The 10th International Workshop on Ring Imaging Cherenkov Detectors (RICH 2018), Moscow

Quasi-spherical modules for Cherenkov water detectors

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Introduction

In a problem of studying cosmic rays with Cherenkov detectors it was always desirable to have a photomultiplier tube (PMT) that would have a response independent of the direction of the incident light and could simultaneously determine this direction. But such PMTs have not yet been created. Nowadays, two types of photomultiplier tubes (PMTs) – with flat and hemispherical photocathodes – are widely used for registration of Cherenkov radiation in cosmic ray experiments.

An important characteristics of PMTs with hemispherical photocathodes which are mainly used in existing large scale experiments such as IceCube, Baikal, ANTARES is almost the same response in a certain range of directions of incident light. For this range, the response to a single charged particle can be represented by a dependence:

$$A(R) = \frac{C}{R} \cdot \exp\left(-\frac{R}{L \cdot \sin\theta_C}\right),$$

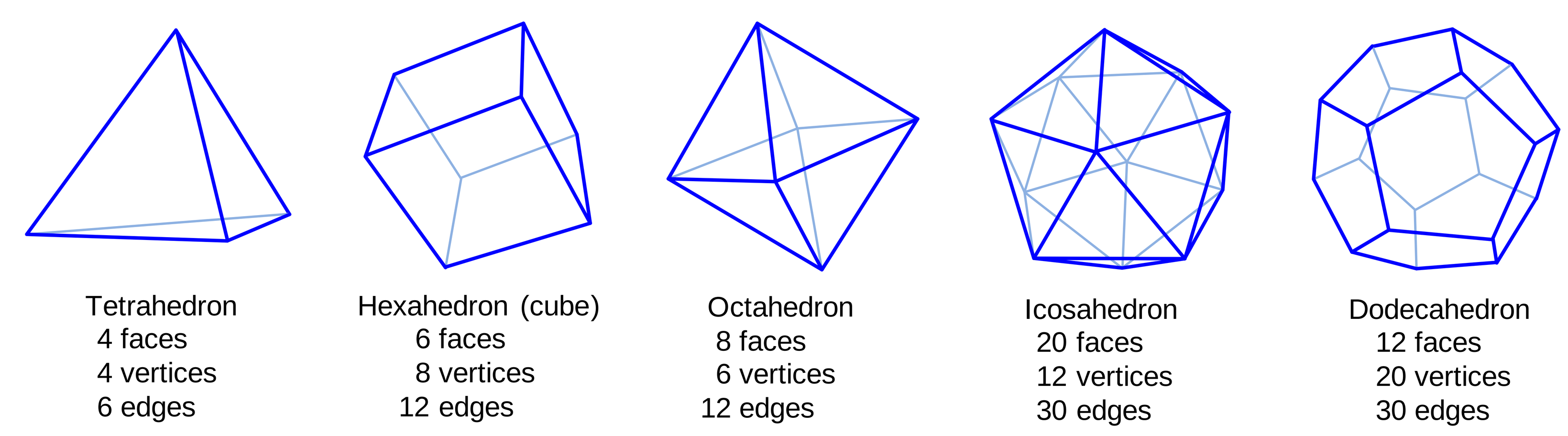
where R is the distance from the photocathode of PMT to the track of a charged particle; L is the light attenuation length in water.

The response of PMT with flat photocathode is determined by the cosine of the angle of incidence of Cherenkov radiation to the PMT cathode:

$$A(R_{PMT}, \alpha) = \frac{C \cdot \cos\alpha}{R_{PMT}} \cdot \exp\left(-\frac{R_{PMT}}{L \cdot \sin\theta_C}\right),$$

where R_{PMT} is the distance from the center of the photocathode of PMT to the track of a charged particle; L is the light attenuation length in water.

The location of PMTs in the QSM that provides the isotropic amplitude response can be determined on the basis of the geometry of regular polyhedrons: the tetrahedron, the cube, the octahedron, the icosahedron, and the dodecahedron.

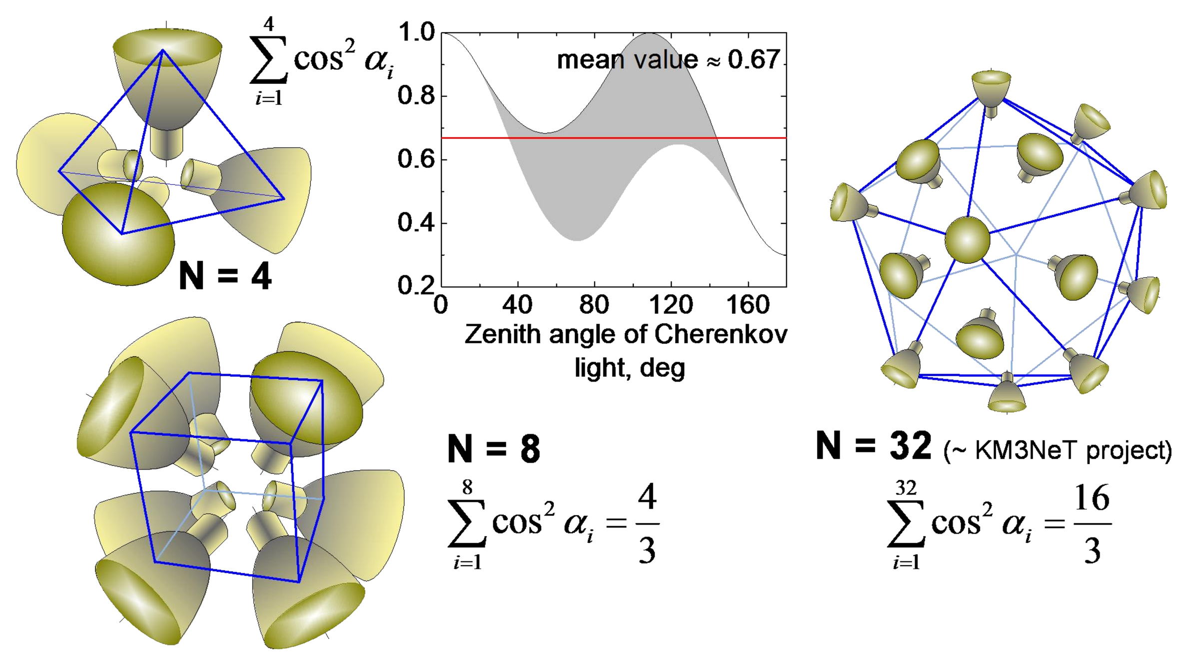


The QSM can be designed if PMTs are oriented towards the vertices or the midpoints of the edges or the centers of the faces of these figures and located at equal distances from the center. The configuration with four PMTs does not provide the property of sphericity, so the tetrahedron-based QSM is only possible with six PMTs placed on the edges.

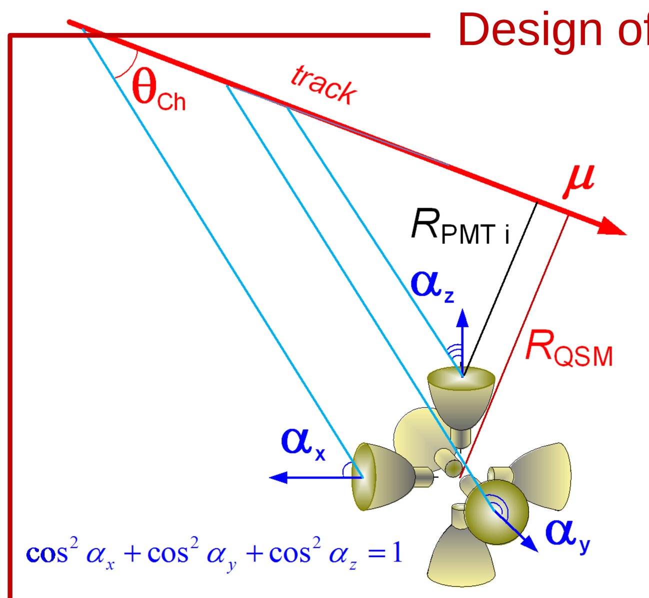
For such QSMs based on PMTs with flat photocathodes the square root of squared responses of all triggered PMTs can be used as a response of the QSM:

$$B = \sqrt{\sum_{i=1}^{N} A_i^2},$$

where N is the number of PMTs in the module.



Design of modules with isotropic response



For such character of the response, the configuration of several PMTs with flat photocathodes allows to design a module that has the properties of a spherical PMT. Such module is named quasi-spherical module (QSM). The module with six PMTs oriented along the axes of an orthogonal coordinate system (see figure) – the simplest configuration of the quasi-spherical module – was proposed for the first time in 1979 by the MEPhI group [1] and was used in practice in the Cherenkov water detector (CWD) NEVOD [2].

From the property that the sum of squared directional cosines is equal to 1.0, it is clear that the sum of squared responses of triggered PMTs should weakly depend on the direction of Cherenkov radiation at the distances several times greater than the size of the module, when $R_{QSM} \approx R_{PMT\,i}$ and the front of radiation can be considered as flat.

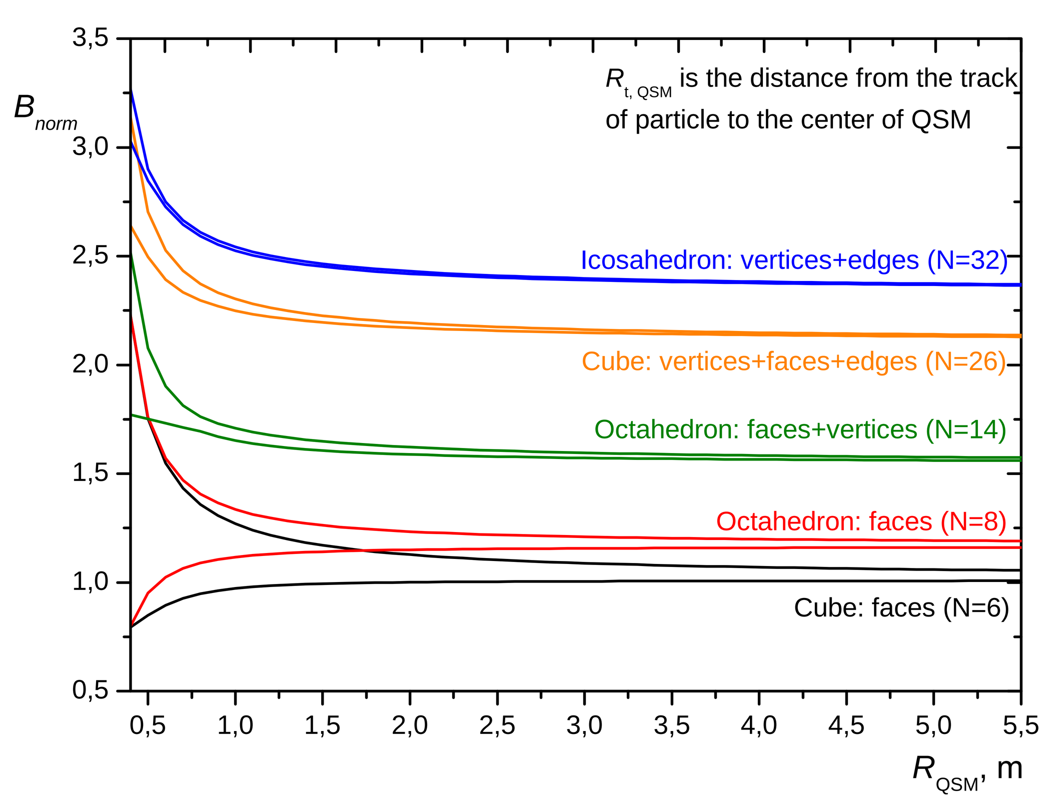
Property of sphericity of QSMs with different number of PMTs

Basing on assumption that the radius of the module is small, i.e. all PMTs are located near its center, and the front of Cherenkov radiation is flat, the module should have the isotropic response. But in fact the size of QSM is finite and the Cherenkov radiation from the track of a charged particle has not flat but conical front. The calculations of the responses of QSMs with different number of PMTs with flat photocathodes and with the same radius of the module equal to 0.25 m on the distance from the track of a charged particle was performed.

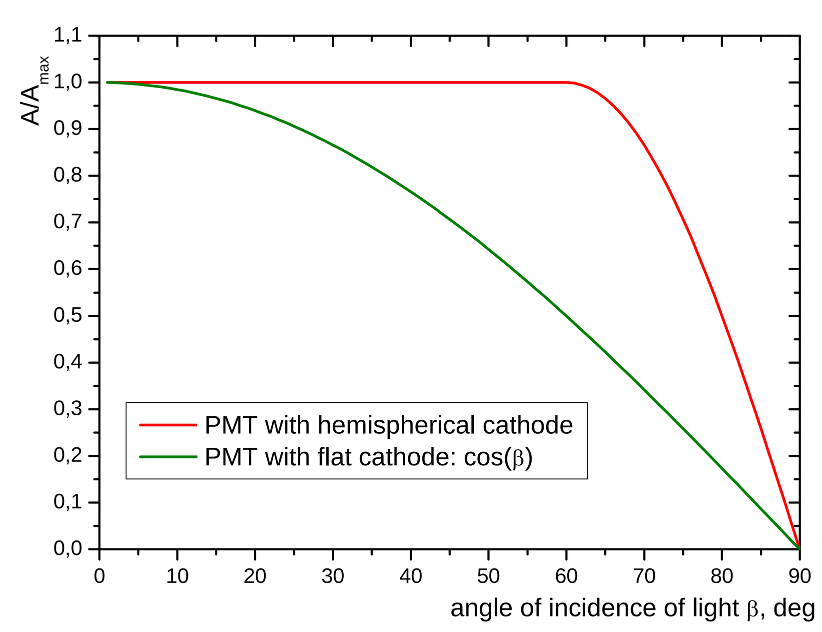
The weakening of the Cherenkov radiation in water because of attenuation and cylindrical divergence of radiation from the track was excluded:

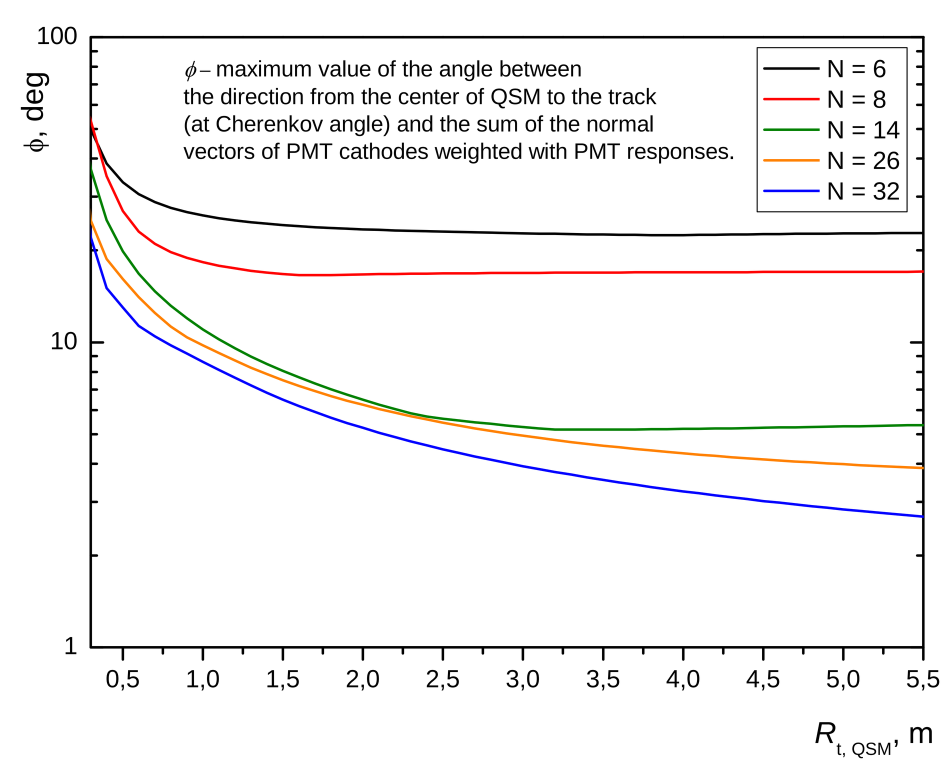
$$B_{norm} = B \cdot \frac{R_{QSM}}{C} \cdot \exp\left(\frac{R_{QSM}}{L \cdot \sin\theta_C}\right),$$

where R_{QSM} is the distance from the center of QSM to the track of the particle. Two curves for each QSM configuration represent minimum and maximum responses at all possible rotations of the module. It is clear from the figure that the property of isotropy of QSM improves with increasing distance from the track and with increasing the number of PMTs. At distances large compared to QSM radius, the QSM response tends to the value $\sqrt{N/6}$.



In addition, some degradation in estimation of the direction of incident light could be caused by using PMTs with not flat but spherical cathodes. The provisional angular dependence of the response for such PMT is presented in the figure below (left). Despite the fact that the hemispherical PMT can register the light from the back hemisphere, the angular dependence takes into account the work of the PMT as a part of the module: the module design in the KM3NeT project [3] and multi-PMT optical module prototype for IceCube-Gen2 [4] show that PMTs in these modules can register the light only from the front hemisphere. Calculations of the quality of reconstructing the direction of light for such type PMT have been done (right figure).





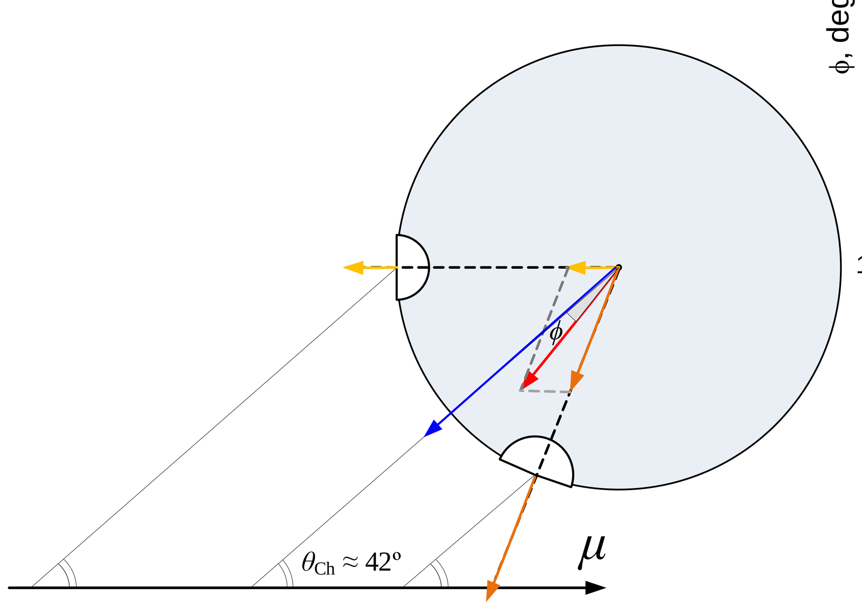
So, the estimation of the direction of Cherenkov radiation with module equipped with PMTs with hemispherical photocathodes leads to greater errors than QSM with flat PMTs. The reason of this fact is that each hemispherical PMT is less sensitive to the direction of incident light. Similar situation takes place with the property of sphericity: modules with PMTs with flat cathodes also show better characteristics. It is easy to see for QSM with 6 PMTs. Depending on the angle of QSM rotation, one, two or three PMTs can be triggered in the case of flat front of incident light. For QSM with flat PMTs the response is always close to 1. For QSM with spherical PMTs the response will vary with the range from 1 to √3 even when using the above formula of QSM response or will reach 3 when using simple sum of PMT responses as the response of QSM.

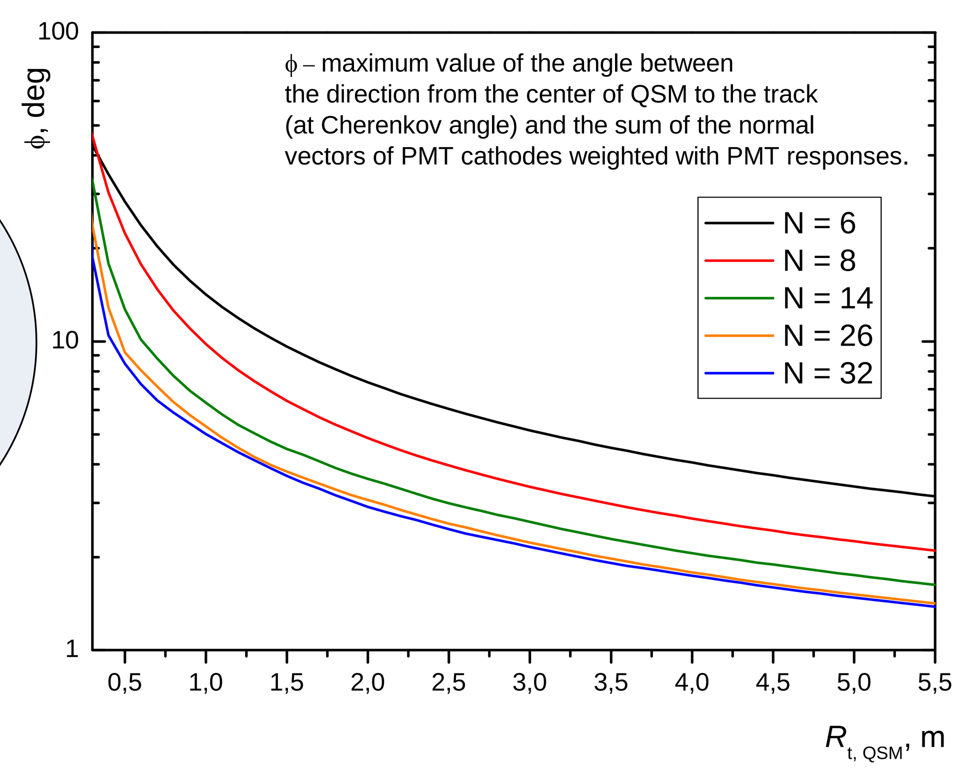
Estimation of the direction of incident radiation by single QSM

Besides of the property of isotropy of the response, the quasi-spherical modules allow to estimate the direction of the incident Cherenkov radiation. This direction can be estimated as the sum of normal vectors of photocathodes of PMTs weighted with their responses (charges):

$$\vec{a} = \sum_{i=1}^{N} \vec{n}_i \cdot A_i$$

The maximum value of an angle between this estimated direction and the direction defined by the Cherenkov angle (left figure) on the distance from the track of a charged particle was calculated for different values of N (right figure).





Quality of estimation of the direction also improves with the distance and with the number of PMTs in the module.

In reality, the problem of designing the quasi-spherical modules is complicated by the fact that with the increase in the number of PMTs the size of the module also increases, or smaller PMTs should be used.

Conclusions

The configurations of multiple PMTs (6, 8, 12, 14, 18, 20, 26, 30, 32, …) with flat photocathodes based on the geometry of Platonic solids have the property of sphericity of the response and allow to determine the direction of incident Cherenkov radiation. The quality of isotropy of the response and the quality of estimation of direction improve with the distance from the track of the charged particle and with the number of PMTs that form the module.

The analysis shows also that the use of PMTs with not flat but hemispherical photocathodes to design optical modules deteriorates its characteristics of sphericity of the response and estimations of the light direction: for the module with 32 PMTs the calculated maximum error in determining the direction of light (at the distance greater than 5 m) is less than 1.5° when using PMT with flat cathodes and about 3° for hemi-spherical PMTs.

First QSM with six PMTs was proposed for the first time in 1979 by the MEPhI group and implemented in CWD NEVOD. Until recently, it was the only application of quasi-spherical modules in Cherenkov detectors. The decisions to use multi-PMT QSMs in modern large-scale projects such as KM3NeT [3] and next generation of IceCube [4] determine the relevance of the problem of studying the properties of quasi-spherical modules.

References

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