Unique Scientific Facility
Experimental Complex
NEVOD

Investigation of the flux of albedo muons with NEVOD-DECOR experimental complex

CR-EX Poster 1
Paper: 391
Board: 235

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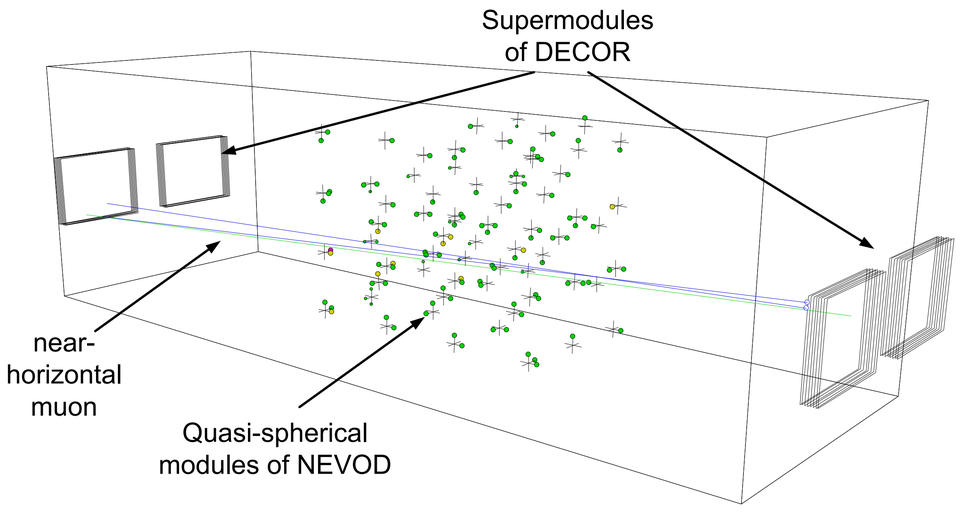
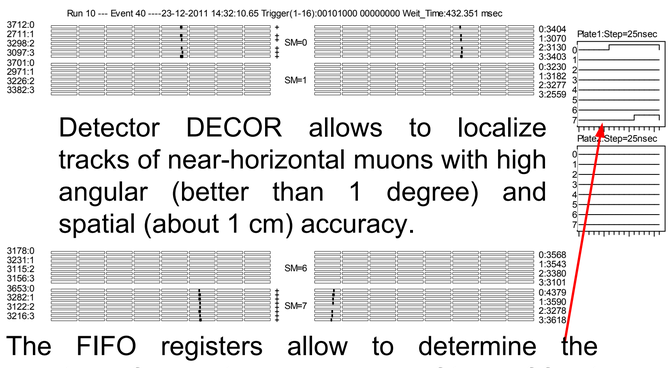
ICRC
The Astroparticle Physics Conference
34th International Cosmic Ray Conference
July 30 - August 6, 2015
The Hague, The Netherlands

The experimental complex NEVOD



Coodinate detector DECOR response

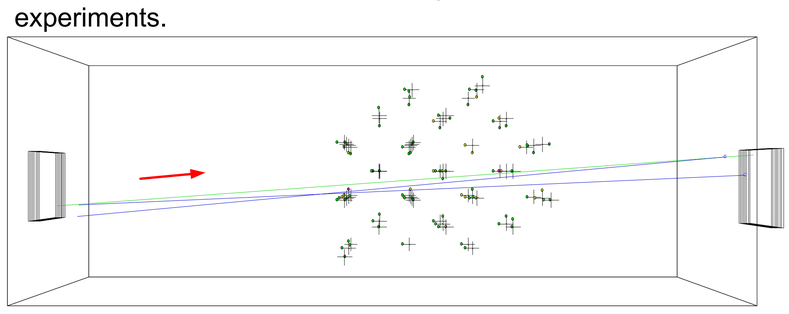


Detector DECOR allows to localize tracks of near-horizontal muons with high angular (better than 1 degree) and spatial (about 1 cm) accuracy.

The FIFO registers allow to determine the direction of muon track by means of time-of-flight technique.

Albedo muons

Atmospheric muons coming from the upper hemisphere may scatter in the soil or water (ice) and thus come from the lower hemisphere; these are so-called albedo muons. Such muons are one of the main sources of the non-apparatus background in shallow depth neutrino experiments.

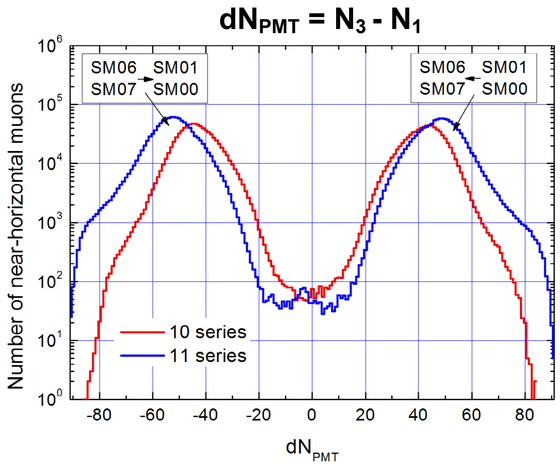


Experimental data

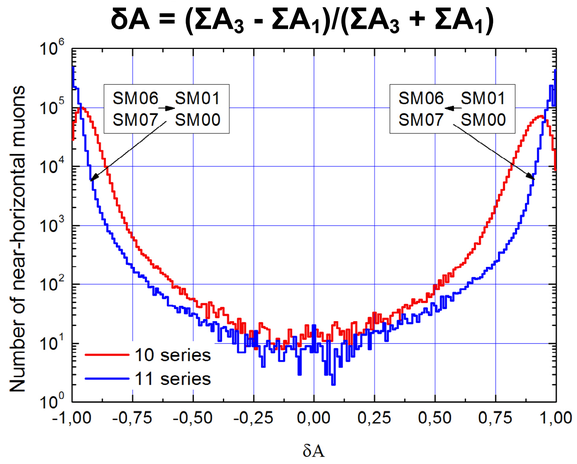
10th series of runs (Dec 23, 2011 – Mar 21, 2013, 7945 hours 'live' time);
11th series (Jul 16, 2013 – Apr 08, 2015, 11897 hours 'live' time);
3.8 million of near-horizontal muons with the threshold energy 7 GeV have been detected.

The experimental complex allows us to determine the muon track direction both by means of Cherenkov radiation (NEVOD) and time-of-flight tecnique (DECOR).

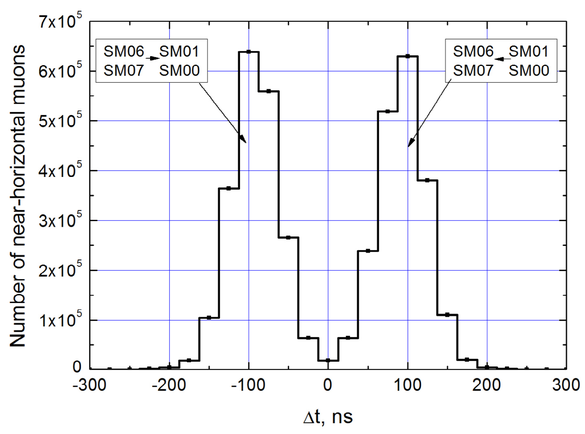
Difference between the total number of opposite PMTs $dN_{PMT} = N_3 - N_1$



Relarive difference between the total amplitudes of opposite PMTs $\delta A = (\Sigma A_3 - \Sigma A_1)/(\Sigma A_3 + \Sigma A_1)$



Time difference between the signals from DECOR supermodules



Selection of criteria for determining the track direction

The amplitude and time-of-flight methods are independent, therefore we can estimate the efficiency and the upper limit of the error of the criterion for the relative difference between the total amplitudes of PMTs by imposing rigid conditions for the time difference Δt, and vice versa.

Estimated efficiency and error rate of the amplitude technique

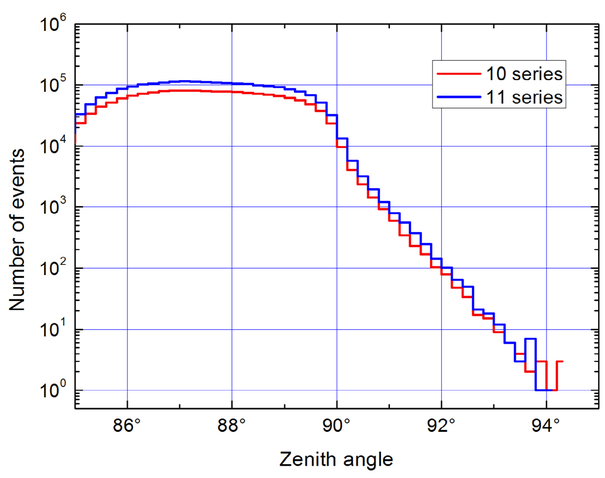
10 series: selection (θ ≤ 89° and θ ≥ 91°, and |dt| ≥ 50 ns)			11 series: selection (θ ≤ 89° and θ ≥ 91°, and |dt| ≥ 50 ns)	
|δA|	Efficiency of identification, %	Error rate	Efficiency of identification, %	Error rate
≥0.6	99.726 ± 0.005	(2.78 ± 0.47) ×10^{-5}	99.899 ± 0.003	(0.91 ± 0.25) ×10^{-5}
≥0.7	99.386 ± 0.007	(1.68 ± 0.37) ×10^{-5}	99.821 ± 0.004	(0.63 ± 0.21) ×10^{-5}
≥0.8	97.410 ± 0.014	(1.38 ± 0.34) ×10^{-5}	99.622 ± 0.005	(0.35 ± 0.16) ×10^{-5}

Estimated efficiency and error rate of the time-of-flight technique

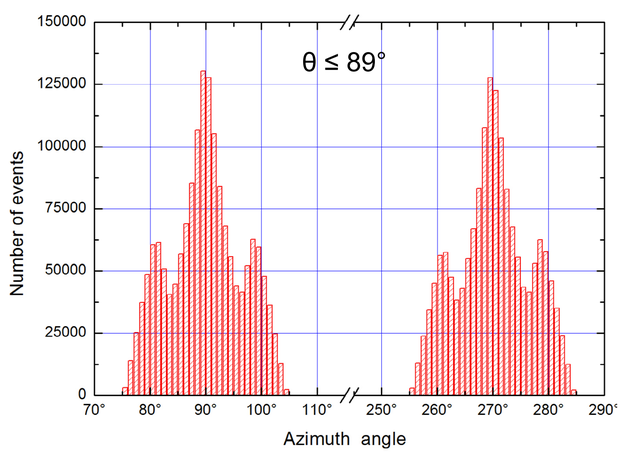
10 series: selection (θ ≤ 89° and θ ≥ 91°, and |δA| ≥ 0.7)			11 series: selection (θ ≤ 89° and θ ≥ 91°, and |δA| ≥ 0.7)	
|dt|, ns	Efficiency of identification, %	Error rate	Efficiency of identification, %	Error rate
≥25	99.27 ± 0.01	(2.66 ± 0.05) ×10^{-3}	99.367 ± 0.007	(2.01 ± 0.04) ×10^{-3}
≥50	96.27 ± 0.02	(1.27 ± 0.03) ×10^{-3}	96.488 ± 0.015	(0.88 ± 0.02) ×10^{-3}
≥75	83.92 ± 0.03	(0.53 ± 0.02) ×10^{-3}	84.10 ± 0.03	(0.32 ± 0.02) ×10^{-3}

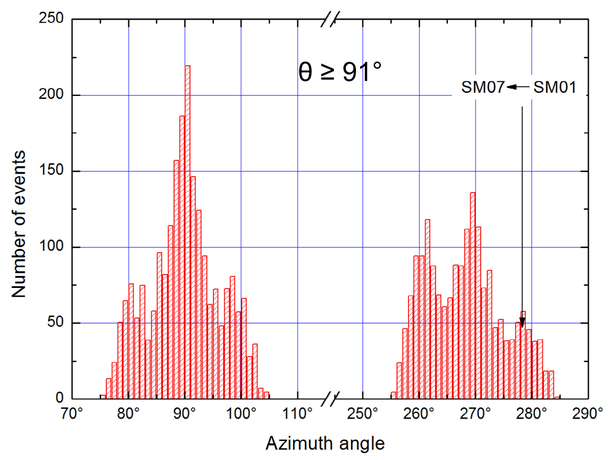
The final criteria are ($\delta A \geq 0.7$ and $\Delta t \geq 50$ ns) or ($\delta A \leq -0.7$ and $\Delta t \leq -50$ ns). The efficiency of the criteria is about 96%, and the rejection factor Is ~10^{-8}.

Zenith and azimuth angle distributions of selected events



4074 albedo muons (θ = 91-94°) were found. Distinct central peaks of azimuth angle distributions correspond to the events in which muon passes through supermodules arranged opposite to each other (pairs SM07-SM00 and SM06-SM01), right and left peaks correspond to cross-direction tracks. The distribution of albedo muons is not symmetric. It is determined by the topography of the surface in the surrounding area. Muons in the range of angles 75˚-105˚ come from the valley of the Moscow river. The lack of muons in the range of angles near 280˚ corresponds to muons coming from the side of a hill.



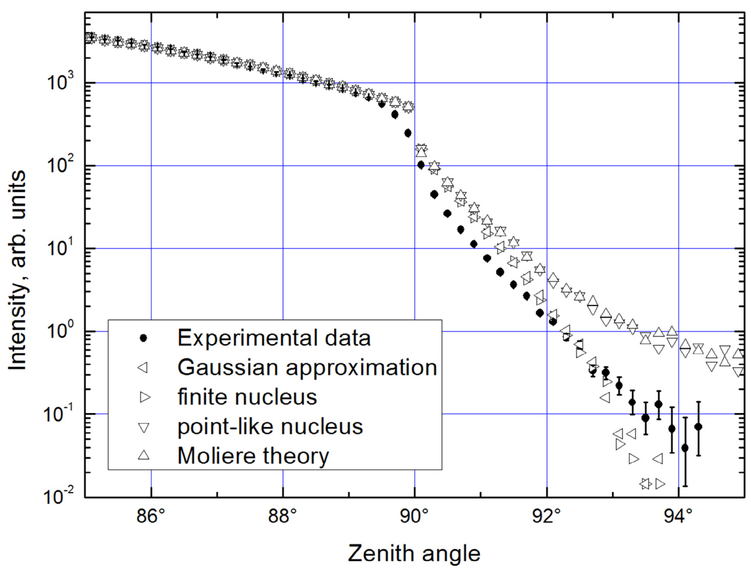


Experimental intensity of the muon flux and comparison with simulation results

Simulation of muon penetration through a flat layer of ground by means of MC method has been performed. In simulations, four models are used: multiple Coulomb scattering in Gaussian approximation; Moliere theory; model taking into account finite size of nucle; point-like nuclei.

Muon energy was simulated as a function of zenith angle based on differential spectrum of muons, calculated by the formulas of L.Volkova and assumption about the power spectrum of primary cosmic rays with integral slope spectrum index γ =1.7.

The number of albedo muons for Moliere theory coincides with the results of point-like nucleus model and with the increase of zenith angle decreases slower than in the model of finite-size nucleus. Results of calculations with Gaussian approximation are close to the dependence obtained for the model with a finite-size nucleus (with accurate nuclear formfactors). The last two models significantly better describe the experimental dependence.



Conclusions

Selection criteria for albedo events in the experimental complex NEVOD on the basis of amplitude and time-of-flight techniques have been developed. The intensity of muons with energies above 7 GeV in zenith angle range 86 - 94° has been measured. Simulation of muon penetration through a flat layer of ground shows that the main process of albedo muon flux formation in the range 91 - 94° is the multiple Coulomb scattering. The calculations for the model of point-like nuclei (including the Moliere theory) lead to an overestimation of the intensity of the albedo muons.

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The work was performed at the Unique Scientific Facility "Experimental complex NEVOD" with the financial support from the State provided by the Russian Ministry of Education and Science (project No. RFMEFI59114X0002), and the grant of the President of the Russian Federation (MK-7145.2015.2).