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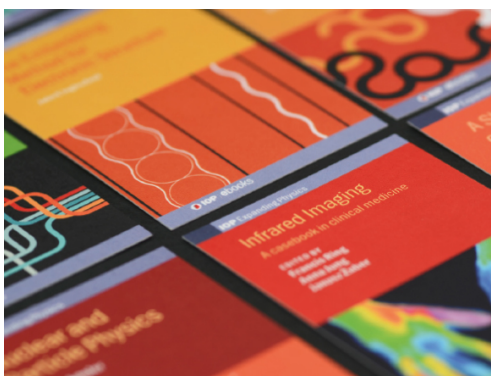
Investigation of cascade showers in the Cherenkov water detector NEVOD

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Abstract. A technique fot the reconstruction of cascade profiles by means of Cherenkov
radiation in the water of the NEVOD detector is discussed. NEVOD is equipped with a dense
spatial lattice of optical modules. The analyzed cascades have been generated either along
near-horizontal muons (zenith angles between 85 and 90°), which's tracks are reconstructed by
means of the tracking detector DECOR, or by muons with unknown tracks over a wider zenith
angle range of 50-90°. Mean cascade profiles and energy spectra of cascades measured during
the experimental series of about 7950 hours of 'live time' are presented.

1. Introduction

In recent years the interest in studying ultrahigh-energy muons and neutrinos of cosmic rays has
grown strongly. The reasons are the so-called 'muon puzzle' [1] (the excess of both muon bundles [2,
3] and UHE muons [4, 5] with the energy increase) and the discovery of the excess of UHE neutrinos
that apparently are indicative of their extraterrestrial origin [6]. In both cases, one of the most
important tasks is to measure the energy of cascade showers generated by muons and neutrinos, in
particular in Cherenkov water detectors (CWD). However in large-scale setups such as NT200+,
ANTARES or IceCube the cascade energy is estimated by Cherenkov radiation from the cascades
using a point approximation because of the large distances between the optical modules (tens of
meters). The cascade energy reconstruction is based on simulation which can result in systematical
uncertainties. However, the direct measurement of the cascade profile in a CWD with a dense lattice
of optical modules allows to verify the models used to describe cascade profiles in Cherenkov
radiation.

2. The NEVOD-DECOR complex and experimental runs

The NEVOD-DECOR experimental complex (figure 1) is a multipurpose facility created for effective
detection of all cosmic ray components at ground level [7, 8, 9]. The setup is located in the campus of

MEPhI in a special four-story building and is equipped with the necessary technical and technological systems to provide the detector operation. The basis of the complex is the Cherenkov water detector NEVOD with a volume of $9 \times 9 \times 26$ m^3. The detecting system is formed by a spatial lattice of quasi-spherical modules (QSM), each of them including six PMTs with flat cathodes directed along the coordinate axes. The QSM lattice allows to detect Cherenkov radiation from any direction with practically the same efficiency. The lattice is formed by a set of vertical strings containing 3 or 4 modules each. The distances between the modules are 2.5 m along the detector, and 2.0 m both across it and over the depth. The current detecting system consists of 91 QSM (546 PMT in total) [10,11].
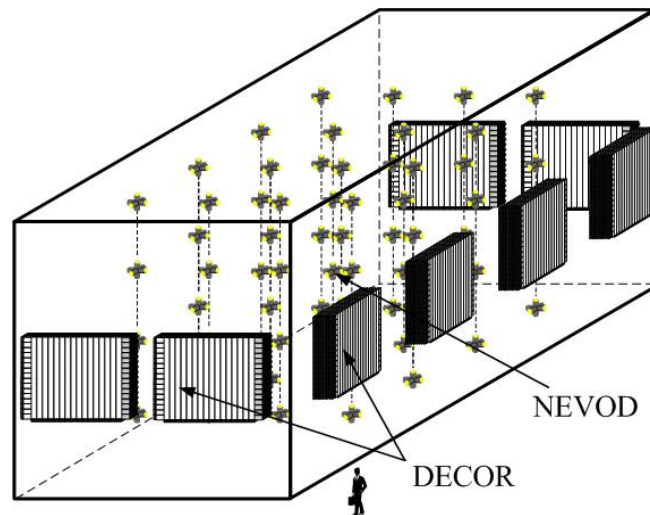

Figure 1. The NEVOD-DECOR
experimental complex.

To improve the event reconstruction accuracy the coordinate detector DECOR [8,9] was constructed around the Cherenkov water calorimeter NEVOD (see figure 1). DECOR is a modular multi-layer system of plastic streamer tube chambers with resistive cathode coating. DECOR includes eight vertically suspended eight-layer assemblies (supermodules, SMs) of chambers with a total sensitive area of 70 m^2. The chamber planes are equipped with a two-coordinate external strip readout system that allows to localize charged particle tracks with about 1 cm accuracy in both coordinates (X, Y). The angular reconstruction accuracy for muon tracks crossing the single SM is better than 0.7° and 0.8° for projected zenith and azimuth angles respectively.

During the period from December 23, 2011 to March 20, 2013 a series of runs with 7945 hours of 'live time' was performed and 375 million events were registered.

Cascade search was conducted in two types of registered events:

• events with a single near-horizontal muon which's track was reconstructed according to the data of the DECOR detector;

• events with large energy deposits in the volume of NEVOD.

A condition the single near-horizontal muon selection was the triggering of two DECOR supermodules located along the opposite short sides of the water tank. If track angles reconstructed on the basis of individual supermodule responses agreed within less than 5°, then it was supposed that the track segments within each SM belong to the same particle. The line connecting midpoints of track segments in each SM is taken as the track of the muon. For such geometry of the experiment, muons with zenith angles larger than 85° are selected. The threshold energy of such muons is about 7 GeV, the mean energy about 100 GeV.

An example of a cascade generated by a near-horizontal muon is shown in figure 2. Hereafter in similar figures, crosses and circles represent triggered QSMs and PMTs. The colors of circles

correspond to different gradations of amplitudes: green denotes $1 \div 7$ photoelectrons (ph.e.); yellow $8 \div 25$ ph.e.; violet $26 \div 75$ ph.e. and red amplitudes larger than 75 ph.e.
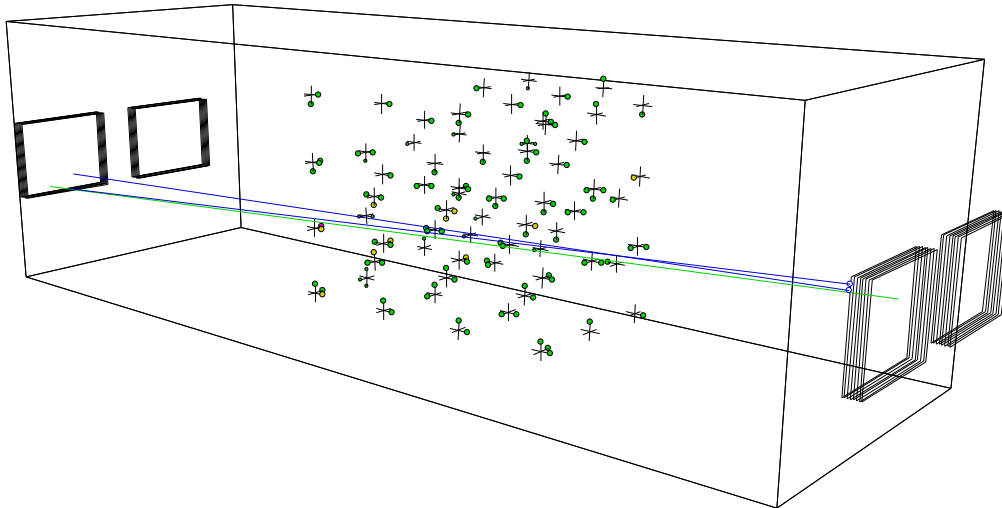

Figure 2. An example of a cascade generated by near-horizontal muon. The track of the muon is reconstructed by means of the DECOR detector.

Events with large energy deposits were selected by the trigger '60c'. A condition for this trigger was that more than 59 QSMs were hit within a time gate of 250 ns. Moreover at least two neighboring PMTs in each of these modules should be hit. This trigger was used from April 3, 2012 (5900 hours of 'live time').

For the events with single near-horizontal muons selected by means of DECOR we know the cascade axis which practically coincides with the muon track. However the statistics of such events is limited by the narrow solid angle, which is determined by the detector geometry. Events selected by trigger '60c' are registered over a wider range of angles, but for them the cascade axis must be reconstructed. In addition, the events selected by this trigger are not only cascades generated by muons but also other multi-particles events (EAS, muon bundles, hadron showers etc.) which have to be separated in the analysis.

3. The technique of cascade profile reconstruction

At distances larger than the photocathode radius, the PMT response to Cherenkov radiation of a single charged particle can be calculated by the equation:

$$A_1(R,\alpha) = \frac{S_{PMT} \cdot \cos\alpha}{2\pi(R + r_{PMT}) \cdot \sin\theta_C} \int_{\lambda_{min}}^{\lambda_{max}} \frac{dN}{d\lambda} \eta(\lambda) \cdot \exp\left(-\frac{R}{L(\lambda) \cdot \sin\theta_C}\right) d\lambda , \qquad (1)$$

where S_{PMT} and r_{PMT} are correspondingly the area and the radius of the PMT photocathode; $dN/d\lambda$ is the wavelength distribution of photons generated per track length unit; α is the angle of Cherenkov radiation incidence on the PMT photocathode; θ_C is the angle of Cherenkov radiation in water; $\eta(\lambda)$ is the PMT quantum efficiency; $L(\lambda)$ is the absorption length of light in water (figure 3); λ_{min} and λ_{max} are the boundaries of the PMT sensitivity range. In figure 4, triangles show the dependence calculated by equation (1) with $\cos\alpha = 1$, squares represent the experimentally measured PMT response to near-horizontal muon selected by means of DECOR. Inside the sensitive volume of the detector, the muon generates secondary particles that initiate additional Cherenkov photons and increase the PMT response compared with the calculated response for a single particle.
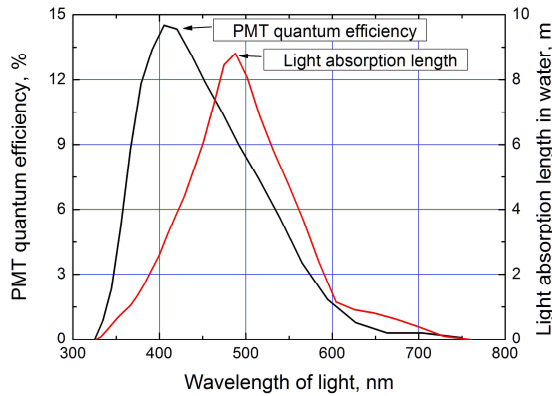
Figure 3. Dependences of the quantum efficiency of PMT and the absorption length on the wavelength of light.
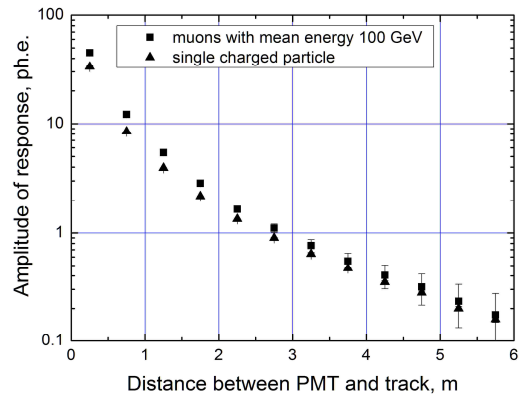

Figure 4. Dependences of the PMT response on the distance to the track, for a single charged particle and for muons with the mean energy 100 GeV.

To reconstruct the cascade profile in NEVOD we determine the number of light-emitting relativistic particles based on the PMT amplitude (figure 5) [12, 13]. This technique is used for the PMT directly illuminated by Cherenkov radiation from the cascade. We assume that the directions of the shower particles are close to the shower axis, and that this axis coincides with the track of the muon. The track is divided into bins equal to one radiation length (for water, 36.1 g/cm^2).

The number of light-emitting charged particles on a bin of the track, N_i, is calculated as the ratio between the PMT response to the event, A_{PMT}, and the PMT response to a single charged particle with the same geometric parameters of the track, A_1:

$$N_i = \frac{A_{PMT}}{A_1(R,\alpha)}. \tag{2}$$

Then the estimated numbers of particles in a bin are averaged for all PMT that "see" this segment of the track.
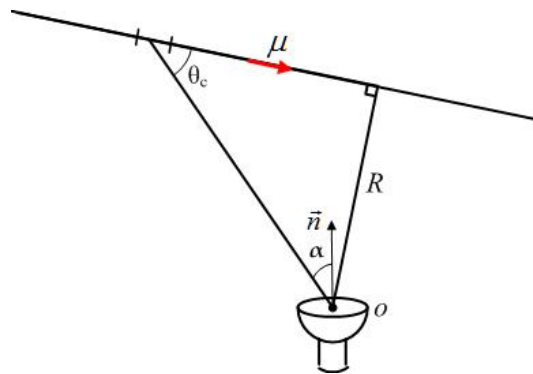

Figure 5. Geometry of the event for calculation of number of charged particles.

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 [14]:

$$N(y_0, x_0, x) = \begin{cases} 1.35, & \text{if } x < x_0 \\ (0.32/\sqrt{y_0}) \cdot \exp\big((x - x_0) \cdot (1 - 1.5\ln s)\big) + 1.35, & \text{if } x \geq x_0 \end{cases}, \tag{3}$$

where $y_0 = \ln(\varepsilon_0/\beta)$, $\beta = 78.3$ MeV is the critical energy of electrons in water, $s = 3(x-x_0)/(x-x_0+2y_0)$ is the shower age, ε_0 is the shower energy, and x_0 is the point of the shower generation.

To verify the technique, cascade events with fixed energy were simulated. Muons with energy $E_\mu = 20$ GeV and gamma rays with energy 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 through the detector. We have generated 5000 Monte-Carlo events for cascades with energies $\varepsilon_0 = 10 \div 316$ GeV and 2700 events for cascades with energies 1 TeV and 3.16 TeV.

To account for the systematic shift, the dependence of the reconstructed parameter y_0 on the cascade energy was fitted by a linear function (figure 6):

$$y_0^{rec} = a \cdot y_0^{sim} + b , \qquad (4)$$

where $a = 1.023 \pm 0.004$, $b = -0.24 \pm 0.03$. Further these coefficients were used as correction factor.

In figure 7, the curve represents the theoretical approximation for a cascade with energy $\varepsilon_0 = 316$ GeV calculated by equation (3), while the squares show the average cascade profiles according to the simulation (black squares are for all shower electrons, open squares are for electrons with energy above the threshold of Cherenkov radiation in water $E_{Cher} = 260$ keV), triangles show the average cascade profile reconstructed by the developed technique.
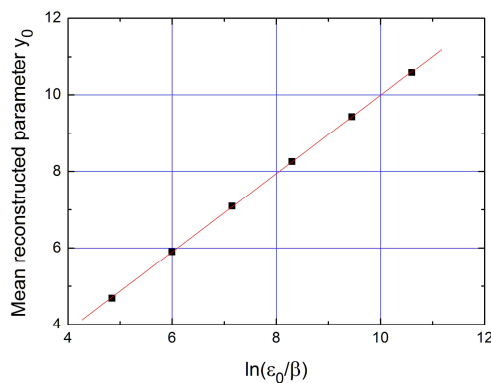

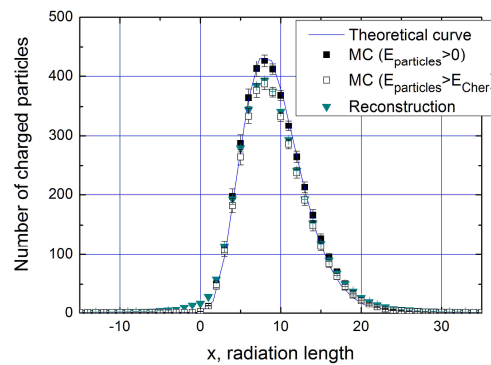**Figure 6.** Dependence of reconstructed parameter y_0 on cascade energy.

Figure 7. Theoretical, mean simulated and reconstructed cascade profiles for cascades with energy 316 GeV.

As can be seen, the average reconstructed profile follows the shape of the average simulated profile for particles with energies above the threshold. A small difference in the tails of the profile is due to the electron scattering in water which is not taken into account in the one-dimensional model of the cascade.

4. Results

4.1. Cascades generated by single near-horizontal muon with known track

1 696 530 events with single, near-horizontal muon selected by means of DECOR were registered. In 123 364 events, cascades with energy from 1 to 3000 GeV were reconstructed. In some events, double cascades were observed. An example of the cascade profile of such an event is shown in figure 8. Reconstructed energies of the cascades are 140 GeV and 42 GeV.

The cascades were sorted into groups according to the decimal logarithm of the energy, and cascade profiles were averaged within each group. The results are shown in figure 9. The mean cascade profile for showers with energy $\varepsilon = 1$ TeV is based on only 30 events, so this cascade profile is not completely smooth.
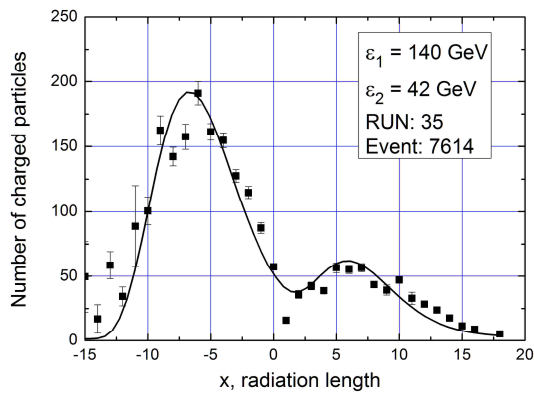
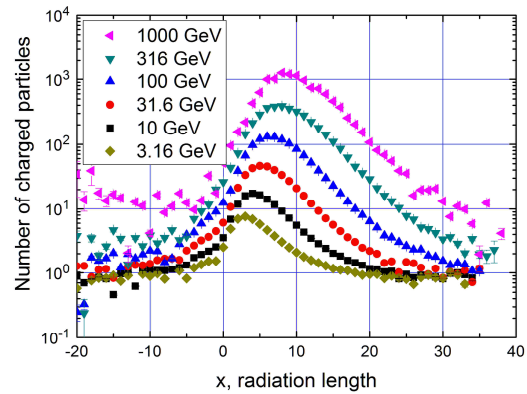**Figure 8.** An example of a double cascade.

Figure 9. Mean cascade profiles.

4.2. Cascades generated by a muon with unknown track

Selection and reconstruction of the parameters of cascade events from the sample selected by the trigger '60c' are based on the compactness of location of QSMs with the highest amplitudes. Techniques were tested on events with known axes selected by means of DECOR.

In NEVOD lattice, optical modules with the highest responses in the cascade events form a compact clusters. The geometry of the cluster can be used as the cascade signature (figure 10). It was found that the rms radius of the cluster of 20 QSM with the highest response does not exceed 2.35 m in 95% of events with cascade showers with energy above 100 GeV.

The cascade axis is drawn through the center of mass of the selected QSMs (weighted with the PMT amplitudes). To reconstruct the direction of the axis in the selected cascade, the sum of the PMT surface normals weighted with their amplitudes is used. As the QSM closest to the cascade axis, with the highest response, can introduce a significant error in the determination of the resulting vector, it is excluded from the direction reconstruction. This technique was applied to the analysis of cascades generated by near-horizontal muons selected by means of DECOR. It was found that the mean error of the axis direction is about 16º and the mean error of the axis location about 30 cm.

To ensure correct cascade energy reconstruction, the events in which the cascades were developed inside the spatial lattice of NEVOD were selected. The center of mass of the QSM cluster should be at least 1.5 m away from the boundaries of the lattice. To exclude hadronic cascades, only the events with the estimated zenith angle in the range from 50° to 90° were selected.
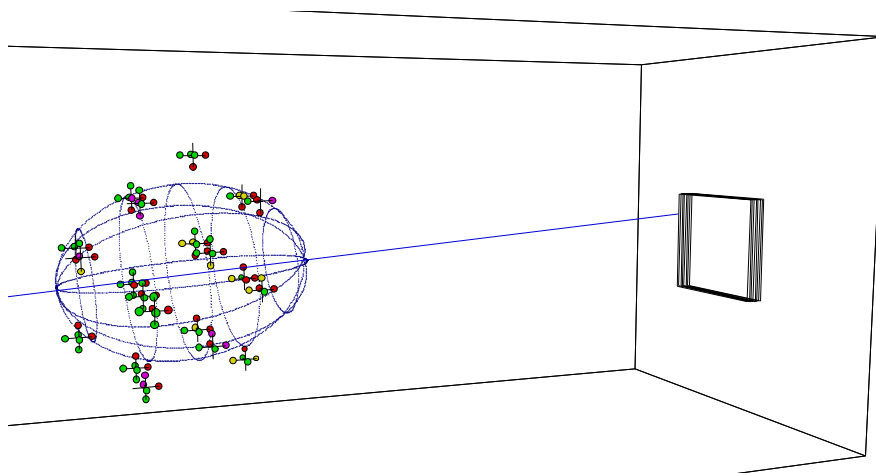

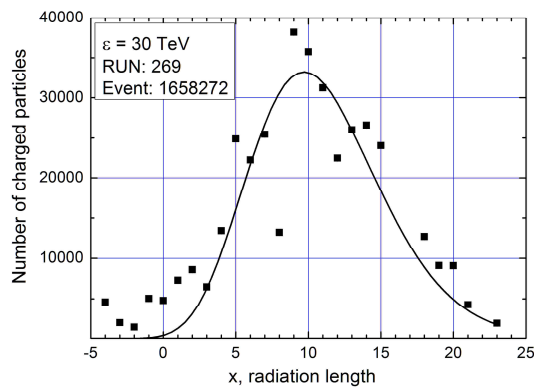**Figure 10.** An example of the cluster of 20 QSMs with maximal responses.

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Figure 11. An example of reconstruction of the cascade profile for experimental shower.
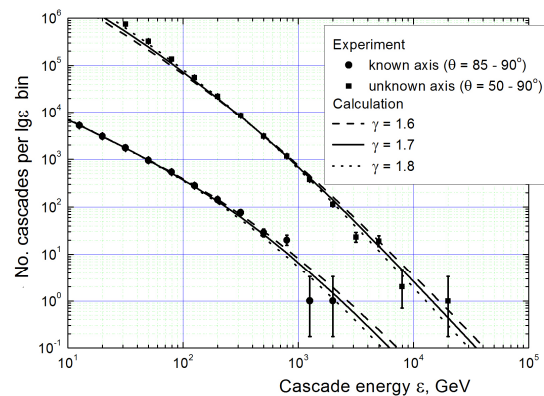

Figure 12. Energy spectra of cascade showers.

During the experimental series, about 80 million events with large energy deposits selected by trigger '60c' were registered. Using the developed criteria, 1 million cascade events with energies above 30 GeV were reconstructed. The energy of the most powerful cascade is about 30 TeV and its zenith angle is about 80°. Figure 11 shows the cascade profile of this cascade.

The differential spectra of cascades generated by muons in water in the range of zenith angles from 50° to 90° were plotted on the basis of estimated cascade energy. In figure 12 the circles show the spectrum of cascades generated by near-horizontal muons with tracks reconstructed by means of the DECOR detector; squares represent the spectrum of cascades registered by trigger '60c'; curves show the results of calculations for different values of the index γ of pion and kaon integral generation spectrum in the atmosphere. As seen from the figure, reconstruction of cascades according to the NEVOD data only increases the statistical reliability of the spectrum at high energies by nearly 2 orders of magnitude.

5. Conclusion

For the first time, cascade profiles (expressed as the number of cascade particles along the shower) were reconstructed from Cherenkov light in water, using the high-density optical module lattice of the NEVOD-DECOR experimental complex. As a result, the experimental cascade profiles in the energy range $\varepsilon = 3 \div 1000$ GeV have been obtained. These profiles can be used to verify the techniques of cascade energy reconstruction in the operating large-scale Cherenkov detectors.

Acknowledgments

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