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

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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\textsuperscript{[1,2]}, have been adopted to be mounted on PMTs by several neutrino experiments, for example, the SNO\textsuperscript{[3,4]} and Borexino\textsuperscript{[5]} experiments, and cosmic ray telescopes\textsuperscript{[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\textsuperscript{[9–14]}. To detect sufficient light and to achieve a high energy resolution for solar neutrino studies using a slow liquid scintillator, the Jinping\textsuperscript{[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\textsuperscript{[17]}. In parallel to this study for Jinping, similar R&D activities on light concentrators are also being developed for the JUNO experiment\textsuperscript{[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 $\theta$ (see Fig. 1 for the conventional definition of $\theta$ and $\phi$) of the light is within a cut-off angle, $\theta_{\text{cut-off}}$. 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\textsuperscript{[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 $\theta_{\text{cut-off}}$ of about 50$^\circ$\textsuperscript{[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\textsuperscript{[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\textsuperscript{[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.
where $N_{Amp}$ is the area of the exit aperture of the concentrator, i.e. the area of the experiment, and $S_{Amp}$ is the total surface area of the detector, that will be filled with PMTs and concentrators, $S_{aperture}$ is identical to the PMT aperture), $\varepsilon_{ref}$ is the reflectivity of the 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 through the G4TessellatedSolid class. We used Geant4 simulation to analyze each concentrator 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.

2.1. Detection efficiency

The light detection efficiency, $\varepsilon$, of a detector configuration with light concentrators can be expressed as

$$\varepsilon = \frac{N_{PMT} \cdot S_{PMT} \cdot Amp \cdot \varepsilon_{ref} \cdot \varepsilon_{col}}{S}$$

$$= \frac{N_{PMT} \cdot S_{PMT} \cdot S_{entry} / S_{exit} \cdot \varepsilon_{ref} \cdot \varepsilon_{col}}{S}$$

$$= \text{coverage} \cdot \varepsilon_{ref} \cdot \varepsilon_{col},$$

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, $\varepsilon_{ref}$ is the reflectivity of the concentrator and $\varepsilon_{col}$ 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, $\varepsilon_{ref}$ 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 $\varepsilon$. Without light concentrators, $Amp$, $\varepsilon_{ref}$ and $\varepsilon_{col}$ are all one, and $\varepsilon$ 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 $\varepsilon_{col}$ are the two critical properties of a light concentrator to be optimized.

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