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Zenith-Angle Dependence of Local Muon Density Spectra of Extensive Air Shower near the Horizon

R. P. Kokoulin[a, †], **N. S. Barbashina**[a], **A. G. Bogdanov**[a, *], **V. S. Vorobev**[a], **E. A. Zadeba**[a], **V. V. Kindin**[a], **K. G. Kompaniets**[a], **A. Yu. Konovalova**[a], **K. I. Mannanova**[a], **A. A. Petrukhin**[a], **I. Yu. Troshin**[a], **S. S. Khokhlov**[a], **V. V. Shutenko**[a], **E. A. Yurina**[a], **and I. I. Yashin**[a]

[a] *National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, 115409 Russia*

**e-mail: agbogdanov@mephi.ru*

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Abstract—The integral local muon density spectra (LMDS) of (extensive air shower) EAS at large zenith angles were reconstructed on the basis of the DECOR experimental data on muon bundles detected in a long-term measurement series from May 3, 2012, to April 7, 2023. The results were obtained at two threshold muon density values of 0.015 and 0.068 particles/m^2, which corresponded to the detection of bundles with a multiplicity of at least 3 and at least 5 muons in the detector. At zenith angles less than 80°, the zenith-angle dependence of LMDS is well described by a power function of the cosine of the zenith angle. However, with a further increase in the zenith angle, this dependence changes significantly, and at angles of 87°–88°, the measured values exceed the specified simple extrapolation by about an order of magnitude. This is due to the inapplicability of the flat atmosphere approximation at such angles. A simple equation was obtained that takes into account the curvature of the Earth's atmosphere.

Keywords: extensive air shower, muon bundle, local muon density spectrum, large zenith angle, sphericity of the Earth's atmosphere, hadron interaction model

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INTRODUCTION

The method of local particle density spectra for studying extensive air showers (EAS) can be used when the detector size is much smaller than the transverse size of the EAS; i.e., the detector can be considered a point detector and the particle density does not change within its limits. This method is particularly effective in detecting EAS muons that reach the detector on the Earth's surface at zenith angles up to $\theta = 90°$. At such angles, the transverse dimensions of the EAS muon component can reach tens of kilometers. This allows the detection of muons from EAS at very high energies using a relatively small facility. The only condition is to ensure high efficiency of detection of muons arriving at large zenith angles, which means that the detector must be placed vertically.

This approach was successfully applied at the NEVOD–DECOR complex [1, 2], which, despite its small size (coordinate detector area ~70 m^2), measured the local density spectra of muons generated in EAS with energies from 10^{15} up to 10^{18} eV. The data analysis methods and previously obtained results were described in detain previously [3–5]. These results showed that the mass composition of primary cosmic rays in the energy range from 10^{15} up to 10^{17} eV becomes heavier, and with a further increase in energy, the explanation of the results obtained requires still much heavier primary particles (heavier than iron nuclei), which are practically not observed in cosmic rays. The NEVOD–DECOR results were confirmed in experiments to study the muon component of EAS at the Pierre Auger Observatory [6], IceTop [7], and some other facilities [8, 9]. This phenomenon has been dubbed the "muon mystery" [10]. However, the results obtained at zenith angles greater than 80°, which correspond to energies of ~10^{18} eV and above, require more detailed analysis, since the development of EAS here is changing significantly.

In this article, the experimental data obtained at the NEVOD–DECOR complex for more than 75000 h of measurements were analyzed with the aim of more accurately assessing the energy of primary particles and their mass composition in a wide energy range, including in the region of 10^{18} eV.

ANALYSIS OF DATA OBTAINED AT THE NEVOD–DECOR COMPLEX

The NEVOD–DECOR complex consists of two detectors: the NEVOD Cherenkov water detector and

† Deceased.

the DECOR coordinate detector. The main feature of NEVOD is the use of quasi-spherical modules: such modules allow one to determine the direction of arrival of Cherenkov radiation, and a spatial lattice of such modules allows one to determine the direction of movement of the detected particles. The main feature of DECOR is the vertical arrangement of the planes of the streamer tubes, which allows for the effective detection of particles at large zenith angles, right up to the horizon. In muon bundle studies, DECOR is used to measure the number and direction of muons in a bundle, and NEVOD is used to measure their energy release. At not very large zenith angles ($\theta < 60°$), at which not only muons but also other components of the EAS reach the Earth's surface, NEVOD (water thickness 9 m) acts as a filter for absorbing these components. This somewhat limits the range of azimuth angles, but increases the reliability of the data obtained.

The analysis of muon groups detected by the DECOR detector in this work included the following stages: selecting muon groups with a multiplicity above a given threshold m, obtaining distributions of detected groups by zenith angle $N_{\text{exp}}(\geq m, \theta)$, and transforming the measured distributions into a detector-independent local muon density spectrum (LMDS) at different zenith angles $F_{\text{exper}}(\geq D, \theta)$; here, D is the local muon density (dimension $[D] = m^{-2}$), which shows how many events with muon density $\geq D$ is detected at the observation point from a given direction θ per unit time per unit solid angle.

It was shown earlier [3–5] that, at angles $\theta < 80°$, the integral local muon density spectra $F(\geq D, \theta)$ are well described by a simple equation

$$F(\geq D, \theta) = CD^{-\beta}\cos^{\alpha}\theta, \tag{1}$$

where $\beta \approx 2.0$–2.3 is the slope of LMDS, $\alpha \approx 4.5$–4.8 is the exponent of the cosine of the zenith angle, and C is the normalization coefficient.

The expected distributions $N_{\text{expect}}(\geq m, \theta)$ of muon bundles was calculated using Eq. (1), which was chosen as the reference model.

The relationship between the experimental and expected LMDS is given by the expression

$$F_{\text{exper}}(\geq D, \theta) = N_{\text{exper}}(\geq m, \theta)/N_{\text{expect}}(\geq m, \theta)F(\geq D, \theta), \tag{2}$$

where the ratio $F(\geq D, \theta)/N_{\text{expect}}(\geq m, \theta)$ actually determines the corrections to the experimental data for taking into account the detection efficiency, trigger conditions, conditions for selecting events with muon groups, etc.

An important point in comparing the experimental and calculated LMDS estimates is the optimal choice of the effective threshold value D_0. For this, it is necessary that the resulting spectrum estimates be weakly sensitive to variations in the exponent $\beta = 2.2$ of the LMDS power spectrum, which is included in reference model (1) of F.

With an accuracy of up to the dependence on the zenith angle and the normalization coefficient, the reference model of the integral and differential LMDS can be represented as

$$F(\geq D) = D^{-\beta} \text{ and } dF(D)/dD = \beta D^{-(\beta+1)}, \tag{3}$$

In this case, the experimental LMDS has the form

$$F_{\text{exper}}(\geq D_0) = (D_0)^{-\beta} N_{\text{exper}}(D)/N_{\text{expect}}(D). \tag{4}$$

Then, taking into account that $N_{\text{expect}} \sim \int \beta D^{-(\beta+1)} dD$ and equating the first derivative with respect to β to zero, we obtain that

$$\ln D_0 = \langle \ln D \rangle - 1/\beta. \tag{5}$$

Thus, the logarithm of the optimal value of the local particle density threshold D_0 for the integral LMDS estimate is equal to the average logarithm of the density for the selected events, reduced by $1/\beta$.

The optimal effective thresholds D_0 calculated by this equation are 0.015 and 0.068 m^{-2} for selection conditions $m \geq 3$ and $m \geq 5$ tracks recorded by DECOR, respectively. Naturally, when the zenith angle changes, the D_0 value changes slightly due to the change in the effective facility area. However, due to the vertical orientation of the planes of the streamer tubes of the DECOR detector, at large zenith angles these changes are insignificant.

Selecting D_0 values is illustrated in Fig. 1, which shows the distributions of modeled events by local muon density in the zenith angle range $\theta = 75°$–$90°$, satisfying the selection conditions for $m \geq 3$ and $m \geq 5$ tracks.

TAKING INTO ACCOUNT THE SPHERICITY OF THE ATMOSPHERE

In this work, the results of the experiment from May 3, 2012, to July 4, 2023 (75200 h of live time) were used for analysis. In total, the two samples used in the further analysis contain:

— 129200 events with angles $55° \leq \theta < 88°$ and the number of tracks $m \geq 5$ ($D_0 = 0.068$ m^{-2});

— 36000 events with angles of $70° \leq \theta < 89°$ and the number of tracks $m \geq 3$ ($D_0 = 0.015$ m^{-2}).

Processing and analysis of these events confirmed that, at zenith angles $\theta \leq 80°$, they are well described by Eq. (1). But Eq. (1) is not applicable as $\theta \to 90°$, since the flow on the horizon must be finite. At $\theta > 80°$, the angular distribution of the experimental data becomes flatter, and the deviation from $\cos^{\alpha}\theta$ increases with increasing zenith angle (Fig. 2).

To approximate the experimental data taking into account the sphericity of the atmosphere, the following dependence was chosen:

$$\cos^{\alpha}\theta \to [\cos^{p}\theta + a^{p}]^{\alpha/p}. \tag{6}$$

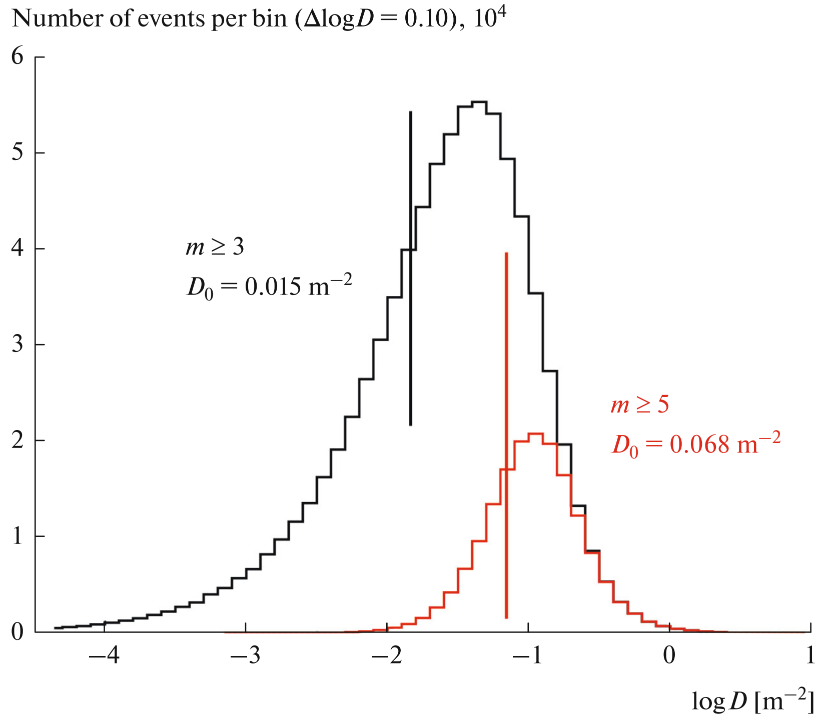

Fig. 1. Distribution of modeled events by local muon density for two selection conditions $m \geq 3$ and $m \geq 5$ tracks in the DECOR detector in the range of zenith angles $\theta = 75°–90°$. The vertical lines indicate the effective threshold values D_0 for the evaluation of integral LMDS.

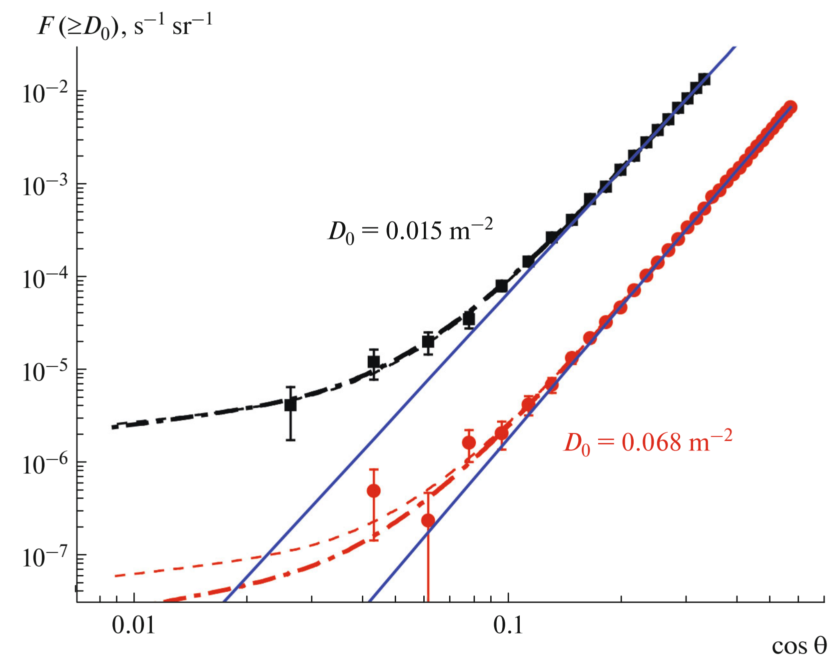

Fig. 2. Dependence of integral LMDS on cosθ for two selection thresholds $m = 3$ ($D_0 = 0.015$ m^{-2}) and $m = 5$ ($D_0 = 0.068$ m^{-2}). The straight, dashed-and-dotted, and dotted lines are approximations by Eqs. (1), (5), and (6), respectively.

The evaluation of the parameters of this equation using the NEVOD–DECOR experimental data by the least squares method yielded the following results:

— for the first sample at $\alpha = 4.61 \pm 0.21$,

$$a = 0.051 \pm 0.008, \quad p = 1.78 \pm 0.16, \quad \chi^2 = 7.05/15;$$

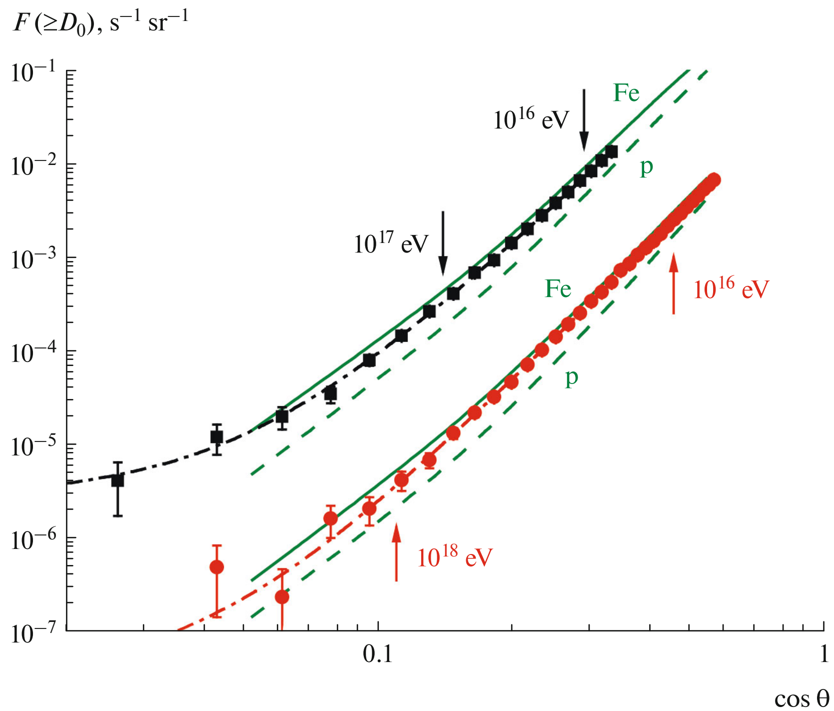

Fig. 3. Experimental and calculated (using the CORSIKA program) LMDS for two selection thresholds $D_0 = 0.015$ m^{-2} (upper points and lines) and $D_0 = 0.068$ m^{-2} (lower points and lines) and two variants of mass composition: iron nuclei (solid lines) and protons (dashed lines). The dashed-and-dotted line is an approximation of the experimental data using Eq. (5). The arrows indicate the estimates of the threshold energies of the PCL.

— for the second sample at $\alpha = 4.81 \pm 0.06$,

$$a = 0.041 \pm 0.012, \quad p = 1.86 \pm 0.21, \quad \chi^2 = 23.6/29.$$

The values of function (6) obtained with these parameters are shown in Fig. 2 (dashed-and-dotted lines). They are in good agreement with experimental data.

To make a quick assessment, one can use a simpler equation

$$\cos^{\alpha}\theta \rightarrow \left(\sqrt{\cos^2\theta + a^2}\right)^{\alpha}, \qquad (7)$$

which, within the error limits, also describes the experimental data well (Fig. 2, dashed lines).

The DECOR data on muon bundles were interpreted by calculating EAS using the CORSIKA program [11] with the CURVED option, which allows taking into account the sphericity of the Earth's atmosphere at zenith angles greater than 80°. The calculations were carried out in the range of zenith angles from 57° up to 87° using three interaction models (EPOS-LHC, QGSJET-II-04, SIBYLL-2.3c) under two assumptions about the mass composition of the primary rays: protons and iron nuclei. The energy spectrum of primary cosmic rays was modeled using the Global Spline Fit (GSF) approximation [12] and the standard atmosphere model proposed by Linsley, taking into account the Earth's magnetic field, which has a significant influence on the angular distribution of muons at large zenith angles [13].

Figure 3 presents the results. To exclude a large number of calculated curves, they were averaged over three interaction models, the maximum difference of which is about 15%. Figure 3 shows that the flattening of the zenith angle dependence of LMDS, which is observed in the experiment as the horizon is approached and is described using simple approximation (6), is confirmed by the results of modeling the muon component of EAS using the CORSIKA program. This indicates that the discovered feature has a natural origin, specifically, the sphericity of the Earth's atmosphere, the influence of which manifests itself in the development of extensive air showers near the horizon. Note that the experimental points lie between the curves calculated for primary protons and iron nuclei, but are closer to the calculation for the heavy mass composition. The primary particle energy threshold estimates calculated using the CORSIKA program are more than two orders of magnitude: from 5×10^{15} up to 2×10^{18} eV (depending on the zenith angle).

DISCUSSION

Unfortunately, the obtained result remains dependent both on the type of energy spectrum of primary cosmic rays and on the model of hadron interaction. The fact is that for the formation of the local density spectra of muons at energies above 10^{15} eV are responsible for three unknown functions: the energy spectrum of primary cosmic rays; their mass composition, which may depend on energy; and the model of hadron interactions. Therefore, by specifying two functions, one can estimate the third. The LMDS method was mainly used to estimate the mass composition under various assumptions about the interaction models, taking into account that the energy spectrum of cosmic particles was reconstructed from the results of studies of other EAS components, mainly electron–photon, as well as Cherenkov, fluorescence, and radio emissions.

The GSF energy spectrum in this energy region was obtained by compiling the EAS energy spectra that were measured at various facilities and were recalculated into the spectrum of primary cosmic rays within the framework of one or another hadron interaction model. Thus, a vicious circle is created. As for the models of hadron interactions, they are based on the results of experiments conducted at accelerators, primarily at the LHC. Extrapolation to the region of higher energies, currently inaccessible to accelerator technology, does not include any new physical processes responsible for the formation of muons.

As was shown [10], the only characteristic of EAS muons that can separate the influence of nuclear-physical (interaction model) and cosmophysical (energy spectrum and mass composition of primary cosmic rays) causes of changes in EAS characteristics is the muon energy. The inclusion of any new muon generation processes in the region of ultrahigh primary particle energies leads to an increase in the EAS muon energy. Any cosmophysical reasons for change in the characteristics of EAS (energy spectrum and mass composition) cannot significantly change the energy characteristics of muons in groups.

A preliminary estimate of the energy release of muon groups, which was made at the NEVOD–DECOR complex [14, 15], supports the first option, but the existing equipment does not allow for the necessary measurement accuracy. To solve the muon mystery, the NEVOD Cherenkov water detector and the DECOR coordinate detector are currently being modernized, and a new coordinate detector TREK [16] is being created, which covers the entire side surface of the NEVOD Cherenkov water detector.

CONCLUSIONS

Based on the NEVOD–DECOR experiment data for more than 75 000 h of measurements, integral spectra of the local muon density at large zenith angles were obtained for two values of the effective threshold of the muon density (0.015 and 0.068 m^{-2}).

An equation for the zenith-angle dependence of LMDS was obtained, which takes into account the sphericity of the atmosphere at $\theta > 80°$. This equation describes the experimental data well and agrees with the results of modeling the EAS component using the CORSIKA program.

The experimental data on integral LMDS are consistent with the results of calculations assuming a heavy composition (iron nuclei) of primary cosmic rays for the post-LHC interaction models and the GSF model of the energy spectrum of primary cosmic rays.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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