Measurements of the energy spectrum of cascade showers initiated by muons in the Cherenkov water calorimeter NEVOD

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Abstract. The technique of cascade shower energy measurements by means of Cherenkov water detector (CWD) NEVOD with a spatial lattice of quasi-spherical modules (QSM) is discussed. A dense QSM spacing allows to reconstruct the number of cascade particles along the shower axis on the basis of amplitude responses of PMTs. The technique of cascade curve reconstruction was applied to showers generated in water by nearly horizontal high energy muons selected by means of the coordinate detector DECOR deployed around the CWD. First results of cascade energy spectrum measurements are presented.

1. Introduction

Experimental complex NEVOD-DECOR (figure 1) is a multipurpose facility created for the study of main cosmic ray components at ground level [1, 2].

![Figure 1. Experimental complex NEVOD-DECOR.](image)

The setup is located in the campus of the National Research Nuclear University MEPhI in a special four-story building and equipped with necessary technical and technological systems to provide the detector operation. The basis of the complex is the Cherenkov water detector (CWD) NEVOD with a
reservoir volume $9 \times 9 \times 26 \text{ m}^3$ constructed inside the building. The detecting system is formed by a spatial lattice of quasispherical modules (QSM) which include six PMTs with flat cathodes directed along the coordinate axes. QSM lattice allows detect Cherenkov radiation from any direction with practically the same efficiency. The distances between the modules are 2.5 m along the detector, and 2.0 m across it and over the depth. Constructively, the lattice is formed by a set of vertical strings containing 3 or 4 modules each. Now the detecting system consists of 91 QSM (546 PMT in total).

To improve the event reconstruction accuracy, the coordinate detector DECOR [2] was created around the Cherenkov water calorimeter NEVOD (see figure 1). DECOR represents a modular multi-layer system of plastic streamer tube chambers with resistive cathode coating. The side part of DECOR includes eight vertically suspended eight-layer assemblies (supermodules, SMs) of chambers with the total sensitive area 70 m$^2$. Chamber planes are equipped with two-coordinate external strip readout system that allows to localize charged particle tracks with about 1 cm accuracy in both XY-coordinates. Angular accuracy of reconstruction of muon tracks crossing the SM is better than 0.7° and 0.8° for projected zenith and azimuth angles, respectively.

If two SMs of DECOR located along the opposite short sides of the water tank are triggered, whereby tracks reconstructed on the basis of individual supermodule responses are within a cone of angles less than 5°, then such events are called “OneTrack”. In this case, it is supposed that the track segments within each SM belong to the same particle. The line connecting midpoints of tracks in SMs is taken as a track of the muon (see figure 1). For the geometry of the experiment, the threshold energy of such muons is 7 GeV, and about 30 % muons have energies higher than 100 GeV. A significant part of these muons generates cascades in the matter of the detector.

2. The technique of cascade curve reconstruction

A high granularity of QSM lattice allows to reconstruct the number of cascade particles along the shower (cascade curve) on the basis of amplitudes of PMT responses.

The technique of cascade curve reconstruction is based on the re-calculation of amplitude responses to the number of emitting particles (see figure 2). Analysis is performed for PMTs illuminated by direct Cherenkov radiation from “OneTrack” events. Let us assume that directions of propagation of shower particles are close to the axis of the shower, and this axis coincides with the track of the muon. The track is divided into bins equal to one radiation length each. Then the estimated numbers of charged particles falling into the appropriate bins form the first approximation of the cascade curve. After analyzing all the responses of hit PMTs, the resulting longitudinal profile is fitted by the approximate analytical expression for the cascade curve [3]:

$$N_i^\text{th}(y_0, t_0, t) = \frac{0.32}{\sqrt{y_0}} \exp\left(\frac{(t-t_0) \cdot (1-1.5 \ln s)}{t-t_0+2 \cdot y_0}\right) ; t > t_0,$$

(1)

where $y_0 = \ln (E_0 / \varepsilon)$, $\varepsilon = 73$ MeV is the critical energy of electrons in water: $s = \frac{3 \cdot (t-t_0)}{t-t_0+2 \cdot y_0}$ is the age of the shower; $E_0$ is the shower energy, $t_0$ is the point of the shower generation.

Fitting is performed by means of minimization of the functional:

$$W = \frac{1}{(m-k) \sum_{i=1}^{i_{\text{mth}}} (N_i^\text{th} - N_i^\text{obs})^2} ,$$

(2)

where $m$ is the number of bins on the track, $k = 2$ is the number of estimated parameters.

The number of emitting charged particles on the bin of the track $N_i$ is calculated as a ratio of PMT response to the event $A_{\text{pmt}}$ and PMT response to a single charged particle with the same geometric parameters of the track $A_1$ (see figure 2):

$$N_i^\text{obs} = \frac{A_{\text{pmt}}}{A_1(R, \alpha)} ,$$

(3)
Estimated numbers of particles in the bin are averaged for all PMT that “see” this segment of the track.

PMT response to a single charged particle was calculated by the formula:

\[
A_i(R, \alpha) = \frac{S_{\text{PMT}} \cdot \cos \alpha}{2\pi (R + r_{\text{PMT}}) \cdot \sin \theta_{\text{C}}} \int_{\lambda_{\min}}^{\lambda_{\max}} d\lambda \frac{\eta(\lambda) \cdot \exp(-\frac{R}{L(\lambda) \cdot \sin \theta_{\text{C}}})}{\lambda} d\lambda,
\]

where \( S_{\text{PMT}} \) and \( r_{\text{PMT}} \) are area and radius of PMT cathode; \( dN/d\lambda \) is the wavelength distribution of photons generated per unit track length; \( \alpha \) is the angle of Cherenkov radiation incidence on PMT cathode; \( \theta_{\text{C}} \) is the angle of Cherenkov radiation in water; \( \eta(\lambda) \) is quantum efficiency of PMT, \( L(\lambda) \) is the absorption length of light in water, \( \lambda_{\min} \) and \( \lambda_{\max} \) are boundaries of PMT sensitivity range.

The results of calculation for \( \alpha = 0^\circ \) are presented in figure 3 (squares). This dependence was fitted by function (5), and the parameters of the function were determined: \( C = 8.9 \) photoelectrons \( \cdot \) meter, \( L_{\text{short}} = 0.7 \) m and \( L_{\text{long}} = 3.8 \) m.

\[
A_i(R, \alpha) = \frac{C \cdot \cos \alpha}{R + r_{\text{PMT}}} \left( \exp(-\frac{R}{L_{\text{short}}}) + 0.5 \cdot \exp(-\frac{R}{L_{\text{long}}}) \right).
\]

The technique of cascade curve reconstruction has been tested on the events in which NEVOD response on the cascade showers with fixed energies 10, 31.6, 100, 316, 1000 and 3160 GeV was simulated by means of Geant4.9.4 code. An example of the reconstruction of the cascade curve for a
simulated shower with energy 316 GeV is shown in figure 4. Dependence of the average reconstructed energy of cascades on simulated energy is shown in figure 5. Linear fitting of the dependence gave the proportionality factor $1.02 \pm 0.03$. Such value of the factor demonstrates the correctness of the cascade energy reconstruction.

Cascade showers with energies less than 5-7 GeV are poorly seen on the background of the light from single muons, which determines the lower boundary of spectrum measurements. The detecting system of the calorimeter allows to measure maximum energy of cascade showers up to about 10 TeV.

3. Measurements of the energy spectrum of cascade showers

The energy spectrum of cascade showers initiated by horizontal muons has been measured during the experimental runs from 23 Dec 2011 to 09 May 2012 (more than 2100 h of effective live time). From experimental data, $5.3 \times 10^5$ “OneTrack” events have been selected, and 6309 cascades with energy more than 7 GeV have been reconstructed.

An example of one of the most powerful detected showers (with estimated energy 1.2 TeV) is shown in figure 6. Results of measurements of the energy spectrum of cascade showers are presented in figure 7. Estimates show that cascade showers with energies less than 100 GeV are mainly initiated by knock-on electrons, and this part of the spectrum cannot be used for determination of muon energy spectrum. However, if statistics of the experiment is improved, the shower spectrum above 100 GeV can be used for investigations of the shape of the energy spectrum of muons.

4. Conclusion

The technique of investigations of cascade showers with energies in the range 7 GeV – 10 TeV initiated by high energy muons in the Cherenkov water detector has been developed and tested. The technique allows to measure the energy spectrum of single muons in a wide range of zenith angles.

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