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Cherenkov water calorimeter on the basis of quasi-spherical modules

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The main experimental capabilities of the Cherenkov water calorimeter NEVOD are determined by two factors: the use of the spatial detecting lattice of quasispherical modules (QSM) and location on the Earth surface. The feature of the QSM is its ability to register the Cherenkov radiation from any direction with practically the same efficiency. It is achieved by the use of six photomultiplier tubes (PMT) FEU-200 with flat photocathodes with diameter of 15 cm directed along the axes of orthogonal coordinate system. The total response of the module weakly depends on the direction of Cherenkov light, that is, the QSM has the property of a spherical PMT. The technique of studying this feature of QSM using the events with single muons detected with the calibration telescope system (CTS) or with the coordinate detector DECOR is considered, and the obtained results are discussed. The features of using the detector NEVOD as a calorimeter are demonstrated by an example of reconstructing the longitudinal profile of the shower produced in water by muon by means of Cherenkov radiation.

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1. Introduction

Cherenkov water detectors are the most widely developing experimental technique for investigation of cosmic rays with high energies in recent decades. Depending on the type of tasks, the detecting systems can be located either under a thick layer of matter to be protected against the penetrating cosmic radiation or on the Earth surface. The Unique Scientific Facility «Experimental complex NEVOD» is situated on the territory of MEPhI (55°39'N, 37°40'E) at an altitude of 161 m above sea level. It includes the detectors of different types, that can operate separately or in the common trigger mode. The basis of the experimental complex is the multipurpose Cherenkov water detector (CWD) NEVOD [1] with the water reservoir of volume 2000 m^3 (26×9×9 m^3). Its experimental capabilities are determined by the properties of the detecting spatial lattice with quasi-spherical modules in its nodes. These modules provide almost the same efficiency of registration of Cherenkov radiation from any direction. The detecting lattice consists of four planes with 16 QSMs and three planes with 9 QSMs each. In its turn, each plane is formed by vertical clusters (strings) consisting of 4 or 3 QSMs. The distance between the modules is 2.5 m along the water reservoir axis, 2.0 m across it and 2.0 m in the vertical direction. The small distance between the QSMs in the lattice enables to reconstruct accurately the tracks of charged particles and provides the characteristics of 4π-detector. The threshold energy of the detector is up to 7 GeV for horizontally moving muons and 2 GeV for vertical muons.

In 2011, the new registration system of the NEVOD detector was developed [2]. But these changes did not affect the geometrical parameters of the QSM. Now the QSM is equipped with low-noise photomultiplier FEU-200 (at the threshold of 0.25 p.e., the noise level is about 5 kHz) produced by "JSC Ekran-optical systems" (Russia). Low-noise background of PMTs allows to refuse from the double coincidence triggering condition which was needed at the use of FEU-49B. The photomultiplier has a semitransparent antimony-potassium-cesium photocathode providing the maximum of spectral characteristics in the range of 410-430 nm. It also has the electrostatic focusing of electrons and the multiplier system with 12 dynodes. The signals from 12^{th} and 9^{th} dynodes are used to extend the dynamic range of PMT. The charge signals from the dynodes are processed with charge sensitive amplifiers having the convertion factors equal to 25 mV/pC and 50 mV/pC for the 12^{th} and 9^{th} dynodes respectively. The PMT amplification factor is equal to 10^6, the gain between the 12^{th} and 9^{th} dynodes is about 50. 12-bit ADC with LSB equal to 1 mV (0.25 p.e.) is used for digital processing of signals from QSM. The dynamic range is 0.04 – 160 pC for the 12^{th} dynode and 0.08 – 320 pC for the 9^{th} dynode. Taking into account the factor of convertion (2 times) and the factor of amplification (50 times), the final dynamic range of signals is 1 to 10^5 p.e.

These two main changes: the increasing of the dynamic range and refusing from the double coincidence of signals of two PMTs as a triggering condition allow to convert the Cherenkov water detector (CWD) into Cherenkov water calorimeter (CWC).

The layout of the detecting systems of the experimental complex NEVOD is shown in Figure 1. The calibration telescope system (CTS) is used for calibration of PMTs in Cherenkov water calorimeter during the long experimental series. The system consists of 80 scintillation detectors: 40 of them are on the top of water reservoir and 40 at the bottom (the upper and lower planes). Any pair including one detector from the upper plane and one from the lower one forms the muon telescope. It enables to register single muon tracks in the zenith angle range from 0º to 50º (the accuracy is about 2º) and to calibrate the PMTs.

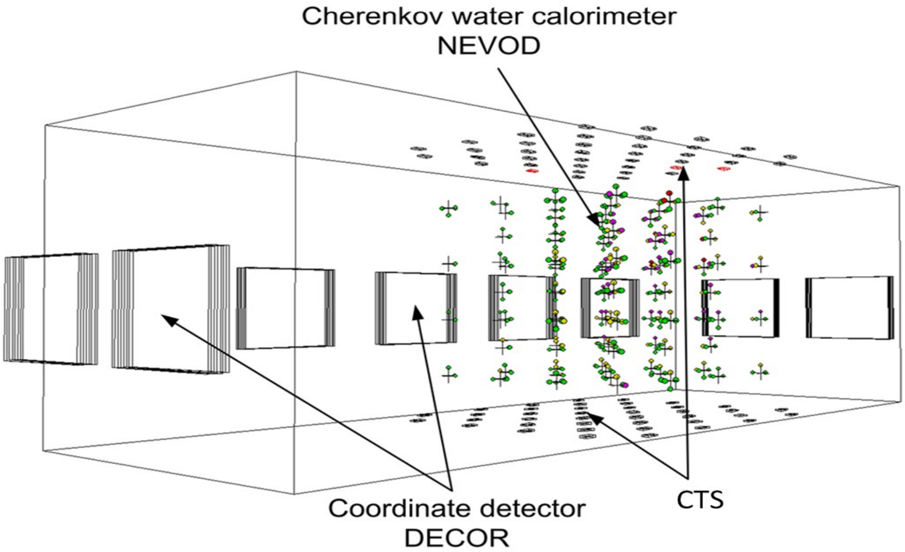

Figure 1: The layout of the detecting systems of the experimental complex NEVOD.

The coordinate-tracking detector DECOR [3] is installed in the galleries along three sides of the water reservoir. DECOR is the first large-scale tracking detector designed for studying cosmic rays on the Earth surface at large zenith angles up to the horizontal direction. The detector includes eight vertically suspended assemblies (supermodules, SMs). Each SM includes eight layers, each layer enables to define *X* and *Y* coordinates of charged particles passing through this layer. The total sensitive area of the detector is ~ 70 m^2, the spatial accuracy of muon track reconstruction is better than 1 cm, the angular accuracy is about 0.7º.

2. Quasispherical module

The detector NEVOD was originally designed to register neutrinos coming from the lower hemisphere. Taking into account its location on the Earth surface, it was necessary to provide the suppression of background events at the level 10^{10}, and ensure the registration of rare events from the lower hemisphere. These factors became determining for the design of the quasispherical module. For the first time, the idea to use the assembly of six photomultipliers with flat photocathodes was proposed at the 16th ICRC in 1979 [4]. The response A_i of the photomultiplier with flat photocathode to a single relativistic charged particle depends on the distance R to the track of the particle and on the angle α of incidence of Cherenkov light to the PMT cathode:

$$A_i = \frac{\eta \cdot n \cdot S \cdot \cos\alpha}{2\pi \cdot R \cdot \sin\theta_c} \cdot \exp\left(-\frac{R}{l \cdot \sin\theta_c}\right), \quad (1)$$

where, η is the quantum efficiency of photocathode; n is the number of photons emitted from the track of unit length; S is the photocathode area; θ_c is the angle of emission of Cherenkov light in water, l is the light attenuation length in water, averages on the frequency spectrum of Cherenkov radiation.

The configuration of several PMTs with flat photocathodes can have the property of the spherical PMT: the isotropic response. The elementary configuration having such property is the module with six PMTs oriented along the axes of the orthogonal coordinate system (the configurations of modules having more PMTs can be designed on the base of the geometry of regular polyhedrons). The sum of the squared amplitudes of three PMTs that register the flat front light does not depend on the Cherenkov light direction, because in that case $\cos^2\alpha_x+\cos^2\alpha_y+\cos^2\alpha_z=1$. The dependence on the distance to the track of the particle only remains:

$$\sum_{i=1}^{3} A_i^2=\frac{\eta^2\cdot n^2\cdot S^2}{4\pi^2\cdot R^2\sin^2\theta_c}\cdot\exp\left(-\frac{2\cdot R}{l\cdot\sin\theta_c}\right)=B^2 . \qquad (2)$$

Besides, the module of such design allows to determine the direction to the part of the muon track, where the Cherenkov light was emitted. As the estimation of that direction, a vector constructed from the normal vectors of PMT cathodes, where the length of each vector is proportional to PMT response, can be used. So, the module having six PMTs with flat photocathodes has the advantage over the PMT with spherical photocathode. Such module having the isotropic response and providing the reconstruction of the light direction is used in CWC NEVOD (see Figure 2).

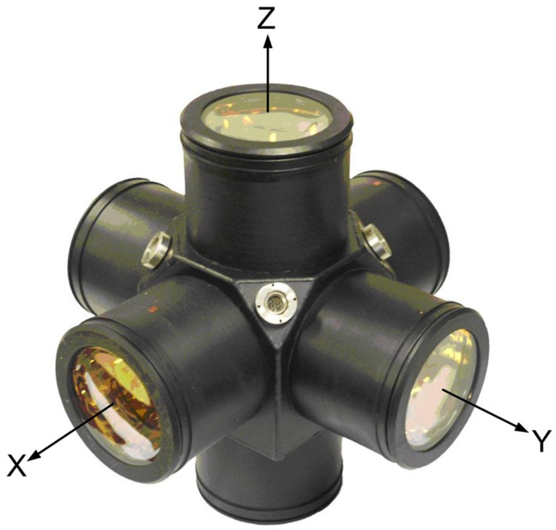

Figure 2: Quasispherical module of the Cherenkov water calorimeter NEVOD.

3. Study of the QSM response to single muons

The events with single muons that passed through the CWC were used to study the response. Such events can be selected by the calibration telescope system or using the coordinate-tracking detector DECOR.

To study the single QSM's ability of determining the direction of Cherenkov light, we selected the events, in which the track of the single particle was detected with the calibration telescope system. The selection criterion was an activation of one detector in the upper plane and one detector in the lower plane. The example of such event is shown in Figure 3a. The direction of light was estimated for each triggered QSM using the above approach. The range of distances from the muon track to the QSM was 0.5 to 2 m. For each triggered QSM, the angle between the estimated direction of light and the direction determined according to the CTS data was calculated. The distribution of the cosine of this angle for 8×10^5 such events is shown in Figure 3b. The average accuracy of determining the direction of light with a single QSM is about 27˚. It enables to reconstruct the muon track by means of Cherenkov detector response with the angular accuracy of 6.5° in the events with single muons, in which dozens of QSMs are triggered [5].

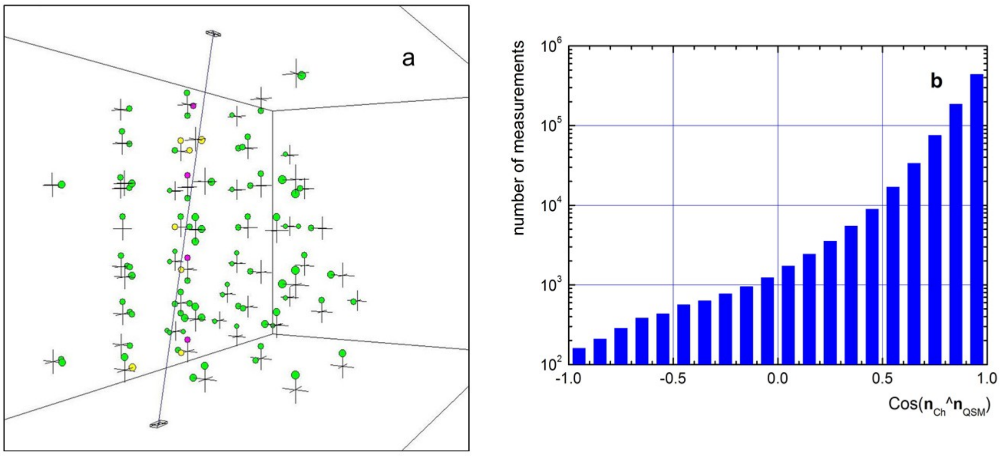

Figure 3: Example of the event detected with CTS: 108 PMTs are triggered (in 57 QSMs), including 31 PMTs oriented upwards, 5 PMTs oriented downwards, the total amplitude response is 390 p.e. (3a). Distribution of the cosine of the angle between the direction of light, determined according to the CTS data and its estimation using QSM responses (3b).

The study of the independence of the QSM response from the direction of Cherenkov light (the characteristics of sphericity) was conducted. The events with single muons detected with the pair of supermodules of the detector DECOR were used. As the characteristics of QSM response, the value of B was used:

$$B=\frac{R}{R_n}\sqrt{\sum A_i^2}\,, \tag{3}$$

where R_n is some normalization distance.

In each event, the QSMs register the Cherenkov radiation from a single particle. Its track was defined with the coordinate detector DECOR. The parameters of the response of each QSM were transferred to the spherical triangle, representing the 1/48 part of the sphere (Figure 4). For QSM with six PMTs, it is the smallest segment that enables to cover the whole sphere using rotations and mirror reflections relative to the symmetry planes of the QSM.

The study was conducted for two ranges of distances R between the muon track and the center of QSM: 0.5 – 1.0 m and 1.0 – 2.0 m. The middle of each range was used as the value of normalizing distance R_n, for the ranges above these values are 0.75 m and 1.5 m, respectively. The zenith angles of selected single muons were

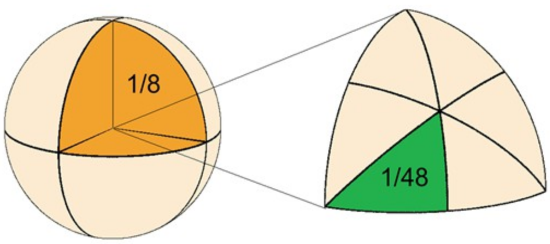

Figure 4: The selection of spherical segment for studying QSM response.

limited with the range from 86˚ to 89˚. The average values of B defined by equation (3) for various locations on the spherical segment are shown in Figure 5a (the projection on a plane is presented). The borders of projection of the spherical segment are marked with yellow lines.

For each of two distance ranges, the rms-deviations from the mean value of QSM response averaged over the sphere (Figure 5b) were calculated. These values characterize the deviations from the sphericity of QSM. These values expressed in percentage are equal to 8% for the range of 0.5 – 1.0 m and less than 5% for the range of 1.0 – 2.0 m.

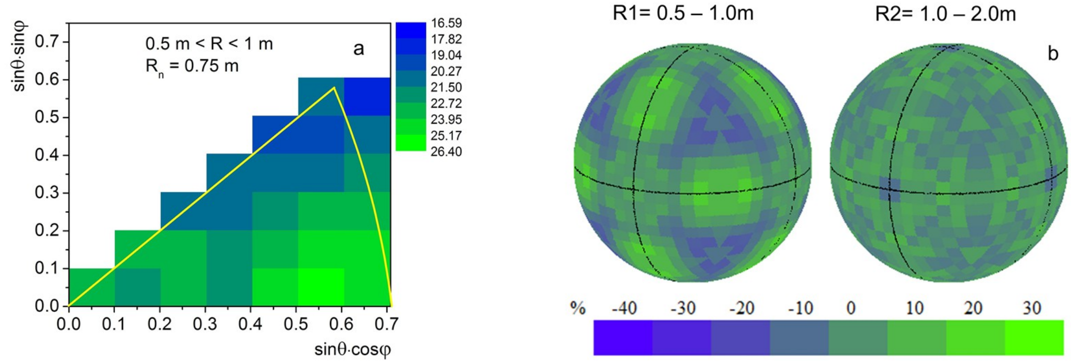

Figure 5: The triangle matrix of QSM response (5a), QSM response for two ranges of distances from the center of QSM to the track of the particle (5b).

4. Cascade shower measurements

The homogeneity of the sensitive substance of the detector and the high density of the detecting spatial lattice enable to reconstruct cascade curves of the showers produced by muons in the sensitive volume of the detector. The technique of reconstruction [6] is based on the amplitude responses of PMTs, which detect the direct light from the cascade axis. It is assumed that the electrons and positrons produced in the shower move along the cascade axis and that the axis coincides with the muon track, that can be defined with a high precision using the DECOR detector.

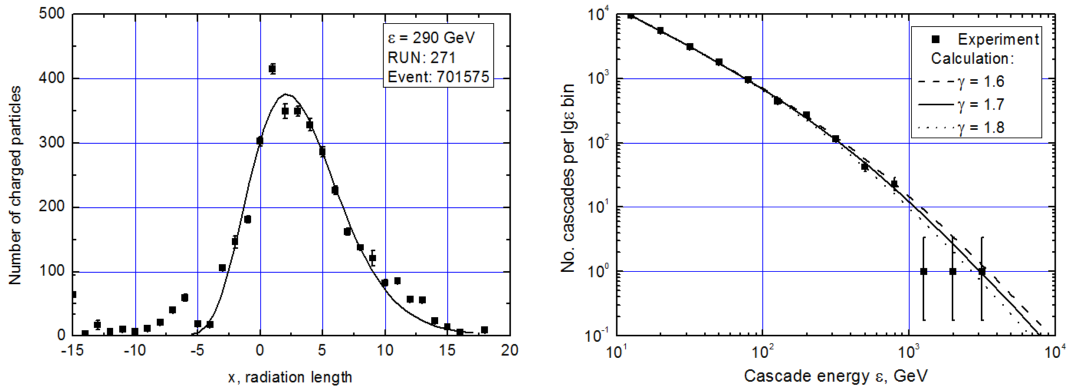

Figure 6: Reconstructed cascade curve of the shower detected in CWC NEVOD (left) and the differential energy spectrum of cascades (right).

So, the problem is to reconstruct the values of two parameters of the theoretical cascade curve in one-dimensional approximation: the energy of the cascade E_0 and the point on the axis, where the cascade was generated. The events of experimental runs with the duration of 7945 hours were used for reconstruction of the parameters of the cascades. About 120 thousand cascades with energy greater than 1 GeV were found in thrse runs. An example of reconstructed cascade curve of the shower with energy of 290 GeV and the differential energy spectrum of cascades in the analyzed experimental data are shown in Figure 6.

5. Conclusion

The design of the detecting module with several PMTs with flat photocathodes enables to reach the isotropic amplitude response. The QSM with six PMTs oriented along the axes of the orthogonal coordinate system, that is used in CWC NEVOD, has suitable characteristics of the sphericity: for distances more than 0.5 m the rms-deviation from the mean value of QSM response is less than 8%. Besides, the configuration of PMTs with flat photocathodes enables to reconstruct the direction of Cherenkov light with a single quasi-spherical module. Accuracy of track reconstruction by the spatial lattice depends on the number and distances between QSMs and in our case for the lattice $6\times6\times7.5$ m^3 with 91 QSMs is better than 7˚. This lattice allows to estimate the direction and location of the axis of the shower produced in the sensitive volume of the Cherenkov calorimeter. The idea of quasispherical module [4] implemented in CWC NEVOD is topical at the moment: the module with a similar design having 31 PMTs is assumed to be used for KM3Net detector [7] that should be deployed in the Mediterranean sea.

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