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Reflectance dependence of polytetrafluoroethylene on thickness for xenon scintillation light

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ABSTRACT

Many rare event searches including dark matter direct detection and neutrinoless double beta decay experiments take advantage of the high VUV reflective surfaces made from polytetrafluoroethylene (PTFE) reflector materials to achieve high light collection efficiency in their detectors. As the detectors have grown in size over the past decade, there has also been an increased need for ever thinner detector walls without significant loss in reflectance to reduce dead volumes around active noble liquids, outgassing, and potential backgrounds. We report on the experimental results to measure the dependence of the reflectance on thickness of two PTFE samples at wavelengths near 178 nm. No change in reflectance was observed as the wall thickness of a cylindrically shaped PTFE vessel immersed in liquid xenon was varied between 1 mm to 9.5 mm.

1. Introduction

Liquid xenon (LXe) detectors have found many applications based on their capability to provide both calorimetry and imaging of particle interactions. Particularly fruitful applications include dark matter [1–4] and lepton flavor violating [5] searches, neutrinoless double beta decay detectors [6], gamma-ray physics experiments [7], medical imaging [8], and neutron detection for Homeland Security [9].

The performance of these detectors is strongly affected by their xenon scintillation light collection efficiency, which depends significantly on the reflectance of the surfaces that surround the LXe volumes. Polytetrafluoroethylene (PTFE) reflector materials are oftentimes the material of choice for LXe detectors. PTFE is known to be highly reflective in the visible and near infrared (NIR) regions [10], where it can reach reflectance of $\mathcal{O}$ (99%). Reflectance remains high even in the vacuum ultraviolet (VUV) region. For xenon scintillation light ($\lambda \simeq 178$ nm) PTFE reflectance of $\mathcal{O}$ (55%) has been measured at room temperature [11,12]. When immersed in LXe, PTFE reflectance is of $\mathcal{O}$ (97%) [13,14], which is much higher than the $\mathcal{O}$ (90%) expected from optical models of the PTFE–LXe surface derived from vacuum measurements with xenon scintillation [15].

It is important to know the magnitude of PTFE reflectance in LXe, since a few percent difference in PTFE reflectance has a noticeable impact on the performance of a LXe detector [16]. Absolute PTFE reflectance in LXe has been measured recently [14], but little is known about the PTFE reflectance in LXe as a function of PTFE thickness at these wavelengths [17]. The need for studying the impact of thickness is driven by the desire to minimize the amount of PTFE reflector materials in rare event searches while maintaining good reflectance and thus high light collection efficiency. Minimizing PTFE thickness is desirable in order to reduce dead volumes around active LXe, outgassing, and potential backgrounds. A lower limit on the thickness is established by the PTFE transmittance to xenon scintillation light, and the need for optical isolation between active and passive regions in LXe detectors.

In this work, experimental results of the reflectance of PTFE immersed in LXe at wavelengths near 178 nm are reported as the thickness of the PTFE material is varied between 1 mm to 9.5 mm. The basic features of the experimental apparatus are described, followed by a discussion of the relative reflectance measurements of two PTFE materials as a function of PTFE thickness. Determination of absolute reflectance of these PTFE samples is beyond the scope of this paper. It has been performed elsewhere [14].

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2. Apparatus

The experimental procedure to measure PTFE reflectance is based on a simple approach [18,19] to measure reflectivity of painted surfaces in light integration boxes.[1] The basic idea is to measure photon detection efficiency f while varying the fractional area F covered by a photosensitive detector in a closed chamber, such that

$$f = \frac{Ft}{Ft + a(1 - F)}, \quad (1)$$

where t is the probability of a photon to be absorbed by the PMT (ie. detection), and a is the probability of a photon to be absorbed by the PTFE (for details see Ref. [20]). Fractional area is defined as the ratio of the photosensitive area over the total surface area of the closed chamber. Eq. (1) shows that for fixed a and t, photon detection efficiency decreases as fractional area decreases (or as the surface area of the closed chamber increases). Although this simple model does not account for Rayleigh scattering and light absorption in LXe, and therefore does not allow to extract the absolute reflectance of the two PTFE materials, it illustrates that the method is very sensitive to changes in reflectance for highly reflective materials, as discussed in Appendix A.

In order to perform the reflectance measurements, a chamber was designed and built that (a) contains reflecting surfaces made of PTFE material, (b) contains a photomultiplier tube (PMT) that is sensitive in the VUV region, (c) contains a bright mono-energetic light source inside the detector, (d) provides a way to easily modify the fractional area of the chamber, and d) allows variation of the PTFE wall thickness without modifying the experimental condition inside the chamber. Good optical coupling between the PMT window and LXe is obtained, since the refractive index of LXe for intrinsic scintillation light (n=1.67 [21]) and that of quartz (n=1.57) are well matched.

A schematic illustration of the detector is shown in Fig. 1. It consists of a cylindrical PTFE chamber (62.2 mm I.D., 117 mm high) with a 3-inch Hamamatsu R11410-MOD PMT [22] on the bottom, a circular PTFE disk (60 mm diameter) that floats on LXe, and a ^{210}Po source (0.1 µCi) that is chemically plated onto a silver disk and attached to the floating PTFE disk facing down. Two different geometries were used to vary the exposed area of the PMT, as shown in Fig. 2. In geometry 1, the PMT area was defined by a 3.3 mm thick and 36.8-mm I.D. aluminum annulus placed on the PMT to protect it from light transmitted through the 2.0 mm thick aperture of the PTFE connector above it with the same I.D. For geometry 2, the aluminum annulus and the PTFE connector had the same I.D. as the cylindrical PTFE chamber. An exploded view of the detector in which the placement of the aluminum annulus, the PTFE connector, and the surrounding pieces for geometry 1 are emphasized, is presented in Fig. 3.

Before the chamber is filled, the floating PTFE disk rests on the PTFE connector (for geometry 1) or on the PMT window (for geometry 2). As the chamber is filled with LXe, the floating disk rises and exposes an increasing fraction of the cylindrical PTFE wall, until it makes contact with the top aluminum plate. The top aluminum plate constrains the floating disk even when the level of LXe exceeds the top of the chamber. A 3.2-mm diameter hole in the bottom of the floating disk provides a near point-like light source of about 1000 cps. Mono-energetic scintillation light is generated by the 5.304 MeV α particles emitted from ^{210}Po through ionization and excitation of xenon atoms and subsequent emission of 178 nm photons from atomic de-excitation and recombination. Thus, as the floating disk rises, the number of light reflections on the PTFE surface of the chamber

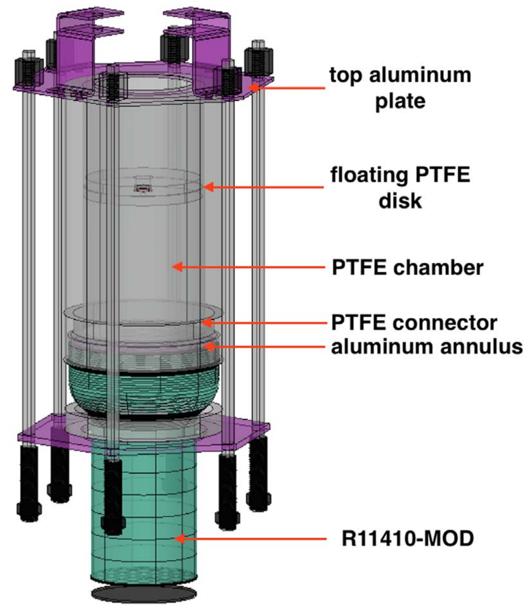

Fig. 1. Schematic view of the reflectivity setup. It consists of a 3-inch Hamamatsu R11410-MOD PMT which covers the bottom part of the 117-mm high and 62.2-mm ID PTFE cylindrical chamber, and a ^{210}Po source, imbedded in a PTFE floating disk, to provide a mono-energetic light source.

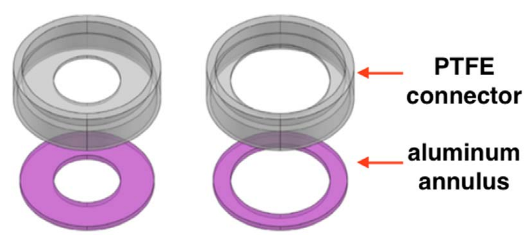

Fig. 2. Visualization of the two geometries that allow to vary the effective PMT area, showing the PTFE connectors and the aluminum annuli. Geometry 1 (left) has a 36.8 mm I.D. for both pieces, while geometry 2 (right) has a 62.2 mm I.D. for both pieces which is the same as the I.D. of the cylindrical PTFE chamber.

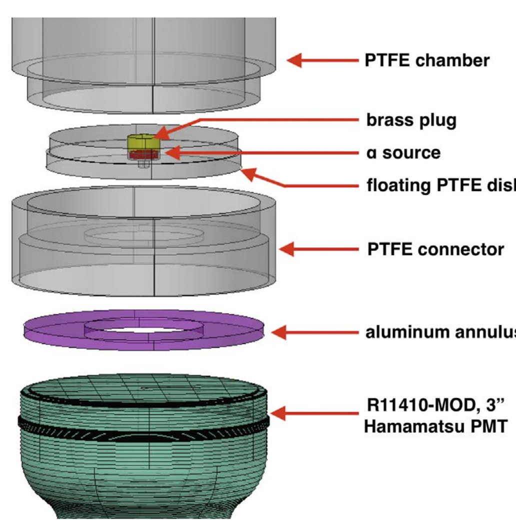

Fig. 3. Exploded view of the reflectivity setup for configuration 1. The ^{210}Po α source, depicted as the small red disk inside the floating disk, is held in place by a brass plug which is secured by a thin sheet of PTFE (not shown) from the backside of the floating disk.

[1] Note that Refs. [18,19] have small errors in their "light collection efficiency" formulae, which slightly alter the results in their publications, but do not significantly alter the general behavior.