MEASUREMENTS OF THE UPWARD-GOING MUON FLUX WITH THE BAKSAN UNDERGROUND TELESCOPE*

Совместно с М.М. Болиевым, А.В. Буткевичем, С.П. Михеевым,
О.В. Суворовой и В.Н. Закидышевым

Updated results of the observations of upward-going muons with the Baksan detector are presented for live time of more than 10 years. The measured flux of upward-going muons, averaged over the downward hemisphere with a threshold of 1 *GeV* is $I(E_\mu^\nu > 1GeV) = (2.72 \pm 0.16)\cdot 10^{-13} cm^{-2}s^{-1}sr^{-1}$. This shows agreement with the expected $(2.62 \div 2.94) \cdot 10^{-13}$ cm^{-2} s^{-1} sr^{-1} and with results of other groups after threshold corrections.

1 Introduction

The interpretation of the anomaly in the flavour composition of the flux of atmospheric neutrinos, reported by several groups [1], depends on the absolute normalization of the flux of atmospheric neutrinos. Using as input different calculations [2] of the atmospheric neutrino spectra one can find either a deficit of muon events or an excess of electron events. Accurate measurements of the neutrino induced muon flux as a function of zenith angle and energy provide data which in comparison with the other sets of data could help provide the solution to this problem. In this paper we report results of the observation of upward-going muons carried out with the Baksan Underground Telescope [3] since December of 1978.

2 Experimental data

The detection of upward-going muons is performed by means of the time-of-flight method [4]. Two hardware triggers are used in order to reject downward-going atmospheric muons. Trigger I covers the zenith angle range 95° ÷ 180° while trigger II selects horizontal muons in the range 80° ÷ 100°. The hardware trigger efficiency of 99% has been measured with the flux of atmospheric muons. These triggers select 0.1% of the initial rate, giving ≈ 1800 events per day for further processing. The majority of the residual events ale caused by inclined multiple muons, which are reconstructed by an offline program (for more details see ref. [4]).

The positions of hit tanks give the particles trajectory while the direction is determined by measurements of $1/\beta$. The following convention is used: the value of $1/\beta$ around +1 is expected for downward-going muons while $1/\beta$ around - 1 is expected for

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upward-going particles. The program selects candidates for upward-going muon events if there is only one reconstructed track and $1/\beta$ is in the range $-1.3 \div -0.7$. However, all events with negative values of $1/\beta$ have been scanned by eye to check possible misinterpretation. Measurements of the distribution of $1/\beta$ for downward-going muons have shown that 95% of single muon tracks are within the range $0.7 \div 1.3$. Additional cuts have been applied to avoid the background caused by atmospheric muons scattered at large angles in the surrounding rock. The particles with zenith angles of $90° < \vartheta < 110°$ and azimuthal of $180° < \phi < 360°$ were excluded. For these arrival directions the flux of scattered muons is expected to be comparable to the neutrino induced muon flux. The data used for this analysis have been collected from December of 1978 until November of 1993, with 10.55 live-years. It was found that 682 events survived these cuts. Thus the rate of upward-going muons measured by the Baksan Underground Scintillator Telescope is 0.177 ± 0.006 events per day.

3 Flux determination and calculations

For flux meaaurements we have used the sample of 424 events that satisfied the following additional criteria: i) the muon trajectory must have entry and exit points (stopping muons and neutrino interactions inside the detector are excluded), and ii) muon range inside detector must correspond to muon energy of 1 *GeV* or more. Also, for trajectories crossing only two scintillator planes (trigger II) we have excluded tracks having entry or exit points closer than l.5 *m* to the plane edge or time-of-flight less than 35 *ns*. In Fig. 1a we show the angular distribution of these events. In Fig. 1b the distribution in *cos(θ)* of the measured flux of upward-going muons is shown together with the muon flux expected from atmospheric neutrino interaction with rock underneath the detector. The integral muon flux as a function of *cos(θ)* has been obtained by

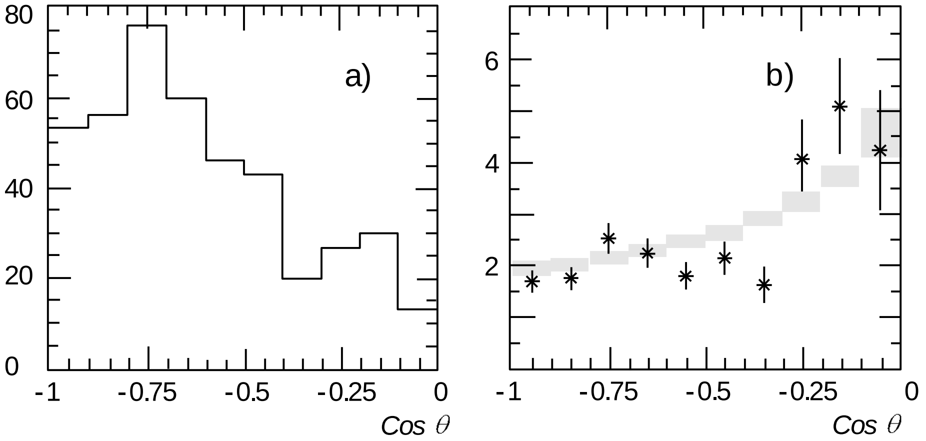

Figure 1: *a) Distribution in cos(θ) (number of events per bin) for upward-going muons observed with the Baksan Underground Scintiltator Telescope. b) Distribution in cos(θ) ($dF(E_\mu>1$ GeV)/ dCosθ x 10^{13} cm^{-2} s^{-1} sr^{-1}) for the upward-going muon flux with threshold energy 1 GeV. Experimental points are shown with statistical errors only. The shaded regions are expectations (see text for*

$$I_{\mu}^{\nu}(E_{th},\cos(\theta_i)) = \frac{N(E_{th},\cos(\theta_i))}{T\cdot\int\limits_{\Omega_i} S'(E_{th},\Omega_i)\, d\Omega_i}\,. \qquad (1)$$

Here $N(E_{th},cos(\theta_i))$ is the number of events in a given angular bin with range inside detector equal or greater than the range for muons with energy E_{th}, and T is the observation time. The function $S'(E_{th},\Omega_i)$ is given by

$$S'(E_{th},\Omega) = \int\limits_{E} S(E,\Omega)\cdot\varepsilon\,(E_{th},E,\Omega)\cdot\Phi_{\mu}^{\nu}(E,\Omega)\, dE\,, \qquad (2)$$

where $S(E,\Omega)$ is the effective detector area (calculated by accounting all cuts), $\varepsilon\,(E, E_{th}, \Omega)$ is the plobabillty that a muon with energy E crossing the detector gives a trajectory which corresponds to threshold energy E_{th}, and $\Phi_{\mu}^{\nu}(E,\Omega)$ is the differential muon flux produced by neutrinos. Then the flux averaged over the downward hemisphere can be calculated simply as the mean value of the zenith-angle distribution. The result is found to be $(2.72 \pm 0.13)\cdot 10^{-13}$ $cm^{-2}\,s^{-1}\,sr^{-1}$. This approach requires *a priori* knowledge of neutrino induced muon spectrum. However, because the shape of muon spectrum is well established, it gives an additional systematic uncertainty of less than 3%.

The flux of upward-going muons induced by neutrinos can be obtained by the convolution of the neutrino flux, the neutrino interaction cross-sections, and muon propagation in the surrounding rock. In real calculations we have used the conventional expression for the cross-section of neutrino charged current interactions on isoscalar targets. The structure functions F_2 and xF_3 have been calculated with EHLQ-parton distributions [5] and multiplied by factors of 1.13 and 1.11 correspondingly. These corrections give agreement with recent accelerator data at energy > 20 GeV with accuracy of 5%. The muon propagation has been calculated for Baksan rock using the energy-loss parameterizations given by Lohman et al. [6]. We estimate the uncertainties in the final result that arise due to uncertainties in muon energy-loss to be of the order of 2%. It is well known that the main uncertainties in the calculation of upward-going muon flux is due to the absolute normalization of the atmospheric neutrino flux. Neutrino induced muon fluxes with E_{th} > 1 *GeV* calculated with different neutrino spectra [7] - [11] are in the range $(2.62 \div 2.94)\cdot 10^{-13}$ $cm^{-2}\,s^{-1}\,sr^{-1}$. The least value corresponds to the neutrino spectrum calculated in Ref. [7] while the largest to that in Ref. [11]. The shaded area in Fig. 2 shows the variation of predicted fluxes for each bin when different calculations of the neutrino spectra are used. It is seen that there is good agreement within experimental and theoretical uncertainties.

4 Comparison with other experiments

Two experimantal groups have also reported the results of measurements of the integral flux of upward-going muons averaged over the downward hemisphere. The measured fluxes in units of 10^{-13} cm^{-2} s^{-1} sr^{-1} are: (3.02 ± 0.19) with energy threshold 1 *GeV* for the IMB-3 experiment, (2.19 ± 0.16) with threshold 1.8 *GeV* for the IMB-1,2 experiment [12], and (2.04 ± 0.13) with threshold ≈ 3.0 *GeV* for the Kamiokande detector [13]. The experimental results and expected fluxes as a function of threshold energy are shown in Fig. 2. One can see satisfactory agreement of the results measured by different groups.

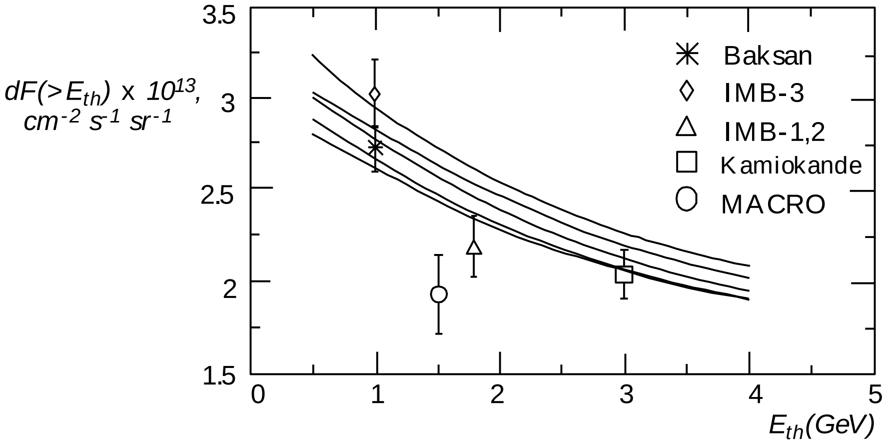

Figure 2: *Observed and expected fluxes of upward-going muons as a funciton of the threshold muon energy. Curves are expected fluxes, calculated with neutrino spectra (bottom to top) [7], [8], [9], [10], [11]*

The MACRO Collaboration has also reported the result of measurements of upward-going muons [14]. The ratio of the observed number of events to that expected with neutrino flux [10] is $0.73 \pm 0.09_{stat.} \pm 0.06_{sys.}$. We show this result in Fig. 2, scaling by factor of 0.73 as calculated by us neutrino induced muon flux using neutrino spectrum [10] and assuming effective energy threshold of the MACRO detector to be of 1.5 *GeV*.

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