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Measurements of integral muon intensity at large zenith angles

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Results of the analysis of near-horizontal muons integral intensity data for threshold energies 1.2 – 1.9 GeV measured by means of coordinate detector DECOR in zenith angle interval 61˚– 90˚ are presented. Experimental results for these regions of zenith angles and threshold energies have been obtained for the first time. These data as well as data of other experiments with smaller threshold energies are well described by a simple formula taking into account muon energy loss and decay in atmosphere.

1. Introduction

Studies of angular and energy dependence of muon flux at the Earth's surface give very 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 down to 90˚ are especially actual since primary particles for such muons have higher mean energies than in vertical direction. Experimental researches 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 1 GeV [1-7] and investigations of integral and differential muon spectra for muon energies higher than 10 GeV (see review [8] and also [9–12]). Regions of measurements of muon spectrum at large zenith angles are presented in Fig. 1. It is remarkable that for threshold energies from 1 GeV to 10 GeV and zenith angles $60^\circ \leq \theta \leq 90^\circ$ muon intensity data are absent.

To explore this region, 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, being a part of experimental complex NEVOD (MEPhI, Moscow), is such a detector. Regions of threshold energies and zenith angles accessible for coordinate detector DECOR are shown by the dashed area in Fig. 1.

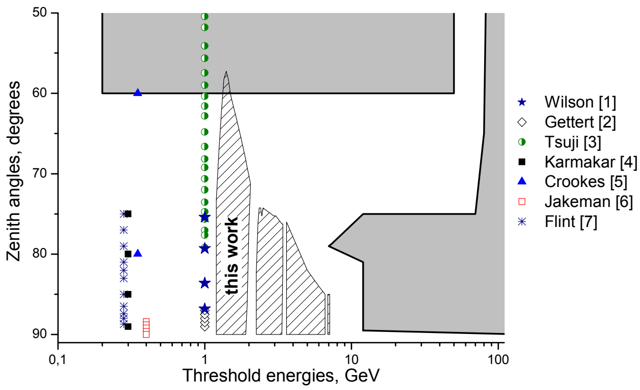

Figure 1. Regions of muon spectrum measurements at large zenith angles. Symbols represent the measurements of integral intensity, shaded areas are the regions of differential spectrum measurements [8].

2. Experimental setup and events selection

Experimental complex NEVOD includes a water Cerenkov calorimeter NEVOD [13] with sensitive volume 2000 m^3 equipped with quasispherical modules of PMTs, and large–area (~ 110 m^2) coordinate detector DECOR (Fig. 2). Eight supermodules (SM) of DECOR are situated in the gallery around the water tank, and four SM on its cover. SM of side part of DECOR represents eight parallel planes with sensitive area 3.1 m × 2.7 m, suspended vertically with 6 cm distance from each other. These planes consist of 16 chambers which contain 16 tubes with inner cross–section 0.9 × 0.9 cm^2. Chambers operate in a limited streamer mode provided by three-component gas mixture and are equipped with two-coordinate external strip read-out system. Thus, X and Y coordinates of passing particle can be obtained for each plane with spatial accuracy of muon track location ~ 1 cm that provides for SM angular accuracy of muon track reconstruction ~ 0.7° [14]. First level trigger is formed when there are not less than two even and two odd triggered planes in a given SM.

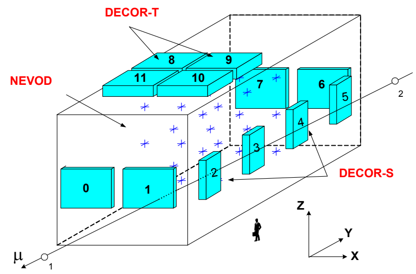

Figure 2. Experimental complex NEVOD–DECOR.

Data collected over a period from December 2002 to June 2003 are analyzed. Total time of registration is equal to 3390 hours. For the analysis, the pair SM1-SM2 (see Fig. 2) is used. Selection procedure includes the following conditions. 1) "OneTrack" criterion: two tracks reconstructed from data of different supermodules must coincide within 5° cone. In this case the tracks in separate SM are considered as tracks of the same particle. Straight line passing through the points of intersection of reconstructed tracks with geometrical planes parallel to corresponding SMs and situated at their middles is taken as the trajectory of the particle. 2) There must be two and only two track projections (X,Y) in each SM for correct reconstruction of geometrical characteristics of muon track (the absence of accompanying particle). 3) The events in which muon passed closer than 3 cm from the boundary of SM are rejected to decrease edge effects. The total number of selected events equals to about 15 millions.

3. Results

Integral muon intensity is calculated in the following way:

$$I(\theta,\varphi,E_{\min}) = \frac{N(\theta,\varphi,E_{\min})}{T\cdot\varepsilon_{SM}^2\cdot\varepsilon_{MCS}\cdot\varepsilon_{add}\cdot S\Omega(\theta,\varphi,E_{\min})} \quad (1)$$

where $N(\theta, \varphi, E_{min})$ is number of registered muons in a given angular ($\theta_i - \Delta\theta/2 < \theta < \theta_i + \Delta\theta$, $\Delta\theta = 1^\circ$, $\varphi_j - \Delta\varphi/2 < \varphi < \varphi_j + \Delta\varphi$, $\Delta\varphi = 1^\circ$, i,j = 1, 2, …) and threshold energy (ΔE_{min} = 50 MeV) bins. Threshold energy E_{min} of muons passed through SM1-SM2 is summarized from energy loss in water, concrete and outer brick wall using path-energy tables [15]. T is "live time" of registration. The parameter ε_{SM} is efficiency of single SM triggering, ε_{MCS} is efficiency of "OneTrack" criterion, and ε_{add} takes into account event rejection due to accompanying particles. Results of simulations and additional experimental data selection give the following values: $\varepsilon_{SM} = 0.936 \pm 0.004$, ε_{MCS} in the interval 0.95 – 1 for different θ and E_{min}, and $\varepsilon_{add} = 0.887 \pm 0.006$. The function $S\Omega(\theta, \varphi, E_{min})$ is the acceptance calculated by means of Monte

Carlo method taking into account the structure of SM and first level trigger requirement. Absolute muon intensity averaged in azimuth angle for zenith angles $61^\circ \le \theta < 90^\circ$ and threshold energies 1.2, 1.5 and 1.9 GeV is represented in Tabl. 2 (only statistical errors are shown). Total systematical errors due to uncertainty of parameters ε_{add} and ε_{SM} are equal to 0.7%. Additional systematical uncertainty reaching 2% appears for angles more than 85°, it is concerned with some uncertainty in threshold energy value caused by the buildings situated near experimental setup.

Table 1. Absolute muon intensity

θ, degrees	$I(\theta)\cdot 10^5$, $(\text{cm}^2\cdot \text{s}\cdot \text{sr})^{-1}$ 1.2 GeV	1.5 GeV	1.9 GeV
61		141.9 ± 2.5	
63		132.6 ± 1.1	
65		116.81 ± 0.74	
67		99.61 ± 0.54	
69		84.54 ± 0.41	
71		70.17 ± 0.32	66.2 ± 1.0
73		57.44 ± 0.26	53.99 ± 0.67
75	45.6 ± 1.9	45.21 ± 0.21	43.39 ± 0.54
77	36.89 ± 0.85	35.12 ± 0.16	33.46 ± 0.45
79	26.15 ± 0.50	25.84 ± 0.13	25.13 ± 0.38
81	17.81 ± 0.32	18.38 ± 0.10	17.99 ± 0.33
83	12.16 ± 0.22	11.967 ± 0.077	11.81 ± 0.27
85	7.36 ± 0.15	7.127 ± 0.056	7.06 ± 0.21
87	3.86 ± 0.10	3.920 ± 0.040	3.53 ± 0.15
89	1.836 ± 0.071	1.852 ± 0.028	1.90 ± 0.12

4. Approximation formula

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

$$I_{app}(\theta, E_{\min}) = \frac{I_o}{E_1^{\gamma}} \cdot \exp\left(-\frac{\gamma}{\gamma+1} \cdot \frac{E_{cr}}{E_1} \cdot \frac{l}{h} \cdot \ln\left(\frac{l}{h}\right)\right). \quad (2)$$

The factor before the exponent reflects the form of muon energy spectrum in the upper atmosphere (parameter γ is the index of integral energy spectrum); $E_1 = E_{min} + a\cdot l$ is muon energy at production. Here a is effective specific energy loss, $l = H / \cos\theta$ is the path of muon in the atmosphere. Exponential function in formula (2) takes into account muon decay. The parameter E_{cr} is the critical energy for muon decay for vertical direction. The parameters H and h are the total thickness of atmosphere (1 kg/cm^2) and effective depth of muon generation (100 g/cm^2), correspondingly; I_o is the normalization. Since at large zenith angles a flat atmosphere approximation cannot be applied, it is necessary to modify formula for path calculation in order to take into account the sphericity of the atmosphere in a following way: $l = H / (\cos^{\alpha}\theta + \Delta^{\alpha})^{1/\alpha}$. As a result of fitting, the following values of free parameters were obtained: $\gamma = 2.01$, $a = 3$ MeV·cm^2/g, $E_{cr} = 1.43$ GeV, $I_o = 0.1793$, $\Delta = 0.06$, $\alpha = 1.32$.

In Fig. 3, dependence of integral muon intensity on zenith angle calculated by Eq. (2) for three threshold energies (1.5 GeV, 1 GeV and 300 MeV) and experimental data of [1-7] as well as DECOR data are shown. Comparison of calculated values with data [1, 4 – 5, 7] and present results shows a good agreement. In works [2] and [6] the intensity is somewhat higher than measured in [1] or calculated by Eq. (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 calculation by Eq. (2), but at angles less than 70° the agreement is quite well.

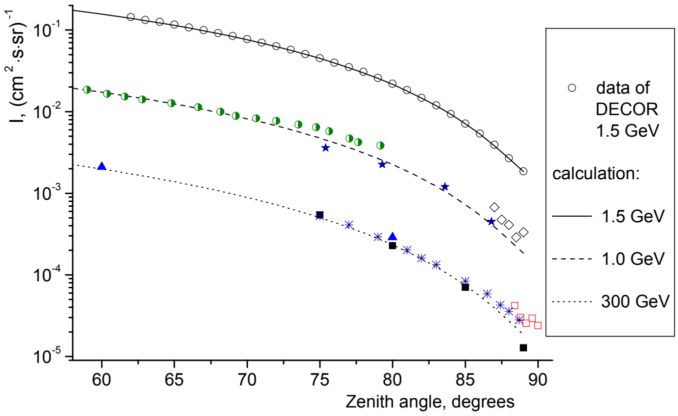

Figure 3. Dependence of absolute muon intensity on zenith angle at several threshold energies. Curves are calculation results by formula (2), values at threshold energy 1.5 GeV are multiplied by 100, at threshold energy 1 GeV are multiplied by 10. Symbols for other experiments are the same as in Fig. 1.

5. Conclusions

The experimental data of coordinate detector DECOR cover earlier unexplored region for integral muon intensity at threshold energies $1.2 < E_{min} < 2$ GeV and zenith angles $61^\circ \le \theta < 90^\circ$. These data are well described by a simple approximate formula which also shows a reasonable agreement with results of other experiments at large zenith angles with lower threshold energies.

6. Acknowledgements

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