on which the bundles were recorded consists of a NEVOD Cherenkov water calorimeter (CWC) [7, 8] with a volume of 2000 m^3 and a DECOR coordinate-tracking detector [9, 10] with an area of 70 m^2. CWC NEVOD consists of quasi-spherical modules (QSM) that form a spatial lattice in the water volume of the tank. Each QSM has six FEU-200 photomultipliers, which contain flat photocathodes 15 cm in diameter. The photomultipliers are directed along the axes of an orthogonal coordinate system that allows us to record Cherenkov light from any direction. Measure Σ of the energy deposit is the sum of the signals of all triggered PMTs in the NEVOD detector, in units of photoelectrons (ph. e.).

The DECOR coordinate tracking detector consists of eight supermodules (SMs) positioned around the Cherenkov calorimeter. Each SM has an area of 8.4 m^2 and contains eight vertical planes of streamer tubes. The angular and spatial accuracies of reconstructing the tracks of muons crossing the SM are better than 1° and 1 cm, respectively. The DECOR detector allows us to determine the number of muons in a bundle (multiplicity) and the direction of its arrival.

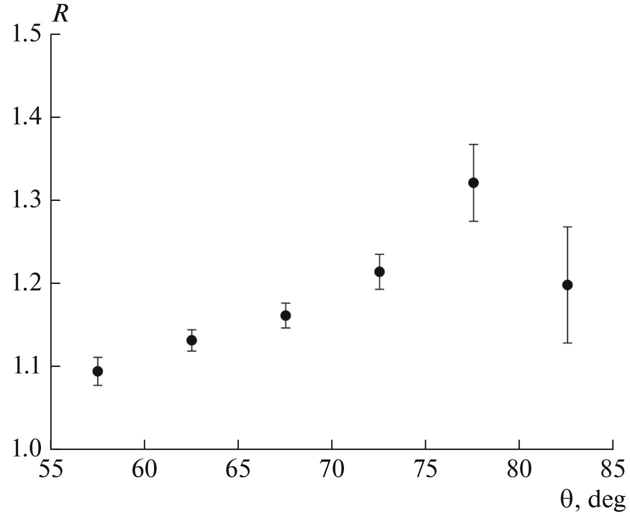

Fig. 1. Dependence of the ratio of a measured specific energy deposit to one modeled for a fixed muon energy of 100 GeV on the zenith angle.

Local density D of an event is estimated as the ratio of multiplicity m to effective area S_{det} of the detector in a given direction, allowing for the bias of the estimate resulting from Poisson fluctuations in the number of particles hitting the detector, and the steeply falling spectrum of density [11]:

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

where $\beta \sim 2.1$ is the integral index of the slope of the local muon density spectrum (LMDS) [11].

In the first approximation, the total energy deposit is proportional to muon density D in an event, so we consider specific energy deposit Σ/D (i.e., the number of photoelectrons divided by the estimated muon density).

To analyze our data, we used 103 thousand events with muon bundles having a multiplicity of at least 5 and zenith angles of more than 55° for 60.1 thousand h of live time (the period of recording from July 2013 to March 2022). The contribution to the NEVOD CWC response from the electron–photon and hadronic components of the EAS [12, 13] in addition to that of muons was significant at zenith angles of less than 55°, which is why we chose this boundary. Events were selected in two 60°-wide sectors of azimuth angles, where most part of the DECOR coordinate detector (six out of eight supermodules) was shielded by the water volume of the NEVOD detector.

AVERAGE ENERGIES OF MUONS IN BUNDLES

A joint model of the DECOR and NEVOD CWC detectors' response to the passage of artificial muon bundles was developed for our physical analysis. Events with bundles of muons were modeled over the spectrum of the local muon density with a slope and angular distribution close to the experimental ones. Both the physical features of the DECOR detector and the conditions of selecting events with muon bundles were considered in the model. The NEVOD CWC's response to the passage of bundles of muons with a fixed muon energy of 100 GeV was modeled for the selected events using the Geant4 software package [14]. The mathematical model of the NEVOD CWC was verified and calibrated against the response to single near-horizontal muons selected by the DECOR supermodules.

Different systematic effects affecting the measuring results were considered, including track masking; the residual contribution to the NEVOD detector's response from the electron–photon and hadronic components of the EAS in the zenith angle intervals of 55°–60° and 60°–65°, which totaled (5.1 ± 1.1) and (0.87 ± 0.30)%, respectively; underestimates of the response due to the threshold of digitization; changes in the conditions of recording in different series of measurements; and the efficiency of the DECOR detector's response.

We moved from average specific energy deposits measured directly to the average energy of muons in bundles by obtaining ratio R of a measured specific energy deposit to one modeled for fixed muon energies of 100 GeV (Fig. 1). Using the dependence of the average losses in water on the muon energy [15], which is virtually linear in the range of hundreds of GeV, we used ratio R to calculate the average muon energies in the Cherenkov water calorimeter and their errors. Figure 2a shows the dependence of the average muon energy in bundles we obtained in the 55°–85° range of zenith angles. The arrows indicate the characteristic energies of primary particles [11]. The curves were obtained by modeling the muon component of EASes formed by primary protons (a lower group of curves) and iron nuclei (an upper group of curves) in the CORSIKA software package [16] for models QGSJET-II-04 (solid curves), SIBYLL-2.3c (dashed curves), and EPOS-LHC (dashed-and-dotted curves) of hadronic interactions. Experimental estimates of the LMDS slope were used in calculating the expected dependences.

Figure 2a shows the increase in the average energy of muons in bundles when the zenith angle increases. The predicted and experimental results are in good agreement.

Figure 2b shows the dependence of the average muon energy on the local muon density, obtained for the 65°–75° range of zenith angles. The denotation of the curves and arrows is the same as in Fig. 2a. The expected dependences were obtained by modeling showers for primary protons and iron nuclei with fixed zenith angle $\theta = 69°$. The excess of experimental estimates of the average muon energy over those calculated for primary protons in different models ranges from 4.2σ to 4.8σ for high densities corresponding to primary energies above 10^{17} eV, and from 3.1σ to 3.7σ

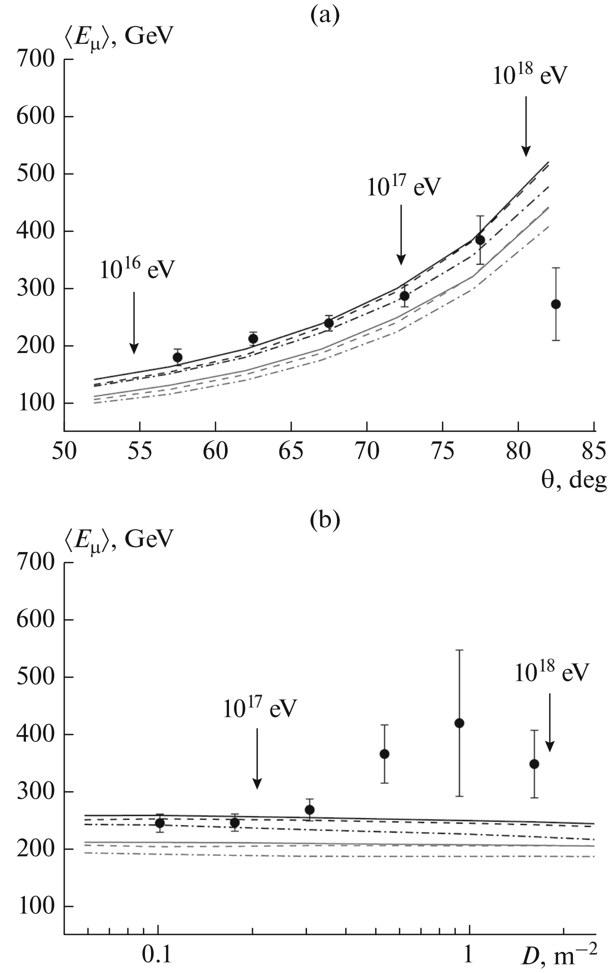

Fig. 2. Dependences of average energy of muons in bundles on the (a) zenith angle and (b) muon density within the $65° \leq \theta < 75°$ range of zenith angles. Dots represent experimental data, while the curves show expected dependences obtained using results from EAS modeling with the CORSIKA software package (a detailed description is given in the text). Arrows indicate the characteristic energies of primary particles of cosmic rays.

for primary iron nuclei (obtained according to the last three points of the dependence).

CONCLUSIONS

At energies above 100 PeV, results from experiments show an exess of the average energies of muons in bundles over those expected, which could testify in favor of inclusion of new mechanisms of the generation of high-energy muons at ultrahigh energies of primary cosmic rays.

ACKNOWLEDGMENTS

Modeling was performed at the high-performance computer center of the National Research Nuclear University MEPhI.

FUNDING

This work was performed at the NEVOD Experimental Complex as part with the support from the RF Ministry of Science and Higher Education, projects nos. 0723-2020-0040 “Fundamental Problems of Cosmic Rays and Dark Matter” and FSWU-2023-0068 “Fundamental and Applied Research of Cosmic Rays.” Modeling was done at the high-performance computer center of National Research Nuclear University (MEPhI).

CONFLICT OF INTEREST

The authors declare they have no conflicts of interest.

REFERENCES

1. Dembinski, H.P., et al., (EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array, and Yakutsk EAS Array Collabs.), *EPJ Web Conf.*, 2019, vol. 210, p. 02004.
2. Soldin, D., (EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array, and Yakutsk EAS Array Collabs.), *Proc. 37th Int. Cosmic Ray Conference*, Berlin, 2021, p. 349.
3. Petrukhin, A.A., *Nucl. Instrum. Methods Phys. Res., Sect. A*, 2014, vol. 742, p. 228.
4. Yurina, E.A., Barbashina, N.S., Bogdanov, A.G., et al., *Bull. Russ. Acad. Sci.: Phys.*, 2019, vol. 83, no. 8, p. 937.
5. Yurina, E.A., Barbashina, N.S., Bogdanov, A.G., et al., *Bull. Russ. Acad. Sci.: Phys.*, 2021, vol. 85, no. 4, p. 455.
6. Yurina, E.A., Barbashina, N.S., Bogdanov, A.G., et al., *Proc. 37th Int. Cosmic Ray Conference*, Berlin, 2021, p. 383.
7. Petrukhin, A.A., *Phys.—Usp.*, 2015, vol. 58, no. 5, p. 486.
8. Kindin, V.V., Amelchakov, M.B., Barbashina, N.S., et al., *Instrum. Exp. Tech.*, 2018, vol. 61, no. 5, p. 649.
9. Barbashina, N.S., Ezubchenko, A.A., Kokoulin, R.P., et al., *Instrum. Exp. Tech.*, 2000, vol. 43, no. 6, p. 743.
10. Amel’chakov, M.B., Barbashina, N.S., Vonsovskii, N.N., et al., *Izv. Akad. Nauk, Ser. Fiz.*, 2002, vol. 66, no. 11, p. 1611.
11. Bogdanov, A.G., Gromushkin, D.M., Kokoulin, R.P., et al., *Phys. At. Nucl.*, 2010, vol. 73, p. 1852.
12. Kokoulin, R.P., Bogdanov, A.G., Dushkin, L.I., et al., *Bull. Russ. Acad. Sci.: Phys.*, 2015, vol. 79, no. 3, p. 365.
13. Bogdanov, A.G., Barbashina, N.S., Dushkin L.I., et al., *Bull. Russ. Acad. Sci.: Phys.*, 2017, vol. 81, no. 4, p. 484.
14. Agostinelli, S., Allison, J., Amako, K., et al., *Nucl. Instrum. Methods Phys. Res., Sect. A*, 2003, vol. 506, p. 250.
15. Groom, D.E., Mokhov, N.V., and Striganov, S.I., *At. Data Nucl. Data Tables*, 2001, vol. 78, p. 183.
16. Heck, D., Knapp, J., Capdevielle, J.N., et al., Report FZKA no. 6019, Karlsruhe: Forschungszentrum, 1998.

Translated by M. Samokhina