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.

Keywords: Liquid xenon target; Noble liquid detectors; Scintillation detectors; Vacuum ultraviolet light; Polytetrafluoroethylene

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, 2, 3, 4] and lepton flavor

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5 violating [5] searches, neutrinoless double beta decay detectors [6], gamma-ray
6 physics experiments [7], medical imaging [8], and neutron detection for Home-
7 land Security [9].

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

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

32 In this work, experimental results of the reflectance of PTFE immersed in
33 LXe at wavelengths near 178 nm are reported as the thickness of the PTFE ma-
34 terial is varied between 1 mm to 9.5 mm. The basic features of the experimental
35 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].

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. Equation 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, Eq. 1 illustrates that the method is very sensitive to changes in reflectance for highly reflective materials. For details see 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

¹Note that Refs. [18] and [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.

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 ($0.1\ \mu\text{Ci}$) 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 1,000 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 increases and the corresponding path for the

Figure 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.

Figure 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.

Figure 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.

90 VUV photons gets longer, resulting in a smaller light yield,² as illustrated in
 91 Sec. 3.

92 The thickness of the PTFE cylinder wall was modified (from 9.5 mm down
 93 to 1 mm) by removing material from the outside of the cylinder. This ensured
 94 that the inner surface of the chamber remained unchanged throughout the mea-
 95 surements. The minimum cylinder wall thickness of 1 mm was chosen to avoid
 96 collapse of the PTFE cylinder, as there is considerable buoyant force on the
 97 PTFE cylinder due to the PMT being immersed in LXe. The thickness of the
 98 floating disk and the PTFE connector remained unchanged to avoid modifica-
 99 tion of the apparent intensity of the light source placed in the floating disk and

²Photon detection efficiency depends both on the properties of the liquid (ie. absorption length and Rayleigh scattering) and on PTFE reflectance.

100 to maintain structural integrity of the PTFE chamber, respectively.

101 The detector described here is integrated into the Michigan Xenon (MiX)
102 detector system which is documented in detail elsewhere [23]. The detector
103 shares all components with MiX, except for data acquisition, since only a single
104 PMT is read out. Instead of using a flash ADC, the PMT signal is read out
105 directly on a digital oscilloscope (Tektronix TDS 3034B).

106 3. Results

107 To prepare for data collection, the PTFE samples were cleaned for 30 min-
108 utes in an ultrasonic bath with a solution of alconox and de-ionized water at
109 50 C, followed by a 30 minute ultrasonic de-ionized water rinse at 50 C before
110 being placed in a dry nitrogen box overnight. Prior to measurements the PTFE
111 samples were kept in vacuum (10^{-3} mbar) for about 24 hours. This is a standard
112 procedure to clean PTFE samples for use in ultrapure LXe detectors.

113 At the start of a measurement cycle, the PTFE chamber was filled with LXe
114 until the floating disk reached the top aluminum plate. The xenon was sub-
115 sequently purified [23] with a high-temperature zirconium SAES PS3-MT3-R-1
116 getter for about 24 hours. Periodic light yield data were recorded at a LXe
117 temperature of (175 ± 0.2) K. Between measurements, the LXe level, measured
118 using a concentric cylindrical capacitor [23] was reduced in steps of about 3 pF,
119 which corresponded to a change in LXe level of about 8.1 mm. This process
120 was continued until the floating disk rested either on the aperture of the PTFE
121 connector at the bottom of the PTFE chamber (for geometry 1) or on the
122 PMT window (for geometry 2). Data was collected for two different types of
123 PTFE materials from Applied Plastics Technology (APT), 807NX and NXT85,
124 at a variety of thicknesses of the cylindrical chamber wall. For 807NX PTFE,
125 data was collected for two different exposed PMT areas to check for consistency
126 among two different chamber geometries, while for NXT85 PTFE, data was
127 only collected for the larger exposed PMT area. In order to avoid PMT satura-
128 tion, the detector was operated at different high voltages for the three different

Figure 4: Scintillation light yield versus chamber height for APT 807NX PTFE, scaled to 100% at the PMT surface. Data were collected at an exposed PMT diameter of 36.8 mm (geometry 1), a PMT high voltage of 1,150 V, and chamber wall thicknesses of 9.5 mm, 5 mm, 2 mm, and 1 mm. The error bars represent the sum of statistical and systematic uncertainties added in quadrature.

129 experimental configurations.

130 The data for 807NX PTFE at an exposed PMT diameter of 36.8 mm are
 131 shown in Fig. 4. All four data sets, scaled to roughly 100% at the PMT sur-
 132 face,³ display the same general shape. The four data sets agree well within
 133 uncertainties, and display variations that are consistent with fluctuations in
 134 reflectance that are estimated to be within 0.4% (see Appendix A).

135 Each data set shows that the scintillation light yield diminishes as the light
 136 source moves away from the PMT surface. This general behavior is expected
 137 since the scintillation light produced from the 5.304 MeV α particles will expe-
 138 rience more wall bounces at larger distance, resulting in more photons absorbed

³The four data sets were scaled with the same factor to roughly 100% at the PMT surface to facilitate reading the fractional decrease in light yield vs chamber height off the graph.

Figure 5: Scintillation light yield versus chamber height for APT 807NX PTFE, scaled to 100% at the PMT surface. Data were collected at an exposed PMT diameter of 62.2 mm (geometry 2), a PMT high voltage of 1,010 V, and chamber wall thicknesses of 5 mm, 2 mm, and 1 mm. The error bars represent the sum of statistical and systematic uncertainties added in quadrature.

on the chamber walls. Furthermore, the path length for the scintillation photons increases, resulting in an even smaller light yield due to photon absorption and Rayleigh scattering in LXe [21]. The combined effect leads to a variation in scintillation light yield of about a factor of 5.8 over the chamber height of 117 mm. Note that if reflectance was lower for smaller PTFE wall thickness, the light yield would diminish more rapidly with increasing chamber height, leading to even larger variations over the chamber height.

The data for 807NX PTFE at an exposed PMT diameter of 62.2 mm are shown in Fig. 5. The data sets at 5 mm and 1 mm agree very well within uncertainties, but the data set at 2 mm displays a slightly lower light yield at large chamber height. This variation in light yield is, however, still consistent within combined statistical and systematic uncertainties and is not necessarily an indication of lower reflectance for a 2 mm wall thickness. The three data sets

Figure 6: Scintillation light yield versus chamber height, scaled to 100% at the PMT surface. Data were collected with APT NXT85 PTFE at a PMT diameter of 62.2 mm (geometry 2), a PMT high voltage of 930 V, and chamber wall thicknesses of 9.5 mm, 5 mm, 2 mm, and 1 mm. The error bars represent the sum of statistical and systematic uncertainties added in quadrature.

display variations that are consistent with fluctuations in reflectance that are estimated to be within 0.6%. The variation in scintillation light yield over the chamber height is only about a factor of 3 for this configuration, which is in agreement with the expectation that the different chamber geometry results in fewer wall bounces and a shorter path length for scintillation photons to reach the PMT.

The two data sets for the two different chamber geometries for 807NX PTFE show distinctly different shapes, but show no decrease in the signal over the measured chamber wall thicknesses. Therefore, decreasing the wall thickness from 9.5 mm to 1 mm does not appear to change the reflectance.

The data for NXT85 PTFE at an exposed PMT diameter of 62.2 mm are shown in Fig. 6. Note that data were only collected for one exposed PMT area since no reflectance dependence on thickness was observed for the two

Figure 7: Comparison of scintillation light yield versus chamber height for NXT85 and 807NX PTFE at an exposed PMT diameter of 62.2 mm (geometry 2). The two data sets, which differ by 1.4% in absolute reflectance [14], were taken with a 5 mm chamber wall thickness, and normalized to unity at the PMT surface. The error bars represent the sum of statistical and systematic uncertainties added in quadrature.

geometries measured with the 807NX sample. All four data sets show the same general shape and agree well within uncertainties. The four data sets display variations that are consistent with fluctuations in reflectance that are estimated to be within 0.4%. The variation in scintillation light yield over the chamber height is only about a factor of 2.3 for this configuration.

Figure 7 shows a direct comparison of scintillation light yield as a function of chamber height for the two PTFE materials. Both data sets were collected with exposed PMT diameters of 62.2 mm and a cylinder wall thickness of 5 mm. The two data sets were normalized to unity at the PMT surface to extract the fractional decrease in light yield from minimum exposed PTFE area to maximum exposed PTFE area. The fractional decrease will be smaller when the reflectance is larger. As shown in Fig. 7, the NXT85 data set displays a higher light yield at large chamber height than the 807NX data set. This indicates that

178 NXT85 PTFE has reflectance that is slightly higher than that of 807NX PTFE,
 179 in agreement with the results obtained for the absolute reflectance measured
 180 from Ref. [14] who report values of 97.5% and 96.1% for NXT85 and 807NX
 181 PTFE, respectively.

182 *3.1. Temperature Dependence and Experimental Uncertainties*

183 In order to quantify the temperature dependence of the capacitive level me-
 184 ter and of the scintillation light signal recorded in the PMT, the temperature
 185 of the LXe was varied within ± 3 K of the nominal temperature of 175 K. The
 186 measurements were performed with the detector filled beyond the top aluminum
 187 plate to ensure that the source location remained fixed, and that the level meter
 188 was fully submerged in LXe. The results are shown on Figs. 8 and 9. Figure 8
 189 exhibits a drop in the level meter reading with increasing temperature. This
 190 behavior is expected, as an increase in temperature leads to a drop in the dielec-
 191 tric constant of LXe, and therefore to a drop in capacitance of the cylindrical
 192 level meter. The temperature dependence of the capacitance is $-0.1\%/K$, in
 193 good agreement with literature values [24]. Figure 9 displays an increase of
 194 scintillation light signal in LXe with decreasing temperature. This temperature
 195 dependence is also expected, but its value of $-1.3\%/K$ is approximately three
 196 times larger than typically reported values [25]. Since the PMT was maintained
 197 at the same temperature as LXe, the larger-than-expected variation in the sig-
 198 nal may in fact be due to the dependence of the PMT gain on temperature.
 199 Control of the LXe temperature at the ± 0.2 K level has been routinely achieved
 200 in the detector, corresponding to a lower than 0.3% variation of scintillation
 201 light yield, and lower than 0.03% variation of the LXe level.

202 Capacitive level meter calibration was achieved at the ± 0.2 pF (ie. ± 0.54 mm
 203 LXe) level, which translates into a variation in the scintillation light yield of
 204 about $\pm 2\%$. Each measurement cycle was repeated at least once, typically
 205 within 48 hours, by refilling the chamber with LXe and letting it settle for at
 206 least 24 hours before starting the next measurement cycle. Scintillation light
 207 yield was found to be stable within typically $\pm 1\%$ between two consecutive

Figure 8: Level meter reading at various temperatures with reflectance measurement setup at a PMT diameter of 62.2 mm. The level meter was fully submerged in LXe at all temperatures. The data were collected with the 807NX PTFE sample.

208 measurement cycles. The total systematic uncertainty was estimated to be
 209 about $\pm 2.3\%$ by adding the individual instrumental uncertainties in quadrature.

210 4. Conclusions

211 In summary, an experimental study has been performed to determine the
 212 change in reflectance of PTFE immersed in LXe at $\lambda = 178$ nm as the thickness
 213 of the PTFE material was reduced from 9.5 mm down to 1 mm. The data, col-
 214 lected with two different PTFE samples, displayed no reduction in reflectance
 215 down to 1 mm wall thickness. The ability of PTFE to maintain good reflectance
 216 and thus high light collection efficiency even at very thin thicknesses is instru-
 217 mental for next generation direct detection dark matter search and neutrinoless
 218 double beta decay experiments. These experiments require large size detectors,
 219 small dead space, low outgassing, minimal potential radioactive backgrounds,
 220 and good optical isolation between active and passive regions within these de-

Figure 9: Scintillation light yield at various temperatures with a PMT diameter of 62.2 mm, normalized to unity at 175 K. PMT held at 1010 V. Source location fixed. The data were collected with the 807NX PTFE sample.

221 tectors, requirements that can all be met by thin sheets of PTFE.

222 No attempt was made to extract the absolute reflectivity of the two PTFE
 223 samples, as this is beyond the scope of this paper. Nevertheless, the data indi-
 224 cate that the reflectance of NXT85 PTFE is slightly higher than the reflectance
 225 of 807NX PTFE for xenon scintillation light.

226 Appendix A. Sensitivity to Changes in Reflectance

227 Simulations of the experimental setup were performed that follow the ap-
 228 proach introduced in Refs. [18, 19, 20] to illustrate the sensitivity of the method
 229 to changes in reflectance. The results of the simulations, shown in Fig. A.10,
 230 display photon detection efficiency as a function of chamber height, rather than
 231 fractional area to facilitate comparison to the experimental data displayed in
 232 Figs. 4, 5, 6, and 7. The left panel of Fig. A.10 shows the variation of the pho-
 233 ton detection efficiency for geometry 1 over a large range of PTFE reflectances,

Figure A.10: Simulations of scintillation light yield versus chamber height for PTFE reflectances between 90% and 100% for geometry 1 (left) and geometry 2 (right). Note that the simulations do not account for Rayleigh scattering and light absorption in LXe, but they do account for the effect of light absorption on the aluminum annulus, as reflected by the small drop in photon detection efficiency below unity for a PTFE reflectance of 100%.

234 while the right panel shows the variation for geometry 2. Sensitivity to varia-
 235 tions of reflectance is high at high reflectances $\mathcal{O}(> 95\%)$, gradually diminishes
 236 as reflectance gets smaller, and gets poor as reflectance gets low $\mathcal{O}(< 50\%)$.
 237 Since absolute PTFE reflectance is of $\mathcal{O}(97\%)$ [14] when immersed in LXe, this
 238 method is very sensitive to small variations of reflectance and thus well-suited
 239 to detect possibly small variations in reflectance with PTFE thickness.

240 Note that the general features of light yield versus chamber height are well
 241 reproduced for the two different geometries. But the model is too simple to
 242 allow an extraction of the absolute reflectance, since it does neither account for
 243 Rayleigh scattering and light absorption in LXe, nor does it include detailed
 244 models for diffuse and specular reflection. Building a model that can determine
 245 the absolute reflectance of the measured PTFE samples is beyond the scope of
 246 this paper.

247 Nevertheless, combining the 1.4% difference in absolute reflectance of the
 248 two PTFE samples [14] shown in Fig. 7 with the general features of these sim-
 249 ulations,⁴ the variations of reflectance were estimated. The fluctuations of the

⁴The general features of these simulations are not expected to differ significantly from those

250 data shown in Figs. 4, 5, and 6 near chamber height of 12 cm are were deter-
 251 mined to be consistent with fluctuations in reflectance of 0.4% for configuration
 252 1 (Fig. 4), of 0.5% for configuration 2 (Fig. 5), and of 0.4% for configurations 3
 253 (Fig. 6), respectively.

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