Cascade showers initiated by muons in the Cherenkov water detector NEVOD

Unique Scientific Facility
Experimental Complex
NEVOD

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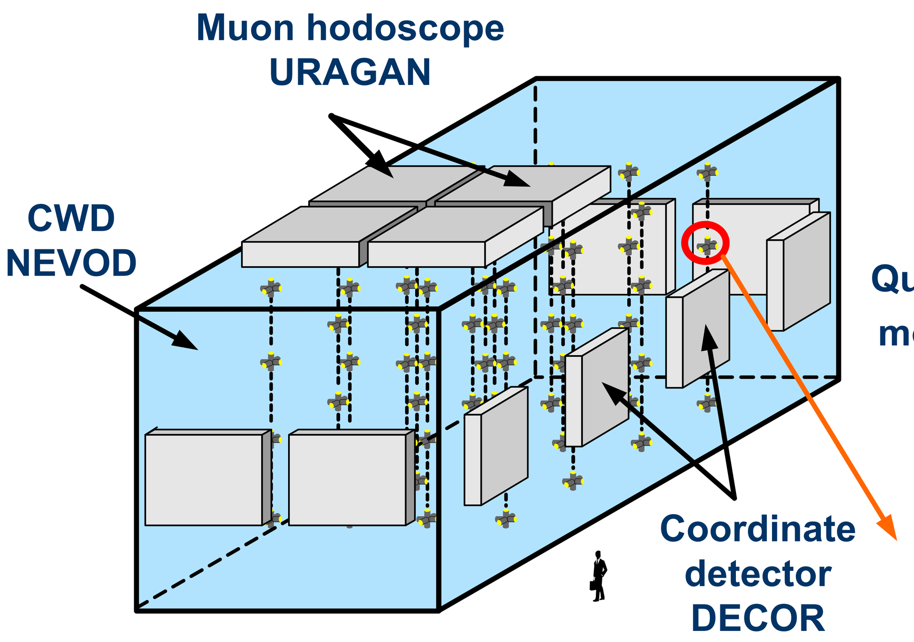
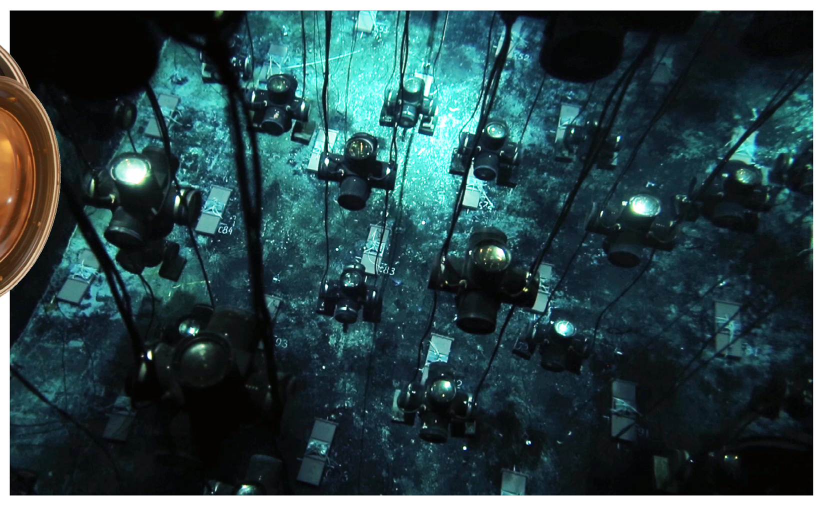
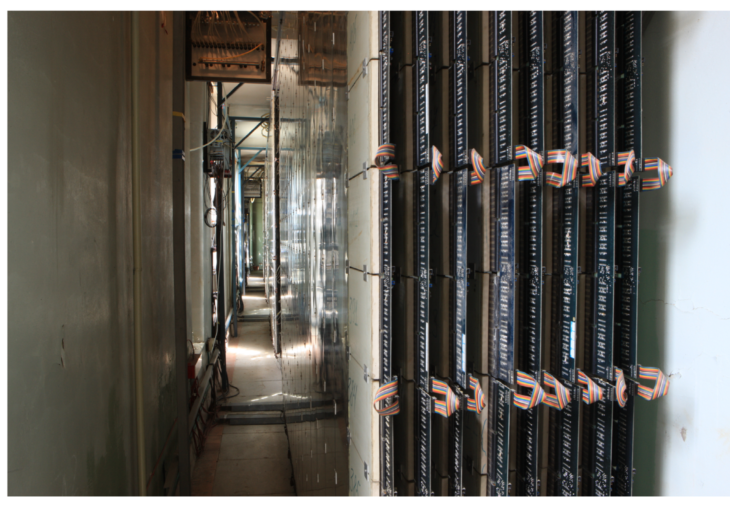
CR-EX Poster 1
Paper: 360
Board: 228

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

Experimental complex NEVOD







Cherenkov water calorimeter NEVOD

- quasi-spherical module (QSM) has an equal sensitivity to any direction of Cherenkov light;
- detector volume - 2000 m^3 of purified water;
- 91 QSM in 25 strings (clusters): 9 strings with 3 QSM and 16 strings with 4 QSM;
- 546 low-noise 12-dynode photomultipliers FEU-200 (Russia) (15 cm diameter);
- signal readout from 12th and 9th dynodes of PMT;
- dynamic range of PMT signals: from 1 to 10^5 photoelectrons;
- 1092 spectrometric channels.

Coordinate-tracking detector DECOR

- 8 vertically suspended 8-layer supermodules (SMs) of plastic streamer tube chambers with resistive cathode coating ;
- total sensitive area ~70 m^2;
- chamber planes are equipped with two-coordinate external strip readout system;
- measurement accuracy - about 1 cm in both coordinates;
- angular accuracy of muon track reconstruction is better than 0.7° and 0.8° for zenith and azimuth angles, respectively.

Single near-horizontal muons

- two SMs of DECOR located at opposite short sides of the tank are triggered;
- tracks reconstructed on the basis of individual supermodule responses are within a cone of angles less than 5°;
- line connecting midpoints of tracks in SMs is taken as a track of the muon;
- muons in the range of zenith angle from 84° to 90° are selected;
- the threshold energy of such muons is 7 GeV, and more than 30 % muons have energies E > 100 GeV;
- 3.84 million near-horizontal muons were detected during 19842 hours of 'live' time;
- significant part of muons generate cascades in the water of the detector.

Experimental runs

- 10th series of runs was conducted from December 23, 2011 to March 21, 2013 (7945 hours of 'live' time);
- 11th series of runs during the period from July 16, 2013 to April 08, 2015 (11897 hours of 'live' time);
- before the 11th series, the system of water purification was modernized.

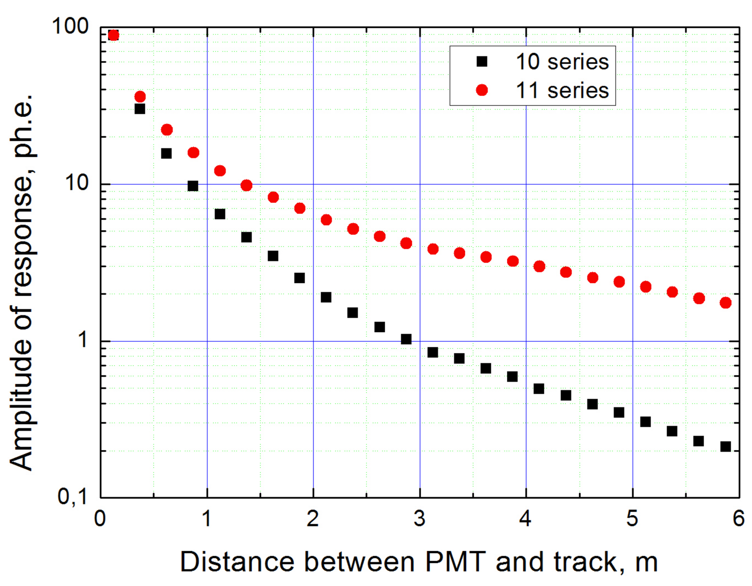
The technique of cascade profile reconstruction

Amplitude responses of PMT are re-calculated to the number of emitting particles. Analysis is performed for PMTs illuminated by direct Cherenkov radiation from near-horizontal muons. It is assumed that directions of the shower particles are close to the shower axis, this axis coincides with the track of the muon, and all Cherenkov photons are emitted at the same angle $\theta_C = 41°$. The track is divided into bins equal to one radiation length.

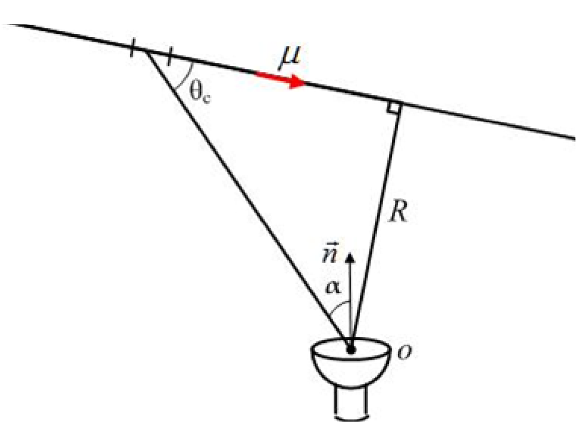
Let us assume that the number of Cherenkov photons emitted by the single muon is proportional to the deposited energy. Then for reconstruction of the cascade profile, the number of light-emitting charged particles in a bin of the track can be estimated on the basis of the PMT response in the event A_{PMT} and the known average PMT response to a single near-horizontal muon $A(R)$:

$$N_i = \frac{A_{PMT}}{A(R)\cdot\cos\alpha}\cdot\frac{\langle dE_\mu / dX\rangle \cdot l}{\beta}$$

where α is the angle of Cherenkov radiation incidence on the PMT photocathode; $\langle dE_\mu/dX \rangle$ is the specific average loss of muon in water (3.009 MeV cm^2/g, since for experimental geometry $\langle E_\mu \rangle$ = 100 GeV); l = 36.1 g/cm^2 is the radiation length in water; β = 78.3 MeV is the critical energy of electrons in water.



The estimated numbers of particles in a bin are averaged for all PMT that 'see' this segment of the track. The resulting dependence of the number of light-emitting particles on the depth is fitted by a function constructed on the basis of the cascade profile in the one-dimensional approximation:

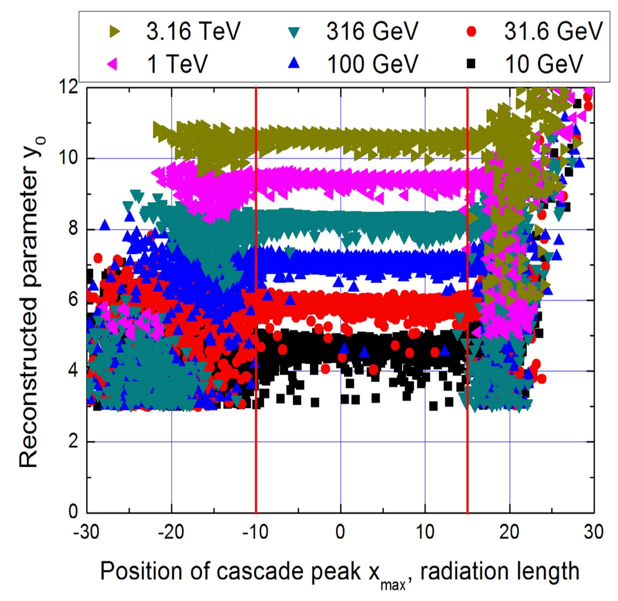


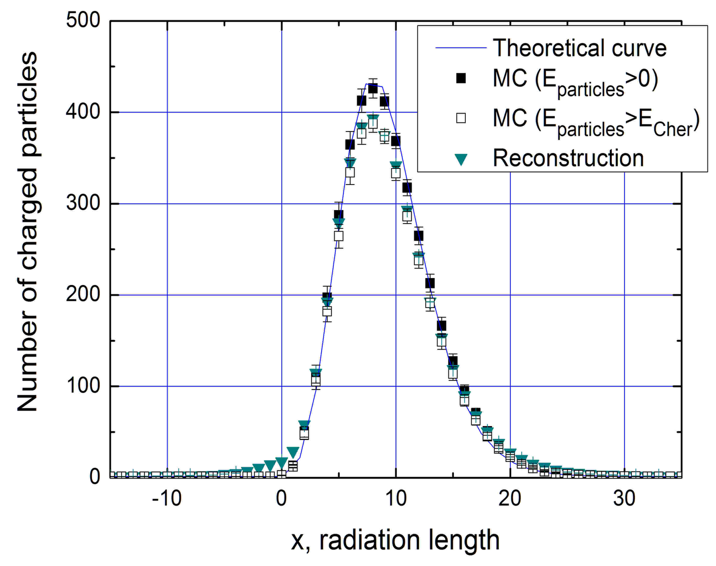
$$N(y_0,x_0,x)=\begin{cases}1.4, \text{ if } x<x_0\\ (0.32/\sqrt{y_0})\cdot\exp\left((x-x_0)\cdot(1-1.5\ln s)\right)+1.4, \text{ if } x\ge x_0\end{cases}$$

where $y_0 = \ln(\varepsilon_0/\beta)$, $s = 3(x-x_0)/(x-x_0+2y_0)$ is the cascade age, ε_0 is the cascade energy, and x_0 is the point of the cascade generation.

Simulation and test of cascade profile reconstruction

To investigate the reconstruction accuracy, cascade events with fixed energy were simulated in the Geant4 code. Muons with the energy E = 20 GeV and gamma rays with energies 10 GeV, 31.6 GeV, 100 GeV, 316 GeV, 1 TeV and 3.16 TeV (with increments of 0.5 in the decimal logarithm of the energy) were thrown into the detector. We have generated 5000 Monte-Carlo events for cascades with energies ε_0 = 10 ÷ 316 GeV and 2700 events for cascades with energies 1 TeV and 3.16 TeV.





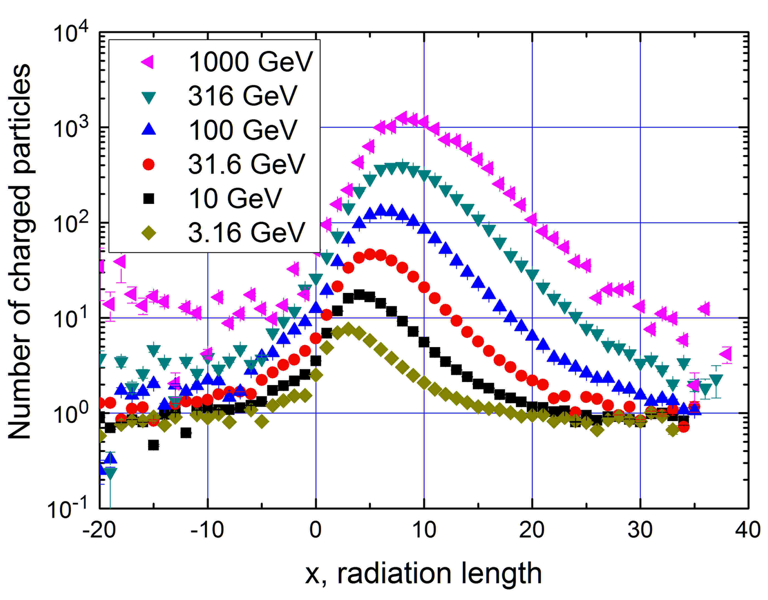
After reconstruction of cascade parameters (profile, energy and point of generation) a cut was applied with a condition -10.0 < x_{max} < 15 radiation lengths marked by red vertical lines. The dependence of the reconstructed cascade energy on the simulated values was fitted by a linear function. The slope coefficient of the line 1.02 ± 0.05 indicates a high accuracy of the developed technique. The difference between reconstructed point of cascade generation and simulated point does not exceed 1.5 radiation lengths.

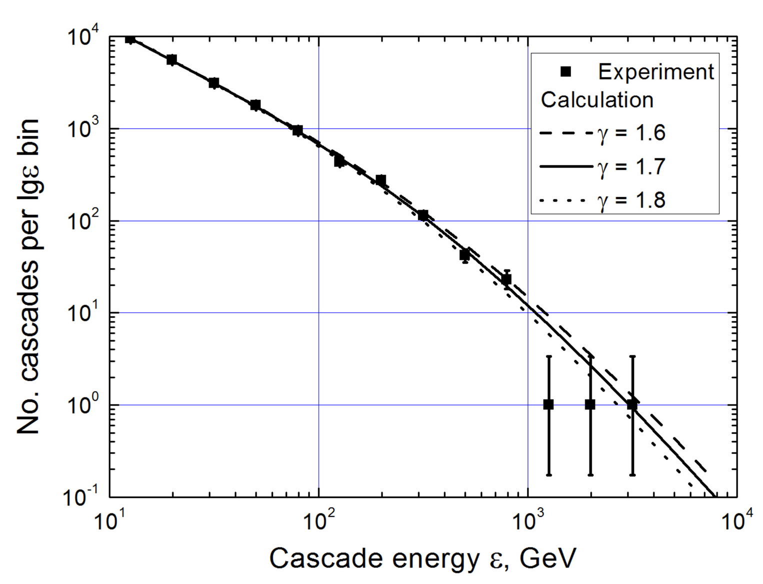
Experimental results

Experimental average cascade profiles and reconstructed energy spectrum

Experimental average longitudinal cascade profiles have been constructed for a set of cascade energies.

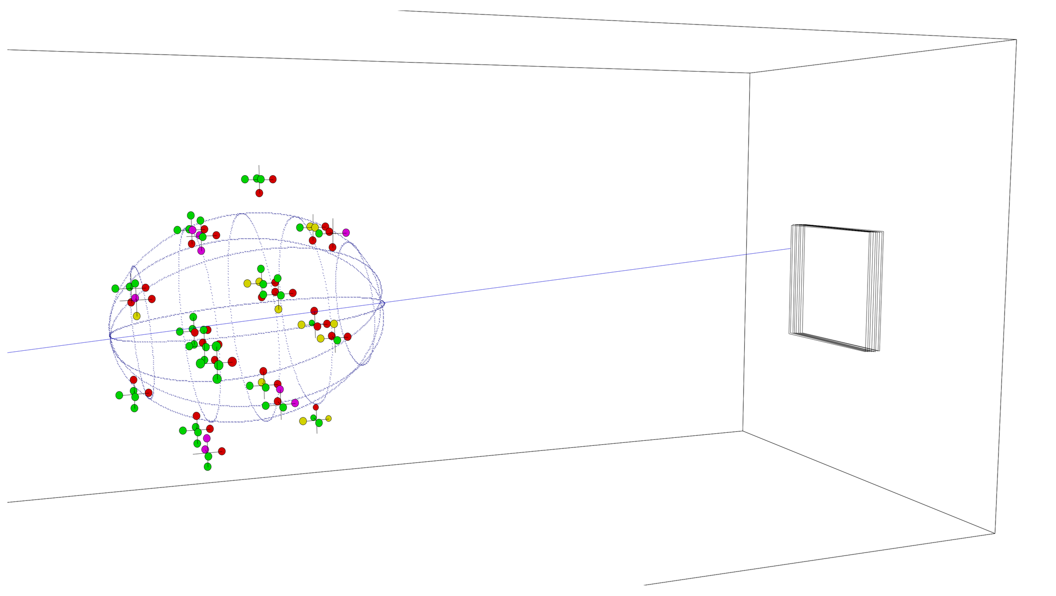
The differential energy spectrum of cascades generated by near-horizontal muons has been measured . The expected spectra of cascades for different values of the power index of pion and kaon integral generation spectrum in the atmosphere were calculated in the range of γ = 1.45 - 1.90 with step 0.05. The value of the optimum index of pions and kaons was found by means of the graphical analysis of the likelihood function. Cascades with energy ε_0 > 10 GeV (21 751 events) were taken into account. The position of the maximum likelihood corresponds to the value of γ = 1.70.





Cascade reconstruction without DECOR data

In the case of the high energy cascade detection, the QSMs with the largest responses form a compact cluster in the CWD lattice. We analyzed 20 QSMs with the largest total amplitudes in the event. To reconstruct the direction of the cascade, the sum of PMT surface normals weighted with their amplitudes is used.



To estimate the spatial location of the cascade axis, the center-of-gravity of these 20 QSMs was calculated.

This technique was checked with the cascades generated by muons selected with DECOR. It was found that the mean error of the axis location is about 30 cm, and the mean error of the direction estimation is about 16°.

Due to a wide angular acceptance, the analysis of cascades selected by the CWD data only will allow to increase statistics of high-energy events by two orders of magnitude.

Conclusion

The dense spatial lattice of quasispherical modules of the detector NEVOD has allowed for the first time to measure the longitudinal cascade profile in Cherenkov radiation in water. As a result, the experimental cascade profiles in the energy range ε = 3 ÷ 1000 GeV have been obtained. The differential energy spectrum of cascades generated by near-horizontal muons has been measured in the energy range of ε = 10 – 3000 GeV, and the value of the index of pion and kaon integral generation spectrum was estimated; 68% confidence interval of this parameter is in the range γ = 1.67 – 1.73.

Acknowledgements

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), government task and RFBR grant No. 15-02-07763.