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Study of characteristics of the quasi-spherical measurement modules of the Cherenkov water calorimeter NEVOD

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Abstract

The use of quasi-spherical modules with several PMTs with flat photocathodes in Cherenkov water detectors is discussed. Properties of the response of such modules are examined. The characteristics of the quasi-spherical module with six PMTs that is used in the Cherenkov water calorimeter NEVOD are considered. The results of studying the isotropy of the amplitude response of this module and the quality of reconstruction of light direction with a single module and with a group of modules are demonstrated.

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Keywords: Cherenkov water calorimeter, quasi-sperical module, photomultiplier tube

1. Introduction

Cherenkov water detectors are at the moment the most widely developing instruments for research of the characteristics of the cosmic rays, for study of muons and neutrinos with extremely high energies. The effective registration of Cherenkov light from any direction is the topical problem related with such detectors. Generally

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speaking, it would be desirable to have the detecting module with the response that does not depend on the direction of Cherenkov light. Besides, it would be great if a single module could reconstruct this direction.

Regarding the first property, the ideal would be a spherical photomultiplier with the isotropic response. But such a device is not created, and the perspectives are uncertain. Nowadays, two types of photomultiplier tubes (PMT) with different response properties are used in real experiments. First of them is the PMT with hemispherical photocathode having almost the same response in some region of spatial angles:

$$A_1(R) = \frac{C}{r} \cdot \exp(-\frac{r}{l}), \quad (1)$$

where, r is the distance to the source of radiation; l is the light attenuation length in water. The PMTs of this type are widely used in large-scale detectors, such as ANTARES, IceCube, BNT-200+. The modules with a single directed downward PMT or the configurations with three PMTs (ANTARES) directed in the lower hemisphere are usually used.

The second type is the PMTs with flat photocathode that has the response determined with cosine of the angle of incidence of Cherenkov light to the PMT cathode (α):

$$A_1(R,\alpha) = \frac{C \cdot \cos\alpha}{r} \cdot \exp(-\frac{r}{l}). \quad (2)$$

Such character of the response allows to make a configuration of several PMTs with flat photocathodes that has the property of the spherical PMT: the isotropic response. The module with such configuration we call hereafter the quasi-spherical module (QSM).

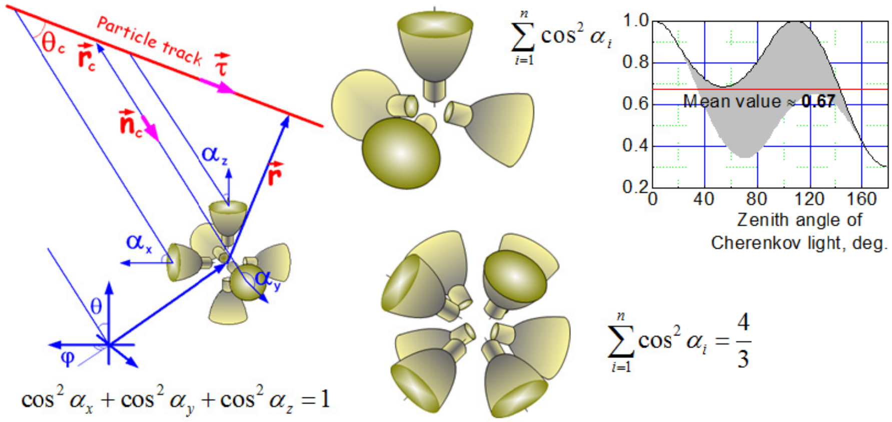

Fig. 1.The configurations of 4, 6, 8 PMTs with flat cathodes and their property of sphericity.

The location of PMTs in the QSM that provides the property of sphericity can be determined on the base of the geometry of regular polyhedrons. There are five such figures: the tetrahedron, the cube, the octahedron, the icosahedron and the dodecahedron. It is allowed to locate PMTs in the vertices or on the midpoints of the edges or in the centers of the faces of these figures. There is an exception for the tetrahedron when we use the configuration of four PMTs (Fig. 1). Each PMT should be directed so that the normal to the photocathode through its center passes also through the center of the polyhedron.

The sum of the squared amplitudes of all PMTs, that register the flat front light, does not depend on the Cherenkov light direction; the dependence on the distance to the track of the particle only remains. It is easy to see for the example for the configuration of six PMTs oriented along the axes of the orthogonal coordinate system. In that case the cosines of the angles of incidence of light to three PMTs are the direction cosines of the vector opposite to the light direction. The sum of squares of these cosines obviously equals to one. Several configurations with the different number of PMTs, including the configuration with four PMTs that does not have the property of sphericity, are shown in Fig. 1.

2. The Cherenkov water calorimeter with quasi-spherical modules

For the first time, the idea to use the assembly of six photomultipliers with flat photocathodes was proposed at the 16th ICRC in 1979 [1]. It is the elementary configuration of the module, whose response does not depend on the direction of Cherenkov light. Besides this property, the proposed module allows to estimate the direction of Cherenkov radiation.

The quasi-spherical module is the basis of the Cherenkov water calorimeter NEVOD that is the main part of the Unique Scientific Facility «Experimental complex NEVOD» [2]. The Cherenkov water calorimeter (CWC) NEVOD is the water reservoir with volume of 2000 m^3 ($26\times9\times9$ m^3) with the detecting spatial lattice placed inside. It has 91 quasi-spherical modules in the lattice nodes. Each QSM includes six photomultipliers FEU-200 with flat photocathodes.

The modules are assembled in 25 strings-clusters: 16 clusters having four QSMs each and 9 clusters with three QSMs. Besides the CWC the experimental complex includes the system of calibration telescopes and the coordinate-tracking detector DECOR. The layout of the detecting systems of the experimental complex NEVOD is shown in Fig. 2.

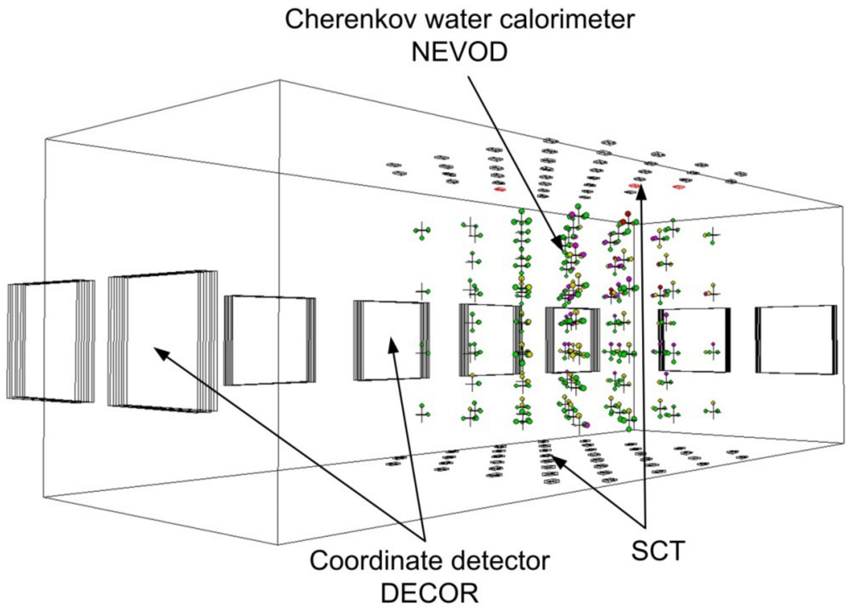

Fig. 2. The layout of the experimental complex NEVOD.

The system of calibration telescopes is used for calibration of PMTs in Cherenkov water calorimeter during the long experimental series. It consists of SCT 80 scintillation detectors: 40 of them are on the cover of water reservoir and 40 on 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 that enables to register single muon tracks in the zenith angle range from 0º to 51º with the accuracy about 2º.

The coordinate tracking detector DECOR [3] consists of 8 supermodules (SMs) placed in the galleries along three sides of the water reservoir. The 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 about 70 m^2, the spatial accuracy of muon track reconstruction is better than 1 cm, angular accuracy is about 0.7º.

3. Study of the properties of the response of the measurment module

The events with single muons that passed through the CWC were used to study the response of the QSM. Such events can be selected using the system of calibration telescopes or the coordinate-tracking detector DECOR. Not a separate module was studied, but the averaged characteristics of QSMs in the lattice.

The study of the property of isotropy of the QSM response was conducted using the events with single muons, detected with the pair of supermodules of the DECOR. The events with the muons with the zenith angles in the range of 86˚ to 89˚ were used. The study was conducted for several ranges of distances *R* between the muon track and the center of QSM.

The direction of incidence of Cherenkov light to the center of QSM was determined for each module that registers the light from the track. The response was analyzed in two versions of characteristics calculated for different ranges of distances:

$$B_1 = \frac{R}{R_n} \cdot \sum A_i; \qquad B_2 = \frac{R}{R_n} \cdot \sqrt{\sum A_i^2}\,. \tag{3}$$

where *R* is the distance from the track of the muon to the centre of the QSM, R_n is some normalization distance corresponding to the middle of the range.

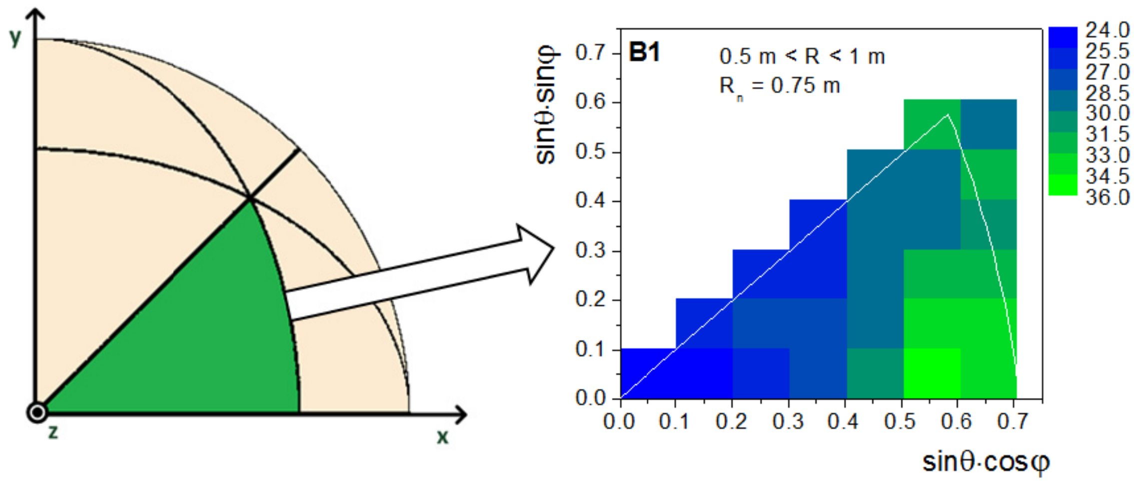

Fig. 3. Spherical triangles (left) and the QSM response (B1 values) in the spherical segment (right).

Taking into account the symmetry of the module, the characteristics of the response were transferred to the spherical triangle, representing the 1/48 part of the sphere. For QSM with six PMTs it is the smallest segment that enables to cover the whole sphere using rotations and mirror reflections to the symmetry planes of the QSM. The average values of B_1 defined by equation (3) for various locations on the spherical segment, for the range of distances between the QSM and the track of muon from 0.5 m to 1.0 m are shown in Fig. 3. The projection of the spherical triangle on a plane is presented in the coordinates sinθcosφ and sinθsinφ, where θ and φ are the zenith and the azimuth angles of the direction of incidence of Cherenkov light to the QSM in the spherical triangle.

Because of the non-zero overall dimension of the QSM (the distance between the cathodes of the opposite PMTs is 54 cm) the distances to the track less than half a meter were not considered.

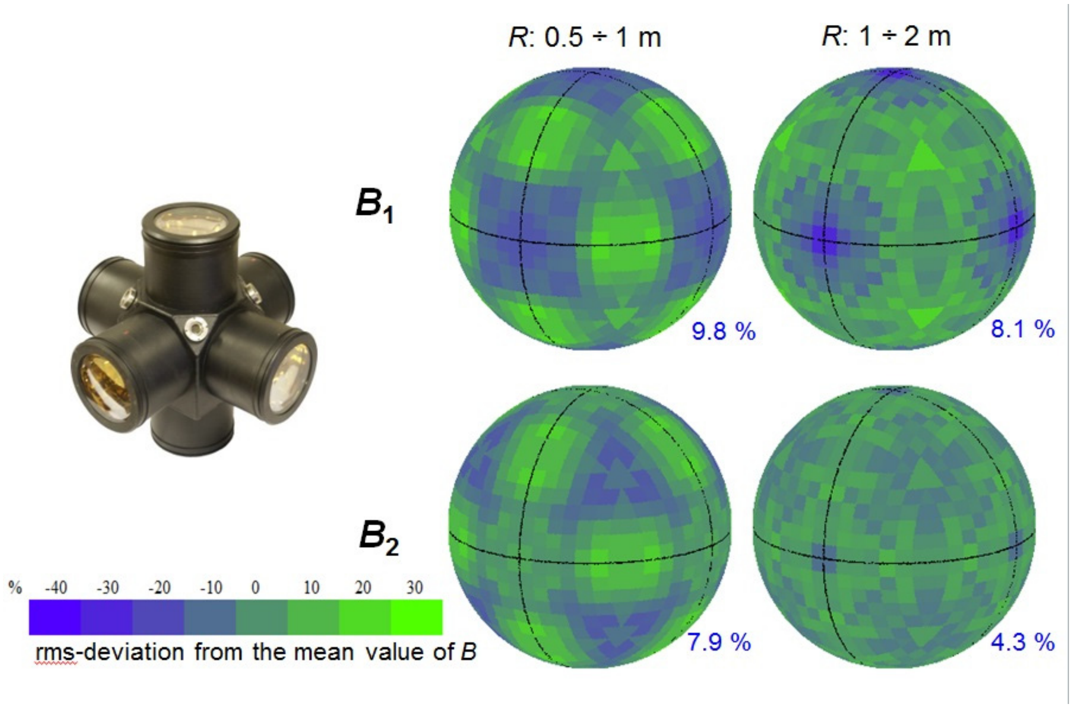

Fig. 4. The QSM responses and the deviation from the sphericity of the QSM

For each range and for each version of calculation of the response (B_1 and B_2), the rms-deviation from the mean value of QSM response averaged over the sphere was calculated (Fig. 4). This value shows the deviation from the sphericity of QSM. For B_2 this value expressed in percentage equals to 8% for the range of 0.5 – 1.0m and is less than 5% for the range of 1.0 – 2.0m.Thus, the results of the analysis have shown that the QSM has the suitable characteristics of the sphericity. Thus the characteristic that is the square root of the sum of the squared amplitudes of triggered PMTs is preferable as the value of the response of the QSM.

The single QSM's ability of determining the direction of Cherenkov light was also studied. We selected the events, in which the track of the single particle was detected with the system of calibration telescopes. The selection criterion was an activation of one detector in the upper plane and one detector in the lower plane. The direction of light was estimated for each triggered QSM. A vector that is the sum of the normal vectors of PMT cathodes, where the length of each vector is proportional to its response, can be used as the estimation of this direction.

The range of the distances between the QSM center and the track that were used for the study is from 0.5 m to 2 m. For each triggered QSM the angle between the estimated direction of light and the direction defined according to the SCT data was calculated. The distribution of the cosine of this value is shown in Fig. 5.

The average accuracy of determining the direction of light with a single QSM is about 27^0. It enables to reconstruct the muon track by means of Cherenkov detector response with the angular accuracy of 6.5^0in the events with single muons, in which dozens of QSMs are triggered [4].

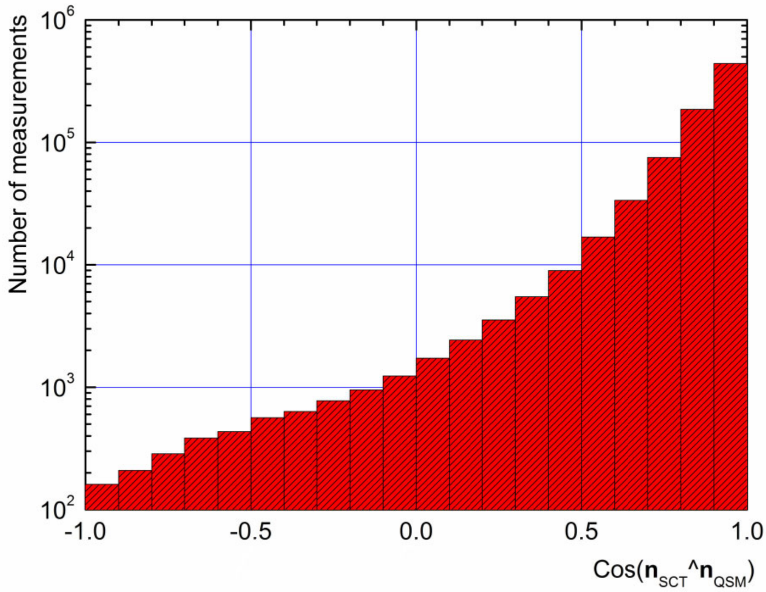

Fig. 5. Distribution of the cosine of the angle between the direction of light defined according to the SCT data ($\boldsymbol{n}_{\mathrm{SCT}}$) and its estimation from QSM responses ($\boldsymbol{n}_{\mathrm{QSM}}$)

4. Conclusions

The detecting module with six PMTs has good characteristics of sphericity of the response to the Cherenkov radiation. The averaged rms-deviation from the mean value of QSM response is less than 8% for distances to the track more than 0.5 m.

Besides, the quasi-spherical module with such design enables to reconstruct the direction of the light. It allows to reconstruct the track of the single muon with the spatial lattice of such modules with accuracy better than 7˚.

The specified properties of the optical module in combination with small spatial lattice spacing (1.25 m along the water reservoir axis, 1.0 m across it and 1.0 m in the vertical direction) and wide dynamic range of signals (1 to 10^5photoelectrons for each PMT) provide the calorimetric properties of the detector NEVOD. In particular, the CWC allows to study the showers produced in the sensitive volume of the detector. In that case the axis of the shower and its longitudinal profile can be reconstructed without data from the coordinate detectors but with the response of the QSMs only.

The idea of the module on the basis of the PMTs with flat photocathodes that was proposed more than 35 years ago, remains topical at the moment in new large-scale experiments. Thus, the quasi-spherical module having 31 PMTs with flat photocathodes is assumed to be used in the neutrino telescope KM3Net [5] in the Mediterranean sea.

Acknowledgments

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