Measurements of albedo muon intensity at the Earth's surface

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Abstract

The experimental complex NEVOD-DECOR provides the possibility to select muons arriving in ascending direction with two independent methods: by means of the time-of-flight analysis, and using the directionality of Cherenkov light in water. On the basis of the data collected during experimental runs 2002-2003, the first statistically ensured estimates of albedo muon flux with 7 GeV energy threshold in zenith angle range up to 95° have been obtained.

1. Introduction

From the point of view of background estimation for neutrino experiments, especially near the Earth's surface, investigations of muon flux close to horizon, including albedo muons with arriving zenith angles exceeding 90°, are important. But there are very few experiments on albedo muons near the surface [1].

The coordinate detector DECOR [2] is a part of the experimental complex arranged at the Earth's surface. The basis of the complex is a multipurpose water Cherenkov calorimeter NEVOD [3] with sensitive volume 2000 m^3. The detection system of NEVOD is represented by a regular spatial lattice of quasisphrerical measuring modules (QSM) [4]. The DECOR setup consists of 12 eight-layer assemblies (supermodules) of limited streamer tube chambers. Eight vertical supermodules (SM), each with area 8.4 m^2, located in the galleries around Cherenkov calorimeter, represent the side coordinate detector intended for investigations of horizontal cosmic ray flux. Each SM provides accuracy of measurements of zenith and azimuth angles 0.75° and 0.78°, respectively. In the present paper, the technique of selection of up-going (albedo) muons by means of NEVOD-DECOR setup is described, and estimates of their intensity are discussed.

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2. Albedo muon selection

Data collected over periods 04.02.2002 – 13.07.2002 and 15.12.2002 – 28.02.2003 (4428 hr live time) were used. Events detected in supermodules of opposite short galleries (Fig.1) were selected. As single muon candidates, the events in which two (and only two) SM were triggered, and the tracks reconstructed on the basis of the data of separate supermodules coincided within 5° cone, were accepted. Then the middles of track segments within each SM were connected by a line, which represented the "average" muon track. For such tracks, the energy threshold is about 7 GeV, zenith angle range is $\theta = 85 - 95°$, and the geometrical factor of the detector is 2×0.34 m^{2}sr. In total, about 10^6 tracks were found.

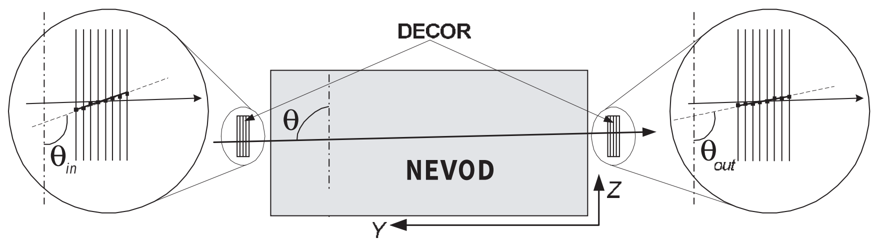

Fig. 1. Scheme of the event with albedo muon. Definition of main angles.

Two independent techniques are used to identify the direction of particle motion: one of them is based on the time-of-flight measurements with coordinate detector SM, whereas the other method utilises the directionality of Cherenkov light detected by QSM. The direction is considered determined, if the difference of the numbers of QSM indicating opposite directions of particle motion along the water tank (ΔN_Y) is more than some threshold value. At selection of the events by means of the timing information, it was required that the measured time-of-flight was more than the respective threshold Δt_{cr}.

In order to optimise the selection parameters, the capability of each method was studied with a test sample of the events selected by means of the other technique with sufficiently rigid criteria. It was found that the requirement $\Delta N_Y \geq 2$ ensures the rejection factor for events with erroneous direction determination $R_{QSM} = (3.6 \pm 0.4) \cdot 10^{-4}$ at useful event selection efficiency $\eta_{QSM} = 0.97$. Accordingly, for time-of-flight technique with $\Delta t_{cr} = 25$ ns, respective values are $R_t = (2.5 \pm 0.1) \cdot 10^{-3}$ and $\eta_t = 0.99$. These two methods are practically independent, and their joint application provides:

$$\eta = \eta_{QSM} \times \eta_t \approx 0.96; \quad R = R_{QSM} \times R_t \approx (9 \pm 1) \cdot 10^{-7}. \tag{1}$$

This rejection factor is sufficient for reliable selection of muons with zenith angles $> 90°$ in the angular range considered here. After the direction of particle motion was determined, every event was characterised with three estimates of zenith angle: "average" track inclination θ, and zenith angles measured in input and ouput supermodules θ_{in}, θ_{out} (see Fig.1).

3. Results

By means of the above techniques, the direction for 8.75×10^5 events was determined. Distribution of these events in zenith angle estimate is presented in Fig.2a. The intensity of muons for angles $\theta > 91°$ was calculated as follows:

$$I_\mu = \Delta N/(T \cdot \Delta S\Omega \cdot \eta \cdot \varepsilon). \tag{2}$$

Here ΔN is the number of particles in a given angular bin, $\Delta S\Omega$ is corresponding geometrical factor calculated by means of MC simulation, T is live time, η - efficiency of particle motion direction determination, and $\varepsilon \approx 0.8$ is the triggering and geometry reconstruction efficiency. Results based on 864 selected events with $\theta > 91°$ are shown in Fig.2b. The statistical errors are plotted only; systematic uncertainties are about 10%.

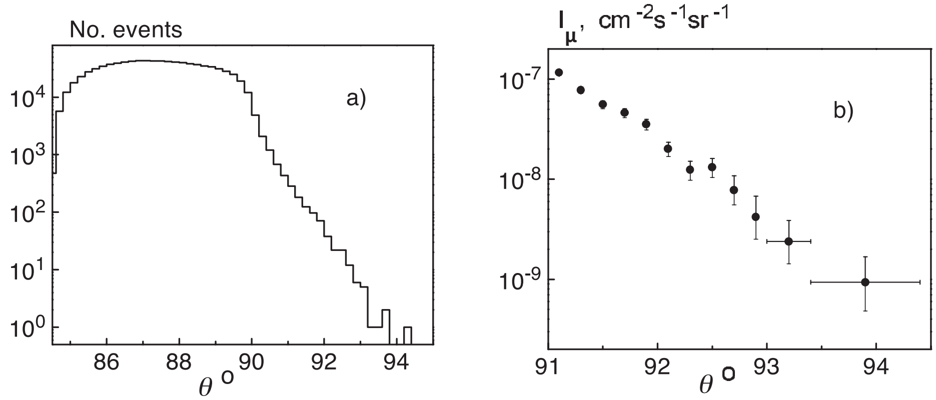

Fig. 2. Left: distribution of selected single muon events in zenith angle estimate. Right: estimated flux of albedo muons with energy more than 7 GeV.

The availability of information on track angles measured in input and output supermodules (θ_{in}, θ_{out}) gives the possibility to check the origin of the events with ascending "average" tracks. In principle, there are four possible combinations of directions at input and output: *up-up* (scattering in surrounding ground outside the detector); *down-up* (scattering inside the water volume); *up-down* (secondary scattering of albedo muon) and *down-down* (imitation of albedo event by a pair of different particles); besides, random coincidences are possible that would contribute equally to all these combinations. The scatter plot of albedo muon candidates (with $\theta > 92°$) in the plane (θ_{in}, θ_{out}) is shown in Fig.3a. More than 80% of the events are contained in the quadrant $\theta_{in}, \theta_{out} > 90°$ that corresponds to albedo events formed in the surrounding ground.

In Fig.3b, distributions of events in spatial angle between the "average" track and track measured in output supermodule for down-going muons ($\theta < 89°$) and for albedo events are confronted. For down-going particles (histogram), distribution is determined mainly by reconstruction errors, since contribution of multiple scattering in water volume for nearly horizontal atmospheric muons (average energy 100 GeV) is small. A more wide distribution for muons with $\theta > 91°$ (points) indicates that albedo flux is formed by relatively low energy particles (close to the detection threshold).

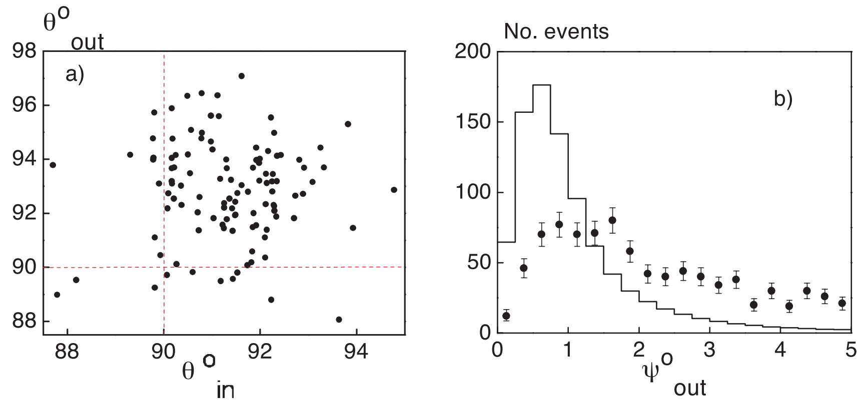

Fig. 3. Left: distribution of albedo candidates with $\theta > 92°$ in the plane (θ_{in}, θ_{out}). Right: distributions of spatial angle between "average" track direction and track measured in output SM for usual and albedo muons. Histogram for down-going muons is normalised to the total number of albedo events.

4. Conclusion

Events corresponding to detection of up-going muons in zenith angle range $91 - 95°$ have been selected, and the first estimates of albedo muon flux at the Earth's surface with threshold energy 7 GeV have been obtained. The intensity of up-going muons in the explored angular range nearly exponentially decreases with zenith angle. However, at $\theta \approx 94°$ it is still about 4 orders of magnitude higher than the flux of muons induced by atmospheric cosmic ray neutrinos.

5. References

1. Abbrescia M. et al. 1993, Proc. 23rd ICRC 4, 430
2. Amelchakov M.B. et al. 2001, Proc. 27th ICRC 3, 1267
3. Aynutdinov V.M. et al. 1998, Astrophysics and Space Science 258, 105
4. Borog V.V. et al. 1979, Proc. 16th ICRC 10, 460