Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008

Vol. 5 (HE part 2), pages 1205–1208

30TH INTERNATIONAL COSMIC RAY CONFERENCE

Measurements of absolute muon intensity at zenith angles from 20° to 90°

A.N. DMITRIEVA[1], D.V. CHERNOV[1], R.P. KOKOULIN[1], K.G. KOMPANIETS[1], G. MANNOCCHI[2],
A.A. PETRUKHIN[1], O. SAAVEDRA[3], V.V. SHUTENKO[1], D.A. TIMASHKOV[1], G. TRINCHERO[2], I.I. YASHIN[1]
[1] *Moscow Engineering Physics Institute, Moscow 115409, Russia*
[2] *Istituto Nazionale di Astrofisica, Sezione di Torino, 10133 Torino, Italy*
[3] *Dipartimento di Fisica Generale dell Universita di Torino, 10125 Torino, Italy*
ANDmitriyeva@mephi.ru

Abstract: High-statistics data collected with Russian-Italian coordinate detector DECOR are analyzed. Precise measurements of muon angular distributions in zenith angle interval from 20° to 90° have been performed. In total, more than 160 million muons have been selected. Dependences of the absolute integral muon intensity on zenith angle for several threshold energies ranging from 1.5 GeV up to 7.2 GeV have been derived. Measurements for all thresholds have been done with a single setup that minimizes systematic uncertainties. The dependence of integral intensity on zenith angle and threshold energy is well fitted by a simple analytical formula. Comparison with data of other experiments at close values of zenith angles and threshold energies shows a reasonable agreement.

Introduction

Studies of angular and energy dependence of muon flux at the Earth's surface give important information as about processes of muon generation and propagation in the atmosphere so about primary cosmic rays. Measurements of muon flux at large zenith angles up to 90º are especially interesting since primary particles for such muons have higher energies than in the vertical direction. Experimental studies of muon intensity at large zenith angles at the ground level can be conditionally separated in two groups: measurements of muon integral intensity with threshold energies less than about 1 GeV [1]–[7] (with the exception of [8] with threshold energies up to 3 GeV) and investigations of integral and differential muon spectra for energies higher than 10 GeV (see review [9]). Regions of measurements of muon spectrum at large zenith angles are presented in Figure 1. To explore the region from 1 to 10 GeV, a setup capable to measure near-horizontal muon flux at different threshold energies with a good angular accuracy of track reconstruction is needed. Coordinate detector DECOR, which is a part of experimental complex NEVOD (MEPhI, Moscow), is such a detector. Regions of threshold energies and zenith angles accessible for DECOR and analyzed in this work are shown by the dashed areas in Figure 1.

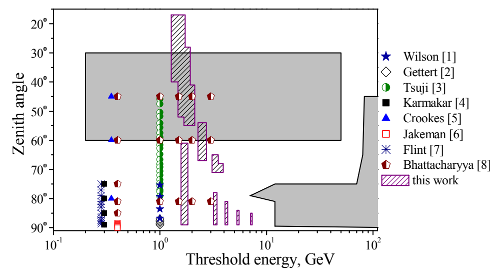

Figure 1: Regions of muon spectrum measurements. Symbols represent the measurements of integral intensity; shaded areas are the regions of differential spectrum measurements. Dashed areas are the regions investigated in the present work.

Experimental setup; events selection

Experimental complex NEVOD includes a water Cherenkov calorimeter NEVOD [10] with volume 2000 m^3 equipped with quasispherical modules of PMTs, and large-area (~ 110 m^2) coordinate detector DECOR [11] (Figure 2). Eight supermodules (SM) of DECOR are situated in the gallery around the water tank (SIDE-DECOR, ~ 70 m^2) and four SM on its cover (TOP-DECOR, ~ 40 m^2). The side SM (respectively, top SM) represents eight parallel planes, arranged vertically (horizontally) with 6 cm (11.5 cm) distance from each other. These planes consist of 16 (20) chambers, each containing 16 tubes with inner cross-section 0.9 cm × 0.9 cm. Chambers are operated in a limited streamer mode and are equipped with two-coordinate external strip read-out system. Thus, coordinates of passing particle can be obtained for each plane with spatial accuracy of muon track location ~ 1 cm. First level trigger is formed when there are at least two even and two odd triggered planes in a given SM.

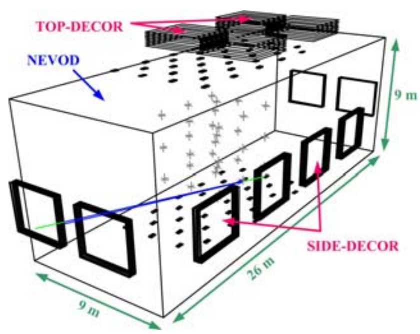

Figure 2: Experimental complex NEVOD-DECOR.

For the analysis, two types of events were selected: 1) particles passing through two SM situated at different sides of the water pool (data collected over a period from December 2002 to June 2003 are analyzed); 2) particles passing through one of the top SM and one of the side SM (December 2004 – April 2005). Total time of registration is equal to 3390 and 1627 hours correspondingly. Total statistics exceeded 160 million selected events. Different pairs of SM correspond to different values of threshold energy. Accuracy of zenith angle reconstruction for tracks passing through selected SM pairs is 0.3°-0.5°. Selection procedure includes the following conditions. 1) "OneTrack" criterion: two tracks reconstructed from data of different supermodules must coincide within 5º cone. In this case the tracks in separate SMs are considered as tracks of the same particle, and straight line connecting the middles of two reconstructed track segments is taken as the trajectory of particle. 2) The events in which muon passed closer than 3 cm to the boundary of SM are rejected in order to decrease the edge effects. 3) There must be two and only two track projections (X, Y) in each SM for unambiguous reconstruction of geometrical characteristics of muon track (the absence of accompanying particles).

Results

Threshold energy $E_{\min}$ of muons passing through the selected pair of SM is calculated by means of range-energy tables [12]. It is calculated for each selected event, and then the event is placed in data array $N(\theta,\varphi,E_{\min})$. The bin of zenith angle $\Delta\theta = 1º$, the bin of azimuth angle $\Delta\varphi = 0.5º$, the bin of threshold energy $E_{\min} = 250$ MeV for the first data set and $E_{\min} = 450$ MeV for the second one. Integral muon intensity is calculated in the following way:

$$I(\theta,\varphi,E_{\min}) = \\ = \frac{N(\theta,\varphi,E_{\min})}{T\cdot\varepsilon_{SM1}\cdot\varepsilon_{SM2}\cdot\varepsilon_{add}\cdot S\Omega(\theta,\varphi,E_{\min})} \quad (1)$$

where $N(\theta,\varphi, E_{\min})$ is the number of registered muons in a given angular and threshold energy bin; T is "live time" of registration. The parameter ε_{SM} is the efficiency of single SM triggering, and ε_{add} takes into account event rejection because of accompanying particles. Results of simulations and additional experimental data analysis give the following values: 1) $\varepsilon_{SM} = 0.936 \pm 0.004$ (first period) and 2) $\varepsilon_{SM} = 0.993 \pm 0.0014$ for side SM and $\varepsilon_{SM} = 0.970 \pm 0.001$ for top SM (second period); ε_{add} varies from 0.83 to 0.91 for different θ and $E_{\min}$ (uncertainty of ε_{add} is less than 0.35%). The function $S\Omega(\theta,\varphi, E_{\min})$ is the setup acceptance calculated by means of MC method taking into account the structure of SM and selection requirements. Absolute muon intensity averaged in azimuth angle for some values of zenith angle in the range $17° \le \theta \le 71°$ is presented in Table 1 and is shown in Figure 3 (points). Errors in the table include statistical and systematical uncertainties (uncertainty of threshold energy estimation, uncertainty of ε_{SM}, muon energy loss in the walls of surrounding buildings). Our numerical data for zenith angles $61° \le \theta \le 89°$ and threshold energies 1.7, 3.3, 4.2, 5.4, and 7.2 GeV may be found in [13].

Table 1: Dependence of integral muon intensity on zenith angle for different threshold energies ($I_\mu \cdot 10^4$, (cm^2 s sr)$^{-1}$).

θ	1.5 GeV	1.7 GeV	1.9 GeV
17	43.4±0.7		
18	43.1±0.7		
20	42.7±0.6		
22	41.8±0.6		
24	40.3±0.6		
26	39.2±0.6		
28	38.3±0.5	35.7±0.6	
30	37.3±0.5	34.7±0.5	
32	36.1±0.5	33.8±0.5	
34	34.9±0.5	32.5±0.5	
36	33.8±0.4	31.4±0.4	
38	32.7±0.4	30.0±0.4	
40	31.2±0.4	28.9±0.4	
42		27.6±0.4	26.5±0.3
44		26.1±0.3	25.3±0.2
46		24.4±0.3	23.7±0.2
48		23.3±0.3	22.0±0.2
50		21.4±0.3	20.6±0.2
52		19.6±0.3	18.9±0.2
54			17.9±0.1
	2.5 GeV	3.3 GeV	
54	14.6±0.1		
56	14.1±0.1		
58	13.2±0.1		
60	12.10±0.08		
62	10.78±0.08		
64	9.31±0.06		
65	9.14±0.06	7.87±0.08	
66	8.11±0.06	7.48±0.07	
67	7.61±0.07	6.96±0.06	
68		6.44±0.06	
69		6.07±0.06	
70		5.48±0.06	
71		4.69±0.07	

Approximation formula

For approximation of measured experimental data, the following simple formula is used:

$$I_{\text{app}}(\theta, E_{\min}) = \frac{C_1}{E_1^{\gamma}} \cdot \cdot \exp\left(-\frac{\gamma}{\gamma+1} \cdot \frac{E_{\text{cr}}}{E_1 + a \cdot h_1} \cdot \ln\left(\frac{h_0}{h_1 \cdot \cos\theta^*} \right) \right). \quad (2)$$

The factor in front of the exponent reflects the form of muon spectrum in the upper atmosphere, and the exponential function takes into account muon decay. Here C_{I} is the normalization; $E_1 = E_{\min} + a \cdot (h_0/\cos\theta^* - h_1)$ is the threshold muon energy (GeV) at production level. In this formula $a = 2.5 \cdot 10^{-3}$ GeV·cm^2/g is effective specific energy loss; $(h_0/\cos\theta^* - h_1)$ is the path of muon in the atmosphere; $h_0 = 1018$ g/cm^2 is the total thickness of atmosphere (altitude of setup location above see level is taken into account); h_1=100 g/cm^2 is the effective depth of muon generation. $E_{\text{cr}} = z_0 \cdot m/(c \cdot \tau_0 \cdot \cos\theta^*)$ is the effective critical energy for muon decay; z_0 is the effective length at which the density of atmosphere is changed by a factor of e; c is the velocity of light; τ_0 is muon life time and m is its mass (GeV); $\cos\theta^* = (\cos^\alpha\theta + \Delta^\alpha)^{1/\alpha}$ is the approximation of the effect of atmosphere sphericity. As a result of fitting, the following values of free parameters were obtained: $C_{\text{I}} = 0.0874$, $\gamma = 1.94$, $z_0 = 5.78$ km, $\Delta = 0.054$ and $\alpha = 1.4$.

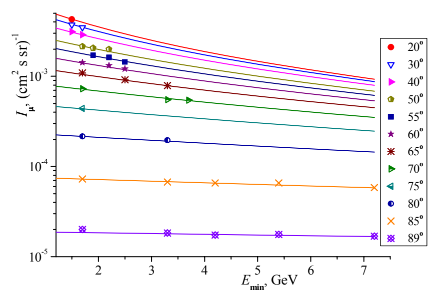

Figure 3: Dependence of absolute muon intensity on threshold energy at several zenith angles. Symbols: experimental data; curves represent the fit by formula (2).

Discussion

In Figure 3, the present experimental data on integral muon intensity and their fit by formula (2) are shown. Dependence of integral muon intensity on zenith angle calculated for lower thresholds (1 and 0.3 GeV) and experimental data of earlier measurements [1]–[8] are presented in Figure 4. Comparison of calculated values with data [1,4,5,7,8] shows a reasonable agreement. In works [2] and [6], the intensity is somewhat higher than measured in [1] or calculated by formula (2). The integral intensity data at E_{min} =1 GeV obtained in [3] decrease with the increase of zenith angle more slowly than it follows from [1] and calculations by (2), but at angles less than 72º the agreement is quite well. In Figure 5, integral muon intensity calculated by formula (2) for several zenith angles (the curves) and present experimental data (points) are compared with results of [4] and [8] (points). Comparison shows a good agreement for next zenith angles: 0° [4] and 45°, 60°, 75° [8]. For vertical direction the integral intensity from work [8] decreases with the increase of threshold energy more slowly. But for zenith angle equal to 81° the situation is inverse.

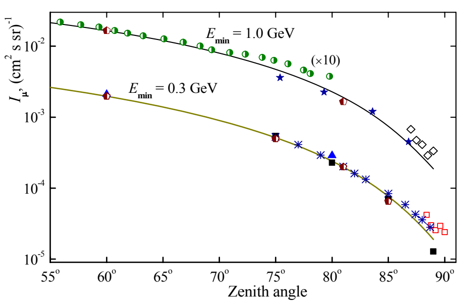

Figure 4: Dependence of absolute muon intensity on zenith angle for thresholds 0.3 and 1 GeV. Curves are calculation results by formula (2). Symbols for experiments are the same as in Figure 1.

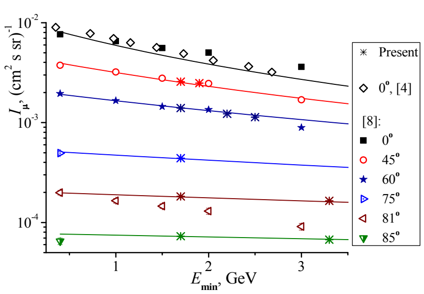

Figure 5: Comparison of present experimental data and calculations by formula (2) with results of [4] and [8].

Conclusion

Experimental data of coordinate detector DECOR for integral muon intensity cover the region of threshold energies $1.5 \le E_{min} \le 7.2$ GeV and zenith angles $17º \le \theta \le 89º$. It is important to mark that the measurements for all thresholds were performed with a single setup, that minimizes systematic uncertainties. Comparison of energy dependence and extrapolation of the present data to lower thresholds shows that with few exceptions there is a good agreement with the results of other measurements.

Acknowledgments

The research is performed at the Experimental Complex NEVOD with the support of the Russian Federal Agency of Education and Federal Agency for Science and Innovations.

References

[1] B.G. Wilson, Can. J. Phys. 37, 19, 1959.
[2] M. Gettert et al., Proc. 23th ICRC, Calgary, 4, 394, 1993.
[3] S. Tsuji et al., Proc. 24th ICRC, Rome, 1, 614, 1995.
[4] N.L. Karmakar, A. Paul and N. Chaudhuri, Nuovo Cimento B, 17, 173, 1973.
[5] J.N. Crookes and B.C. Rastin, Nucl. Phys. B, 39, 493, 1972.
[6] D. Jakeman et al., Can. J. Phys., 34, 432, 1956.
[7] R.W. Flint, R.B. Hicks, and S. Standil, Can. J. Phys., 50, 843, 1972.
[8] D.P. Bhattacharyya, Phys. Rev. D, 13, 566, 1976.
[9] P.K.F. Grieder, "Cosmic rays at Earth", Elsevier, 2001.
[10] V.M. Aynutdinov et al., Astrophysics and Space Science, 258, 105, 1998.
[11] M.B. Amelchakov et al., Proc. 27th ICRC, Hamburg, 3, 1267, 2001.
[12] D.E. Groom, N.V. Mokhov, and S.I. Striganov, Atomic Data and Nuclear Data Tables, 78, 308, 2001.
[13] A.N. Dmitrieva, D.V. Chernov, R.P. Kokoulin, et al., arXiv:hep-ex/0611051.