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Acrylic studies for Hyper-Kamiokande experiment

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ABSTRACT

This work illustrates a prototypal polymeric cover of multi-photomultiplier detector for the Hyper-Kamiokande neutrino experiment. The cover was made of a high transmittance poly-methyl methacrylate (PMMA). The main objective of the present research is to investigate the structural properties of PMMA, correlating them to material parameters and numerical models to evaluate its application to the cover implementation.

1. Introduction

Large-volume neutrino observatories with monolithic liquid targets are able to address key issues of particle and astro-particle physics by extrapolating existing data with neutrino detection technologies. Detectors with large target masses assure a significant improvement in the sensitivity of proton decay, only if background processes remain controlled. Moreover, measurements of neutrino oscillations with a sufficiently long baseline would allow for a precision computation of atmospheric oscillation parameters. For this reason, a growing interest exists in the US, Europe and Japan to propose and realize these very large projects [1]. Among them, water Cherenkov (WC) is an attractive technology to measure long baseline neutrino oscillations because it can be scaled up to very large sizes. Over the last three decades, large WC detectors have been very important in uncovering several fundamental properties of neutrino. The Kamiokande experiment program is one of the successful results of this technology [2,3]. The Super-Kamiokande (Super-K) experiment is an imaging underground WC detector to study neutrinos from various sources, mainly searching for proton decay, located in the Kamioka mine in Gifu Prefecture (Japan). The detector consists of a large cylindrical tank (39.3 m diameter and 41.4 m height), filled with 50 kilotons of ultra-pure water, in which the photomultiplier tubes (PMTs) are internally and externally facing [4]. A high-intensity muon neutrino beam travels from the J-PARC facility in Tokai to Kamioka (T2K), covering a distance of 295 km. Cherenkov rings produced by charged particles created by neutrino interactions are imaged using the PMTs, reconstructing the direction and momentum of the resulting particles [5]. For that purpose, the T2K experiment may obtain a hint for a finite CP phase, but an order of magnitude more events are necessary before a firm conclusion can be reached by using a much larger detector [6]. The Hyper-Kamiokande (Hyper-K) is a third generation WC detector and a natural extension of Super-K, planned to be located in the Tochibora mine in Gifu Prefecture (Japan), consisting of one-million-liter water target. The off-axis angles of the J-PARC neutrino beam with the Hyper-K is same of that with the Super-K [7]. Hyper-K will search for CP violation using the upgraded neutrino beam from J-PARC and will have a broad physics program including studies of atmospheric neutrinos, supernova burst neutrinos, geo-neutrinos and innovative searches for proton decay. Hyper-K will also extend sensitivity to proton decay, a definitive herald of new physics, by an order of magnitude and serve as an exquisitely sensitive observatory for neutrinos from astrophysical sources [8]. The baseline design of Hyper-K is based on the well-proven technologies employed and advanced at Kamiokande and Super-K, involving two separated caverns, each with an egg-shape cross section of 48 m wide, 54 m tall and 250 m long. The inner detector is an array of 100,000 20-in. PMTs, uniformly surrounding the active region with a photocathode coverage of 20% whereas the outer detector consists of 25,000 8-in. PMTs forming a veto [9]. The actual detector configuration considers two cylindrical tanks, each 74 m in diameter and 60 m in height, to deploy in stages [10]. Data analyses for solar neutrino observations with Kamiokande detectors are well known [11].

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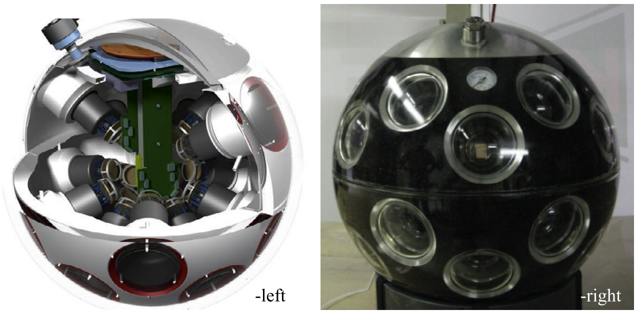

Fig. 1. Technical drawing (left) and assembled DOM (right) of the KM3NeT show the geometrical configuration and distribution of the several PMT [18].

2. Light detection system

Excellent performances, long term stability and reliability and low manufacturing costs are some key factors guiding the design of a new innovative PMT. Additional specifications require a large photocathode area to achieve a wide photo-coverage with a limited number of PMTs [12]. The R3600 (Hamamatsu Photonics K.K, Japan) PMT is actually used in the baseline design of the Super-K. This sensor represents an established technology due to its well understood characteristics and its capability of stably operating over long periods. Several new PMTs are actually under development. Preserving the same shape factor and evolving the electronics, two alternatives replace the venetian blind dynode of the Super-K with a box-and-line dynode (R12860) or with an avalanche diode (R12850). In both cases, the collection efficiency, timing and charge resolutions are improved [13,14]. From the manufacturing point of view, the 20-in. glass bulb of the R3600 is manually blown by skilled operators because the large size, small quantities and low production rates make the investment in automation not convenient. Some alternatives investigated the use of a smaller size to allow the automatic bulb manufacturing and decrease the risk of implosion [15].

Another interesting opportunity is to operate with a multiple PMTs (mPMT) within the footprint of a single PMT. A starting point is the experience of the KM3NeT collaboration, aimed to build up a multi-km^3 neutrino telescope in the Mediterranean Sea, exploiting the Cherenkov emission of relativistic charged particles in water [16,17]. The Digital Optical Module (DOM) used in KM3NeT consists of two pressure-resistant glass hemispheres with a 17-in. diameter containing 31 3-in. PMTs [18], distributed in 5 rings, plus a PMT at the bottom, looking directly downward, and all the related electronics needed to manage them [19]. The technical drawing (right side) from KM3NeT and the related assembled DOM (left side) are reported in Fig. 1.

This mPMT design presents some advantages over the more traditional DOMs with a single large area PMT. The total photocathode area is between 3 or 4 times the total area of a single PMT module, the angular coverage is almost uniform, and the rejection of optical background is improved due to directional information. Moreover, the identification of the arrival of more than one photon is efficiently detected because of the photocathode segmentation [20]. Some differences exist between the working conditions of Hyper-K and KM3NeT, influencing the design of the DOM such as: (i) the media in which the DOM will be installed is ultra-pure water (with a small concentration gadolinium sulfate in solution) instead of marine water as in the case of KM3NeT, (ii) the operative depth is 60 m much less than 4000 m typically of KM3NeT, (iii) very low failure rate is required for Hyper-K DOMs to avoid cavern emptying whereas KM3NeT DOMs are accessible for maintenance.

An enhanced DOM design is thus needed, concurrently looking to a high quality-controlled production for ensuring that each DOM can withstand to the operative pressure during its planned lifetime. Fig. 2 shows a technical drawing of the proposed DOM, adapted to the operative conditions of the Hyper-K experiment above described, included the issue of the radioactive contamination [21].

Table 1
Material data reported are the minimal values of the mechanical and optical properties declared from the supplier, for normal conditions and applications.

Properties	Value	
Mechanical		
Density	1.19	g/cm^3
Elongation at break	≥5	%
Tensile strength	≥60	MPa
Flexural strength	≥90	MPa
Elastic modulus	≥2500	MPa
Optical (transmission in the UV range 315 nm*)*		
3 mm thickness	≥80	%
8 mm thickness	≥70	%

26 3-in. PMTs are uniformly arranged on the inner and outer detector side, distributed in 3 rings each. 6 PMTs are spaced in each ring at 60° in azimuth and successive rings are staggered by 30°. A two-halves 3D-printed support is used for precisely aligning them. The plain structure between the two 3D-printed hemispheres, actually under construction, consists of an aluminum flange (AA5082), fulfilling the two important tasks of supporting the electronic boards and acting as a cooling device. Cooling is necessary to dissipate heat generated by the electronic device. All internal sub-structure is protected by a polymeric cover divided into two halves and assembled with mechanical fasteners. A plastic case envelope avoids a potential chain reaction accident caused by DOM implosion in water and it protects PMTs from the surrounding environment. The choice of this mechanical system is justified by the need to avoid fluorescence emissions caused by glue [22], guarantee a long endurance, simplify a stable anchorage to the tank frame and implement an efficient cooling system. The atmosphere in the sphere is radon free air to control the radioactive background event rate in solar neutrino and other low energy observation [21].

The objective of the present research is to assess the use of PMMA for the realization of a DOM cover produced by casting process. The material characterization from the technological point of view and the numeric computations of a prototype in the operative conditions are performed.

3. Material characterization of the DOM cover

A high transmittance poly-methyl methacrylate (PMMA) was used as a glass substitute for the actual design of the DOM cover. The candidate resin was the Plexiglas GS 2458 (Evonik Industries AG, Darmstadt, Germany), a specially developed polymer with a high ultraviolet transmission and resistance coupled to high mechanical strength at low weight [23]. The material, supplied in as-cast sheet, is characterized by no molecular chain orientation. The data sheet is reported in Table 1.

The supplier only specified the minimum values of the material properties with no information about their evolution over time. For this reason, some in-depth tests were performed to acquire a better knowledge on material characteristics. In fact, an accurate description of the mechanical behavior is crucial to predict the final performances of the DOM polymeric cover in real operative conditions. Compression testing under uniaxial loads allowed the basic deformation mechanisms of specimens to be recorded and the behavior under static conditions to be studied. Moreover, material data and material laws for compression are needed for structural reliability assessments to perform with simulation tools. Tests were carried out on cylindrical specimens (20 mm in diameter and 18 mm in height) cut from 18-mm thick sheets directly delivered from the material supplier. The sheets were produced by casting liquid methyl-methacrylate between two glass plates and polymerized it inside the cell. The polymerization techniques employed a water bath, a hot-air oven and a Rostero process [24]. The specimen