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Wide field-of-view and high-efficiency light concentrator

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ABSTRACT

To improve light yield and energy resolution in large-volume neutrino detectors, light concentrators are often mounted on photomultiplier tubes to increase the detection efficiency of optical photons from scintillation or Cherenkov light induced by charged particles. We propose a method to optimize previous light concentrators design in order to attain a field of view of 90° and a geometrical collection efficiency above 98%. This improvement could be crucial to Jinping and other future neutrino experiments whichever it is applicable.

1. Introduction

Many neutrino detectors use water, heavy water or liquid scintillator as neutrino target and detection material. Cherenkov and scintillation light induced by charged particles, products of neutrino interaction, are detected by photomultiplier tubes (PMTs). Light concentrators (or reflectors), developed based on Winston cone [1,2], have been adopted to be mounted on PMTs by several neutrino experiments, for example, the SNO [3,4] and Borexino [5] experiments, and cosmic ray telescopes [6–8]. Water-based liquid scintillator or slow liquid scintillator, both of which feature Cherenkov and scintillation separation, may be available and very interesting in the near future [9–14]. To detect sufficient light and to achieve a high energy resolution for solar neutrino studies using a slow liquid scintillator, the Jinping [15,16] neutrino experiment is also considering the use of light concentrators. Other neutrino experiments are also interested in light concentrators. It may be the default option in the LENA experiment [17]. In parallel to this study for Jinping, similar R&D activities on light concentrators are also being developed for the JUNO experiment [18,19].

Fig. 1 shows how a light concentrator is used with a PMT. By design, incident light that may have missed the photocathode can be reflected on to it, if the incident angle θ (see Fig. 1 for the conventional definition of θ and ϕ) of the light is within a cut-off angle, $\theta_{cut-off}$. In principle, no acceptance of photons occurs beyond the cut-off angle. The technique effectively enlarges the aperture of a PMT by a significant factor, for example, 1.8 for SNO, and 2.7 for Borexino. The use of light concentrators is favored because of the low cost compared with the expense of increasing the number of PMTs or pursuing larger PMT diameters.

The neutrino detectors of future experiments require a high light collection efficiency and a large target mass [15,18]. When employing light concentrators in a very large neutrino detector, for example 10 m diameter for a central target region, a wide field of view is needed. In previous cited experiments, the detector configuration requires a $\theta_{cut-off}$ of about 50° [3–8]. The used design method, also known as the String method, can be further considered to achieve better performance. In particular, we focus on two aspects: (1) Within the cut-off angle, the perfect light collection efficiency designed in two dimensions (2D) cannot be preserved in three dimensional (3D) condition [1–3]. This obstacle is especially serious for wide-view concentrators. (2) Light concentrators with circular apertures cannot achieve a gapless configuration. The hexagonal design in Cherenkov telescope experiments may solve this problem [6–8].

In Section 2, we further explore the defect of the String method, introduce a modification in its application, and explore the effects of addition of a hexagonal opening. In Section 3, the performance and cost of different designs are compared. Finally, discussions and conclusions are presented in Section 4.

2. Design method

In this section, the detection efficiency of light concentrators is first defined. The simulation tools for analyzing concentrators are then explained. The defect of the String method is explained. Finally a modified method and a hexagonal light concentrator are introduced.

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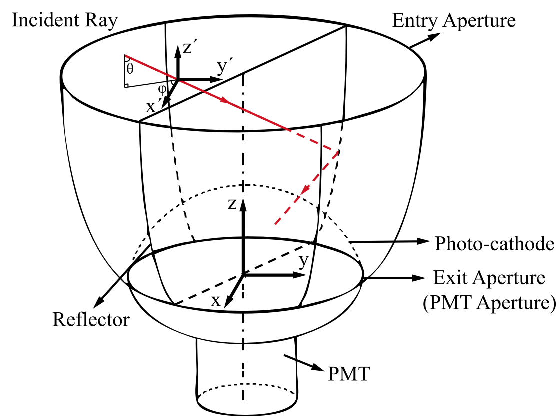

Fig. 1. Illustration of a PMT with a concentrator. The incident angle, θ, is the angle between the incident ray (red line) and the symmetry axis (z axis). The azimuth angle, ϕ, is the angle between the x-axis and the projection of incident ray on the x–y plane. The x-axis is arbitrary unless specified. The entry aperture, exit aperture (PMT aperture) are parallel to the x–y plane. More details are explained in the text. (Color online)

2.1. Detection efficiency

The light detection efficiency, ε, of a detector configuration with light concentrators can be expressed as

$$\begin{aligned}\varepsilon &= \frac{N_{PMT} \cdot S_{PMT} \cdot Amp}{S} \cdot \varepsilon_{ref} \cdot \varepsilon_{col}, \\ &= \frac{N_{PMT} \cdot S_{PMT} \cdot S_{entry}/S_{exit}}{S} \cdot \varepsilon_{ref} \cdot \varepsilon_{col}, \\ &= coverage \cdot \varepsilon_{ref} \cdot \varepsilon_{col},\end{aligned} \quad (1)$$

where N_{PMT} is the total number of PMTs with concentrators, S_{PMT} is the area of the exit aperture of the concentrator, i.e. the area of the photocathode if it is treated as a flat disk (see Fig. 1), Amp gives the ratio of the entry and exit aperture areas of the concentrator (the exit aperture is identical to the PMT aperture), S is the total surface area of the detector, that will be filled with PMTs and concentrators, ε_{ref} is the reflectivity of the concentrator and ε_{col} is the geometrical collection efficiency for all the optical photons upon the entry aperture and within the cut-off angle, $\theta_{cut-off}$.

The first term of Eq. (1) gives the effective coverage of all photocathode, ε_{ref} is close to 90% for aluminum coatings, and is not the emphasis of this article, and the last term gives the geometrical acceptance for photon detection with a single concentrator. The total light detection efficiency of a detector is proportional to ε. Without light concentrators, Amp, ε_{ref} and ε_{col} are all one, and ε is simply the photocathode coverage $N_{PMT} \cdot S_{PMT}/S$.

N_{PMT} typically has a significant impact on the total cost of an experiment, and Amp and ε_{col} are the two critical properties of a light concentrator to be optimized.

2.2. Simulation tools and setup

The concentrator geometry was first designed in SolidWorks, a software program commonly used for solid modeling. The SolidWorks model was then transformed into triangular facets in FASTRAD, which is a 3D CAD tool for radiation shielding analysis. The output data was used to build concentrator geometries in Geant4 [20,21] through the G4TessellatedSolid class. We used Geant4 simulation to analyze each concentrator. Light rays were generated uniformly on the entry aperture of the light concentrator, and incident angles were set according to the interest of test.

The sensitive part of the photocathode geometry was approximated as a spherical section with a diameter of 28 cm and a height of 10.46 cm; this geometry coincides with that of an XP1807 PMT [22]. We set the reflectivity of the concentrator to be one.

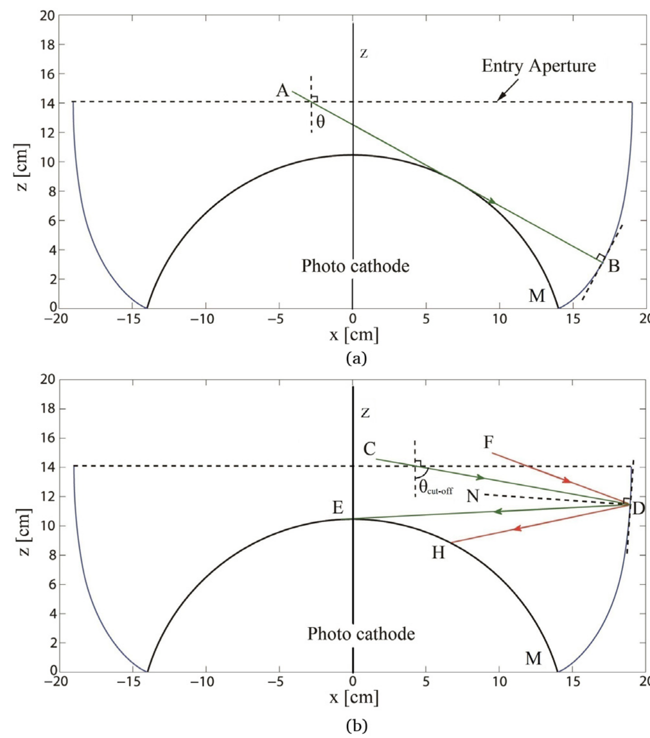

Fig. 2. Illustration of the principle of the String method. In panel (a) AB is the critical ray for point B, where the incident angle $\theta < \theta_{cut-off}$. The slope of the concentrator at B is perpendicular to AB. In panel (b) CD is a incident ray, where $\theta = \theta_{cut-off}$. ED is the reflection of CD and the critical ray. ND is the angular bisector of CD and ED. The slope of the concentrator is perpendicular to ND. Thus any rays with $\theta < \theta_{cut-off}$ can reach the photocathode, similar to FD's reflection onto HD. See the text for more details. (Color online)

2.3. Introduction to the string method

The String method is an improved design method of concentrators based on the Compound Parabolic Curve (CPC, also known as the Winston Cone [1,2]) method. Compared with the CPC method, the String method considers the shape of the PMT photocathode, which results in an increase in the area of the entry aperture and allows a reduction of the number of PMTs per unit area.

In the String method, given $\theta_{cut-off}$, the reflector surface is obtained by rotating a 2D reflector profile (Fig. 2) around its symmetrical z axis. The way to construct the profile curve is explained below.

For any point on the reflector curve, a critical ray is a ray starting from the point and tangential to the photocathode.

Starting with point M (see Fig. 2, a), if the incident angle θ of the critical ray is less than $\theta_{cut-off}$, the slope of the reflector curve must be perpendicular to the critical ray. An infinitesimal step is added along the slope just determined to create the next point of the curve. Such a process continues until the incident angle θ of the critical ray equals $\theta_{cut-off}$. Afterward the slope must be perpendicular to the angular bisector between the critical ray and the ray with $\theta = \theta_{cut-off}$ (see Fig. 2, b). The iteration continues until the curve is perpendicular to the entry aperture plane. Any incident rays with $\theta < \theta_{cut-off}$ will directly arrive at or be reflected onto the photocathode in the 2D plane.

In the 3D case, this simple feature is not preserved. For example in Fig. 3, for a concentrator with $\theta_{cut-off} = 80°$, all photons incident upon the entry aperture with $\theta = 60°$ and $\phi = 0°$ are traced. Photons with small or large y values may miss the PMT photocathode, because the arch of the photocathode off the central z axis is not as high as that in the 2D profile design. The 3D geometry of the photocathode will be considered next.