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Cascade showers initiated by muons in the Cherenkov water detector NEVOD

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A technique for the measurement of the cascade energy by means of Cherenkov radiation in water of the NEVOD detector is discussed. NEVOD is equipped with a dense spatial lattice of optical quasispherical modules which allows to reconstruct the number of charged particles moving along the cascade axis (cascade profile) on the basis of amplitudes of PMT responses. The technique of cascade profile reconstruction has been tested on cascades generated by near-horizontal muons with the mean energy 100 GeV. The muons were selected by the DECOR coordinate-tracking detector deployed around NEVOD. Mean cascade profiles and energy spectrum of cascades measured during the experimental runs of about 19850 hours of 'live' time are presented.

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1. Introduction

Modern investigations of muons and neutrinos in the ultrahigh-energy region are carried out using Cherenkov water detectors (CWD). Such detectors are located in large water volumes of natural or artificial origin containing optical sensors placed in a regular spatial lattice. One of the most important tasks of Cherenkov water detectors is to measure the energy of cascade showers generated by muons and neutrinos. However in large-scale setups such as ANTARES [1] or IceCube [2] 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. The direct measurement of the cascade profile in the CWD with a dense lattice of optical modules allows to verify the models used to describe cascade profiles registered in Cherenkov radiation.

A special interest represent the measurements of the cascade spectrum from the horizontal flux of cosmic rays in CWD located at the ground level. With the increase of the zenith angle, the mean muon energy grows rapidly and reaches a value of 100 GeV near the horizon. A significant part of the particles have TeV energies. Such investigations are conducted at the NEVOD experimental complex.

2. The NEVOD complex and experimental runs

The NEVOD experimental complex (Figure 1) is a multi-purpose facility created for effective detection of all cosmic ray components at ground level [3,4,5]. The setup is located in the campus of MEPhI in a special four-story building and is equipped with 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 $9\times9\times26$ m^3. The detecting system is formed by a spatial lattice of quasi-spherical modules (QSM), each of them including six PMTs with flat 15 cm cathodes directed along the coordinate axes. The QSM lattice allows to detect Cherenkov radiation from any direction with practically the same efficiency. To ensure the calorimetric mode, signal read-out is produced from the 12th and 9th dynodes that allows to achieve a dynamic range from 1 to 10^5 photoelectrons (ph.e.). 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 across it and over the depth. The currently operating detecting system consists of 91 QSM (546 PMT in total) [6,7].

To improve the event reconstruction accuracy the coordinate detector DECOR [4,5] 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 angular reconstruction accuracy for muon tracks crossing a single SM is better than 0.7° and 0.8° for projected zenith and azimuth angles respectively.

We analyzed data of two experimental series: 10th series of runs which was conducted from December 23, 2011 to March 21, 2013 (7945 hours of 'live' time); and 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 had been modernized.

The technique of the energy deposit measurements inside the detector volume was tested on the single near-horizontal muons. A condition of single near-horizontal muon selection was the triggering of two DECOR supermodules located along the opposite short sides of the water tank. If the 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 was taken as the track of the muon. For such geometry of the experiment, muons in the range of zenith angle from 84° to 90° are selected. In total, 3.84 million near-horizontal muons were detected.

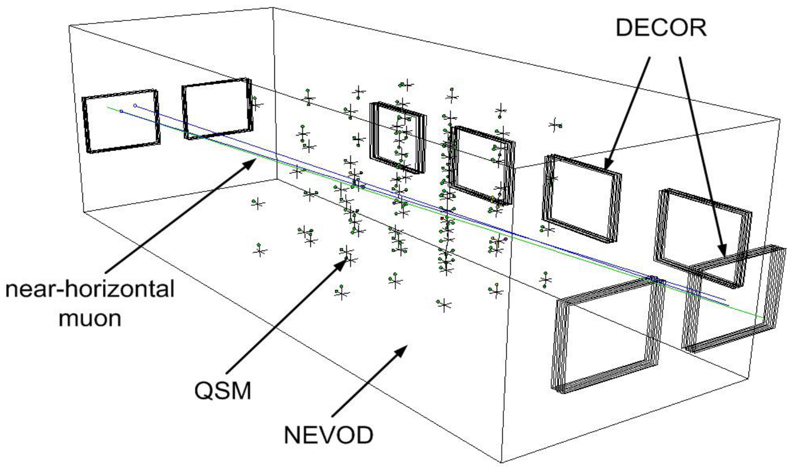

Figure 1: NEVOD experimental complex.

3. The technique of cascade profile reconstruction

To reconstruct the cascade profile in NEVOD, we determine the number of light-emitting relativistic particles based on the PMT amplitude (Figure 2, left) [8,9]. This technique is used for the PMTs directly illuminated by Cherenkov radiation from the cascade. We assume that the 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 PMT response to a single near-horizontal muon $A(R)$:

$$N = \frac{A_{PMT}}{A(R)\cdot\cos\alpha}\cdot\frac{\langle dE_\mu / dX\rangle\cdot l}{\beta} \quad , \qquad (1)$$

where α is the angle of Cherenkov radiation incidence on the PMT photocathode; $<dE_\mu/dX>$ is the specific average loss of muon in water (3.01 MeV cm^2/g, since for experiment geometry the average muon energy $<E_\mu>$ = 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 experimentally measured dependences of the PMT response (for cosα = 1) on the distance between PMT and muon track for 10th and 11th series are shown in Figure 2 (right).

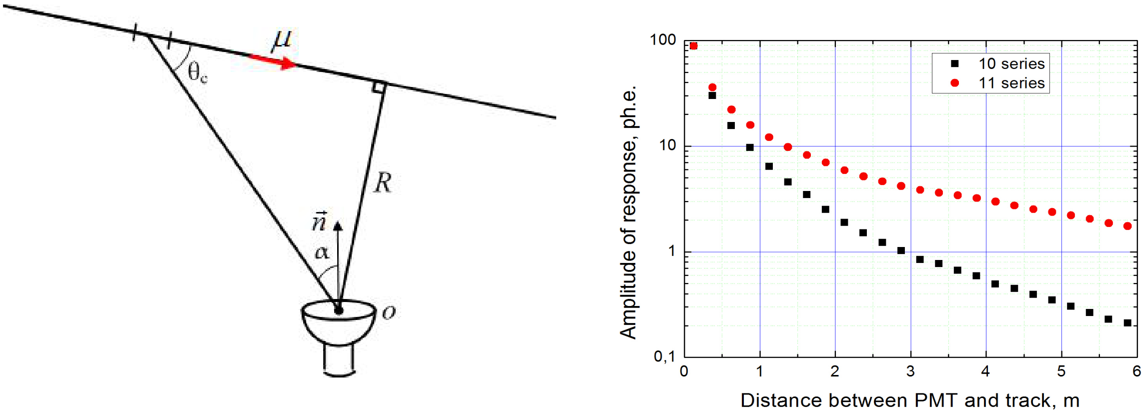

Figure 2: Geometry of the event for estimation of the number of charged particles (left) and dependences of the PMT response on the distance to the track of muons with the mean energy 100 GeV (right).

The estimated numbers of particles in a bin are averaged for all PMTs 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 [10]:

$$N(y_0, x_0, x) = \begin{cases} 1.4, \text{ if } x < x_0 \\ (0.32/\sqrt{y_0}) \cdot \exp((x - x_0)(1 - 1.5 \ln s)) + 1.4, \text{ if } x \geq x_0 \end{cases} \quad (2)$$

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.

To verify the technique of cascade profile reconstruction, a mathematical model of CWD NEVOD has been created in the Geant4 code [11]. The model takes into account the geometry and composition of the building elements, optical properties of water and properties of measuring channels. The analysis showed that basic characteristics of NEVOD responses in the simulation and in the experiment differed by less than 8 %.

To investigate the accuracy, cascade events with fixed energy were simulated. 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 $\varepsilon_0 = 10 \div 316$ GeV and 2700 events for cascades with energies 1 TeV and 3.16 TeV.

Cascade profiles of showers generated long before the lattice of CWD and near the end of the lattice are often reconstructed incorrectly. The registration scheme of boundary events is shown in Figure 3; for the certainty, it is a muon passing from the SM 06 (07) to the SM 00 (01).

The dependence of the reconstructed cascade parameter y_0 on the position of the reconstructed cascade profile maximum x_{max} is shown in Figure 4. The zero reference datum is the cross point of the muon track and first of the seven QSM planes.

If the cascade profile maximum has coordinate $x_{max} < -10.0$ radiation lengths, then the part of the cascade (s<1) can be seen by a small number of PMT placed far from the cascade axis.

Responses of such PMTs to the single muon is less than 1 ph.e. so an error of the number of charged particles in a bin of the depth can be significant.

The distance between the external planes of the spatial lattice of CWD is ~21 radiation lengths. If the cascade profile maximum is close by next-to-last or last plane of QSM, then the cascade part with the age $s>1$ is either seen by a small number of PMTs, or not visible at all. So, parameters of cascades with coordinate of maximum x_{max} > 15 radiation lengths are also reconstructed incorrectly.

Therefore, after reconstruction of shower 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 in Figure 4.

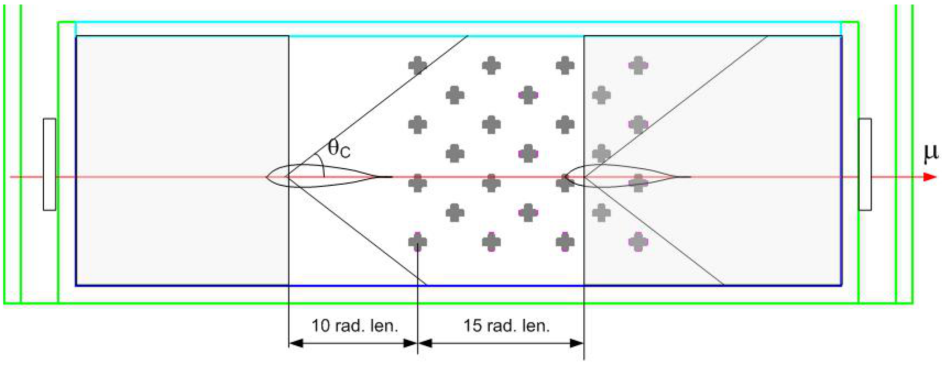

Figure 3: Selection of cuts in depth.

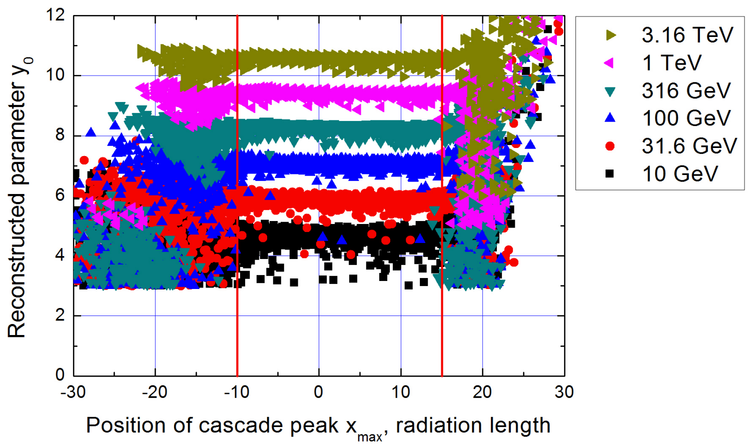

Figure 4: Dependence of reconstructed cascade parameter y_0 on the position of the maximum of reconstructed cascade profile.

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 the correctness of the developed technique. The difference between the reconstructed point of cascade generation and the simulated point does not exceed 1.5 radiation lengths. Such result is acceptable since QSM lattice step (distance between odd- and even-numbered planes) is about 3.5 radiation lengths.

The use of the one-dimensional approximation of cascade development leads to a some distortion of the reconstructed cascade profile. In figure 5, the curve represents the theoretical approximation for a cascade with the energy ε_0 = 316 GeV calculated by equation (2), while the squares show the average cascade profiles according to the simulation (black squares are for all

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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 means of the developed technique.

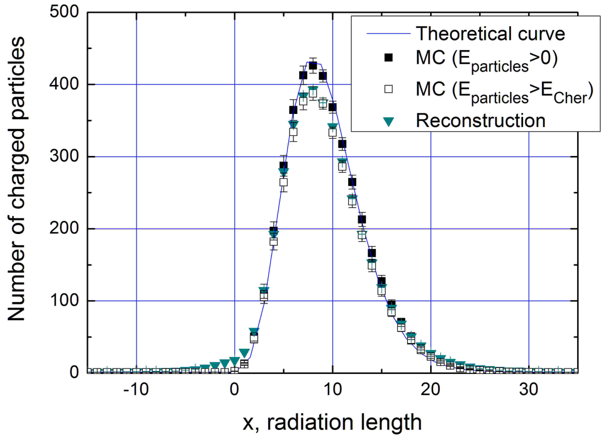

Figure 5: Theoretical, mean simulated and reconstructed profiles for cascades with energy 316 GeV.

As it can be seen, the average reconstructed profile follows the shape of the average simulated profile for particles with energies above the Cherenkov radiation 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

During the experimental runs, 3.84 million events with single near-horizontal muons selected by means of DECOR were registered. In 237 790 events, cascades with energy from 1 to 3000 GeV were reconstructed. 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 6 (left). In some events, double cascades were observed. An example of the cascade profile of such event is shown in figure 6 (right). Reconstructed energies of the two cascades in this event are 12 GeV and 16 GeV.

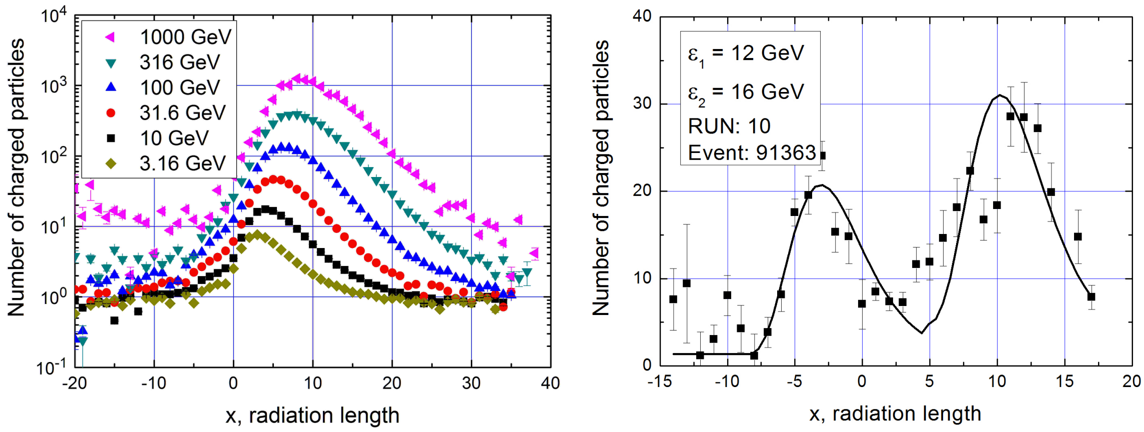

Figure 6: Mean cascade profiles (left) and an example of a double cascade (right).

The differential energy spectrum of cascades generated by near-horizontal muons is presented in Figure 7 (left). On the basis of the formalism developed in papers of G.T. Zatsepin and L.V. Volkova [12], 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 calculation results for some values of γ are shown in Figure 7 (left). The position of the maximum likelihood corresponds to the value of γ = 1.70; 68% confidence interval of the parameter is in the range γ = 1.67 – 1.73.

Parameters of cascades generated inside the NEVOD volume can be reconstructed also without data of the coordinate detector DECOR. In the NEVOD lattice, optical modules with the highest responses in the cascade event form a compact cluster. The geometry of the cluster can be used as the cascade signature. It was found that the rms radius of the cluster of 20 QSM with the highest responses does not exceed 2.35 m in 95% of events with cascades 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, and 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.

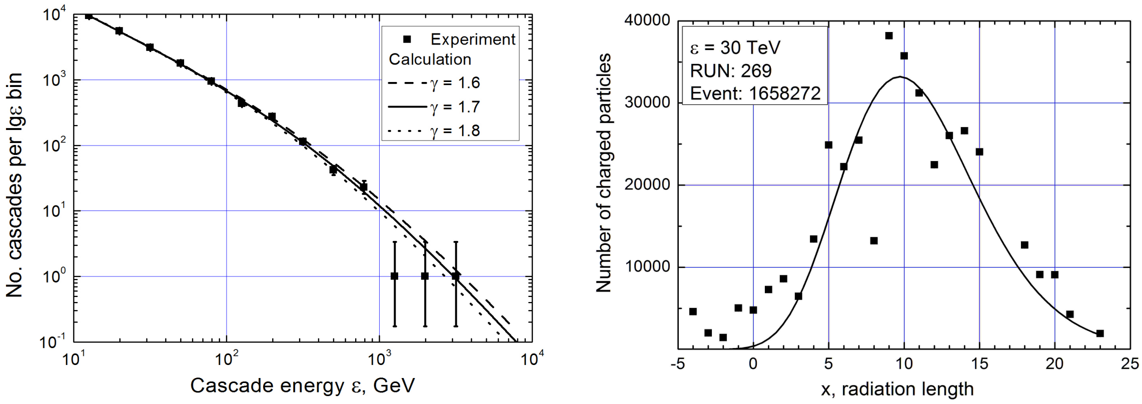

Figure 7: Energy spectrum of cascades (left) and an example of cascade profile reconstructed only on the basis of the NEVOD data (right).

Events with large energy deposits were selected for the preliminary analysis. A condition for these events was that more than 59 QSMs were hit. The preliminary analysis confirmed the possibility of cascade reconstruction on the basis of NEVOD data only. The energy of the most powerful cascade is about 30 TeV, and its zenith angle is about 80º. Figure 7 (right) shows the profile of this cascade. This approach allows to increase the statistics of the cascade spectrum at high energies by nearly 2 orders of magnitude since in this case the geometry of events is not limited by the coordinate detector aperture.

5. Conclusion

The dense spatial lattice of optical 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 $\varepsilon = 3 \div 1000$ GeV have been obtained, the differential energy spectrum of cascades generated by near-horizontal muons has been measured in the energy range of $\varepsilon = 10 - 3000$ 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 $\gamma = 1.67 - 1.73$.

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References

[1] S. Mangano, (ANTARES Collaboration), *Nucl. Instr. Meth. in Phys. Res*, **A 588**, 107 (2008).

[2] M.G. Aartsen et al. (IceCube Collaboration), *J. Instr.*, **9**, 03009 (2014).

[3] V.M. Aynutdinov et al., *Astrophysics and Space Science*, **258**, 105 (1997).

[4] N.S. Barbashina et al., *Instrum. Exp. Tech.*, **43**, 743 (2000).

[5] M.B. Amelchakov et al., *Izv. Akad. Nauk: Ser. Fiz.*, **66**, 1611 (2002), in Russian.

[6] S.S. Khokhlov et al., *Astrophys. Space Sci. Trans.*, **7**, 271 (2011).

[7] V.V. Kindin et al., *Proc 24rd ECRS (Kiel, 2014). Submitted to J. Phys.: Conf. Series* (2015).

[8] S.S. Khokhlov et al., *J. Phys.: Conf. Ser.*, **409**, 012134 (2013).

[9] S.S. Khokhlov et al., *Bull. Leb. Phys. Inst.,* **41**, 292 (2014).

[10] S. Hayakawa, *Cosmic Ray Physics*, NY: J. Wiley & Sons (1969).

[11] S. Agostinelli et al., *Nucl. Instr. Meth. in Phys. Res.*, **A 506**, 250 (2003).

[12] T.P. Amineva,V.A. Astafiev, A.Ya. Varkovitskaya, L.V. Volkova et al., *Study of high energy cosmic ray muons with X-ray emulsion chambers*, 'Nauka', Moscow (1975, in Russian).