Measuring Reflective Properties of PTFE for Applications in Liquid Xenon Detectors

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Abstract

The XENON100 experiment uses 161kg of liquid xenon divided in two concentric cylinders. The inner volume is the time-projection chamber, the outer volume is the veto, and they are separated by PTFE (Teflon) panels. In the region 350nm to 1200nm, PTFE has a measured reflectivity of 99%. However, xenon emits in the UV region, and the reflectivity distribution is not sufficiently understood here. The XENON group uses a vacuum spectrograph to attempt to determine a reflection distribution for the PTFE that encloses the XENON100 TPC. The spectrograph will be used to measure a reflectivity distribution for the type of PTFE used in the detector. Measurements will be repeated after the PTFE sample is cooled to deduce the effect of low temperature on the reflectivity distribution. In the future, this same tool can also be used to determine how low temperatures affect the quantum efficiency of the PMTs used in the XENON100 experiment.

1 Introduction

1.1 The XENON100 experiment

There is much evidence to suggest that 83% of the matter in the universe exists as "dark matter" (Aprile, 2010). Despite comprising so much of the universe, dark matter particles are extremely difficult to detect. Extensions of the standard model provide a candidate for dark matter in the form of, or Weakly-Interacting Massive Particles. One way to find WIMPs is to measure the energy they deposit in a detector after collision with target nuclei. True to their name, WIMPs interact very weakly, so the detectors must be very sensitive. For this reason, liquid noble gas detectors are good way to achieve that sensitivity. Liquid xenon provides a promising environment for WIMP detection. Xenon is very heavy, so its atoms contain many protons and neutrons, increasing the likelihood of a WIMP interaction. Liquid xenon is also very cold, at -95° Celsius.

The XENON100 experiment utilizes one such detector, which uses two concentric cylinders with 161kg of liquid xenon. The inner cylinder is the active time-projection chamber, and the outer cylinder is the veto region. The two cylinders are separated by a layer of PTFE (Teflon) panels. PTFE is employed in the detector because it has a high reflectivity, and this helps to prevent loss of emitted light from scattering events. To shield the detector from disruptive background, it is housed beneath a mountain at LNGS is Laboratori Nazionali del Gran Sasso in Italy.

Though PTFE is known to have a high reflectivity in the 350nm to 1200nm range (Weidner and Hsia, 1981), its reflective properties are not sufficiently understood in the vacuum ultraviolet (VUV) region, which is the region in which xenon emits light. A group at the University of Coimbra has measured reflectivity distributions for PTFE, but their samples were treated differently than those in the XENON100 detector (Silva et al., 2009). More importantly, their reflectivity measurements were taken at room temperature. The effect of low temperature on reflectivity is a crucial element to consider when testing the PTFE used in XENON100. Reflectivity data for the the XENON100 PTFE is essential for understanding the behavior of the detector and the signals it records, so the XENON group set up an experiment to perform this measurement.

1.2 Modeling the Reflectivity

We are concerned with two types of reflection: diffuse and specular. Specular reflection is familiar; it is defined as when the incident angle of the light equals the reflected angle. One example of this is reflection of light off of a mirror. Most surfaces however, reflect light in a combination of specular and diffuse reflection (Silva, 2009). Diffuse reflection is a property of uneven surfaces, where incident light rays are reflected in many different directions. One important type of diffuse reflection is Lambertian reflection, in which the apparent radiance of the surface stays constant even as the reflected light rays scatter in many different directions. The reflected light obeys the Lambert cosine law

$$I \propto A cos\theta \tag{1}$$

Most surfaces reflect both specularly and diffusely, in some combination to be modeled. To model the combined reflectance, it is common to use a bidirectional reflection intensity distribution function (BRIDF),

$$\chi = \frac{d\Phi_r}{d\Omega_r}\frac{1}{\Phi_i}[1/sr] \tag{2}$$

where $d\Phi_r$ is the flux reflected to solid angle element $d\Omega_r$, and Φ_i is the total incoming intensity. BRIDFs must also be able to handle switching the incident and reflected light vectors, and outgoing beam intensity must not exceed incoming beam intensity (Aprile et al., 2009).

2 Experimental Setup

2.1 Monochromator and Vacuum Chamber

The main component of the setup is the monochromator with light source. The monochromator receives light from the attached McPherson Model 632 deuterium light source, and the light is reflected along a system of mirrors inside the monochromator. The deuterium light source provides VUV spectral lines from 110nm to 170nm, and continuous emission from 170nm to 400nm. The light exits the monochromator through two slits, each adjustable from 10μm to 2mm. The monochromator region is kept at a pressure of about 0.1 mbar.

From there the beam enters the vacuum chamber, where the PTFE sample is kept. The vacuum chamber requires a much lower pressure than the monochromator. In air, VUV light has a mean free path of only about 0.5 cm before it is absorbed. Therefore, pressure in the chamber must be reduced to below 10^{-3} mbar. The light from the beam is incident on the PTFE sample and the reflected light is detected by the PMT (Hamamatsu R8520-06-AL). Readings from the PMT have been interpreted in several ways, including with a Keithley picoammeter, Fluke hand multimeter, and through individual photon counting.

2.2 Temperature

The measurements described in this paper have been performed at room temperature. However, the setup also includes a mechanism for controlling the temperature of the PTFE and PMT. Atop the vacuum chamber is a cold head, which attaches to a pulse tube refrigerator (PTR). The cold head is connected to the PTFE and PMT by two copper braid wires each. The PTFE is attached to a copper holding structure and insulated with a ceramic plate. The PTFE is placed in a copper case and insulated by teflon panels. This ensures that the samples can be selectively cooled instead of cooling the whole chamber.

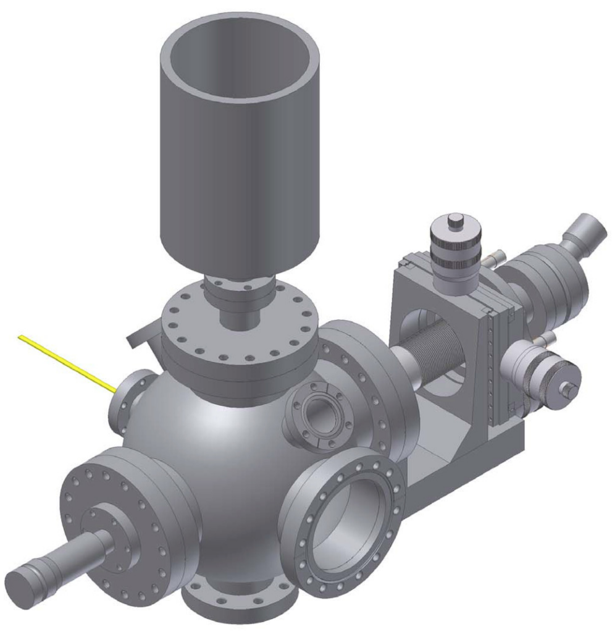

Fig. 1 An outer view of the vacuum chamber. (Aprile et al., 2009)

2.3 Geometry and Inner Setup of PTFE Sample and PMT

The orientation of the PTFE sample and PMT with respect to each other can be varied from outside the chamber with the use of rotational feed-throughs. The incident and reflected light beams are defined with respect to the line normal to the PTFE's surface. When the PTFE surface normal is perpendicular to the incident light beam, the PTFE is angled flat so that no light is incident on the surface. This corresponds to an angle of 230° on the PTFE rotational feed-through and an incident angle of 90°. When the PMT is rotated so that it directly faces the incident beam and the maximum amount of light is collected, the PMT feed-through reads 156°.

The correction in angle for the PMT depends on the angle of the PTFE. To get the geometrically correct value for each angle from the angle on the scale, only a simple correction was needed. The PTFE is merely offset. Call α the reading on the scale. Since 320° corresponds to a corrected angle of 0°, $\theta_i = 320 - \alpha$. If we call the angle on the PMT feed-through scale β, we arrive at the correct angle with the correction $\theta_r = 24 - \theta_i + \beta$. Again, the corrected value of β depends on the angle of the PTFE.

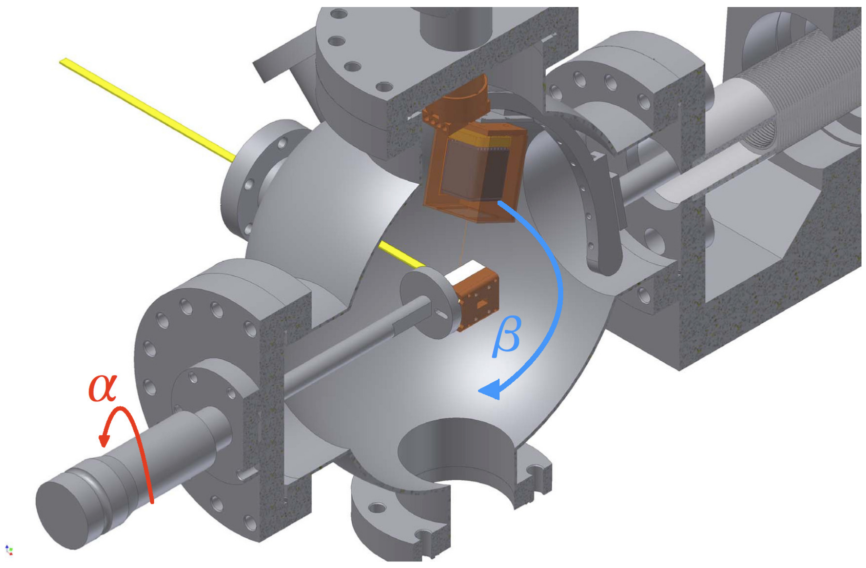

Fig. 2 A cutaway view of the vacuum chamber, with unscaled angles labelled. (Aprile et al., 2009)

2.4 Method

2.4.1 Photon Counting for Reflection Measurements

Various methods for measuring the PMT signal were tried. When current was measured with a Keithley Model 6487 Picoammeter, it was difficult to distinguish the diffuse lobe from the background. A more sensitive method was then employed, the method of single photon counting. The PMT signal is amplified with an Ortec 673 Spectroscopy Amplifier, passed through a Lecroy 623B Octal Discriminator, and then passed to a Model 1880B Dual Channel BCD Scaler, which provides the photon count. Waveforms were displayed on a Tektronix MSO 4104 Mixed-Signal Oscilloscope. Using this method, a rather large light leak at the heating diode feed-through was identified. Photon detection frequency decreased from 2kHz to below 10 Hz when the diode was covered with foil.

To take reflection measurements, an angle for the PTFE sample is selected. The incident angles we are generally interested in are 80°, 70°, 65°, 60°, 55°, 45°, and 30°. For each incident angle, the PMT is rotated through a range of angles from $\beta = 160°$ to $\beta = 0°$, in steps of 5°. Photon frequency is taken three times for each PMT angle, for 50 seconds each.

2.4.2 PMT Gain Determination

The gain of the PMT is another important quantity to understand. In this experiment, the relative value of the gain in high and low temperatures is important to understand, as the gain will almost certainly change with temperature. Gain is defined as the number of electrons produced by an electron emitted from the photocathode. Most PMTs come with an estimated value for the gain, but because of the statistical nature of gain, single photon events will give varying pulse heights. As such, it is important to measure the pulse height distribution to know where to set the pulse threshold for the single electron region.

After the events are plotted, they can be fit to a function that consists of an exponential and the sum of two Gaussians. The exponential drop corresponds to events recorded where no signal is present. The first Gaussian accounts for single photoelectron events, and the second Gaussian accounts for double photoelectron events. By taking the integral of the distribution, the gain can be obtained (Melgarejo, 2008).

3 Results

3.1 Reflection measurements

Reflection measurements with the new photon counting method are underway. Below is a sample reflection measurement, taken at an incident angle of 65°. The photon count is displayed in blue. The background level as measured by the photon counter with no PTFE sample inside the chamber was also included, displayed in red. The measurement is displayed in blue as photons per second. As of now, BRIDFs are not employed, though they will be useful later. The same characteristics of the reflection can be seen when plotting single photon count versus reflected angle.

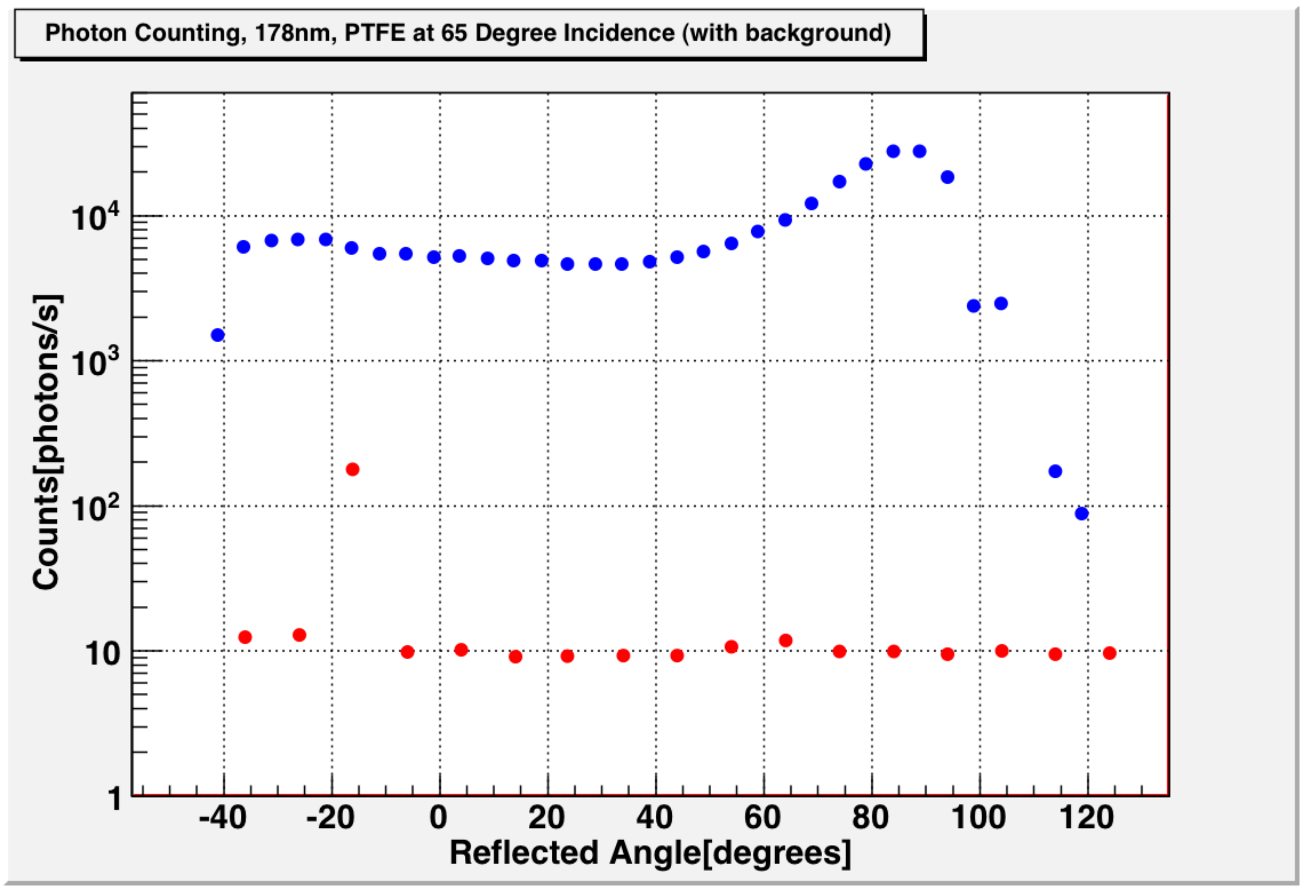

Fig. 3 Reflection measurement with photon counting method for 65° incidence, λ=178nm, with background

3.2 PMT Gain

The following plot shows the peaks of 1000 waveforms plotted by height. To obtain the gain, we focus on the portion of the plot fitted with the Gaussian function. Since the waveform is Gaussian, the integral is

$$\int_{-\infty}^{\infty} h \cdot e^{-(x-b)^2/2c^2} = hc \cdot \sqrt{2\pi} \tag{3}$$

The parameter c is related to the full width at half maximum (FWHM) of the pulse. Using an approximate height of 16 (where we see the peak), the gain is estimated at 0.9×10^6. This is approximately what would be expected for the type of PMT used. Other PMTs have gains in the orders of magnitude 10^7 or 10^8, but the PMTs used in the XENON experiment are metal channel PMTs; their special properties make them well-suited to function in low-temperature, high-pressure environments.

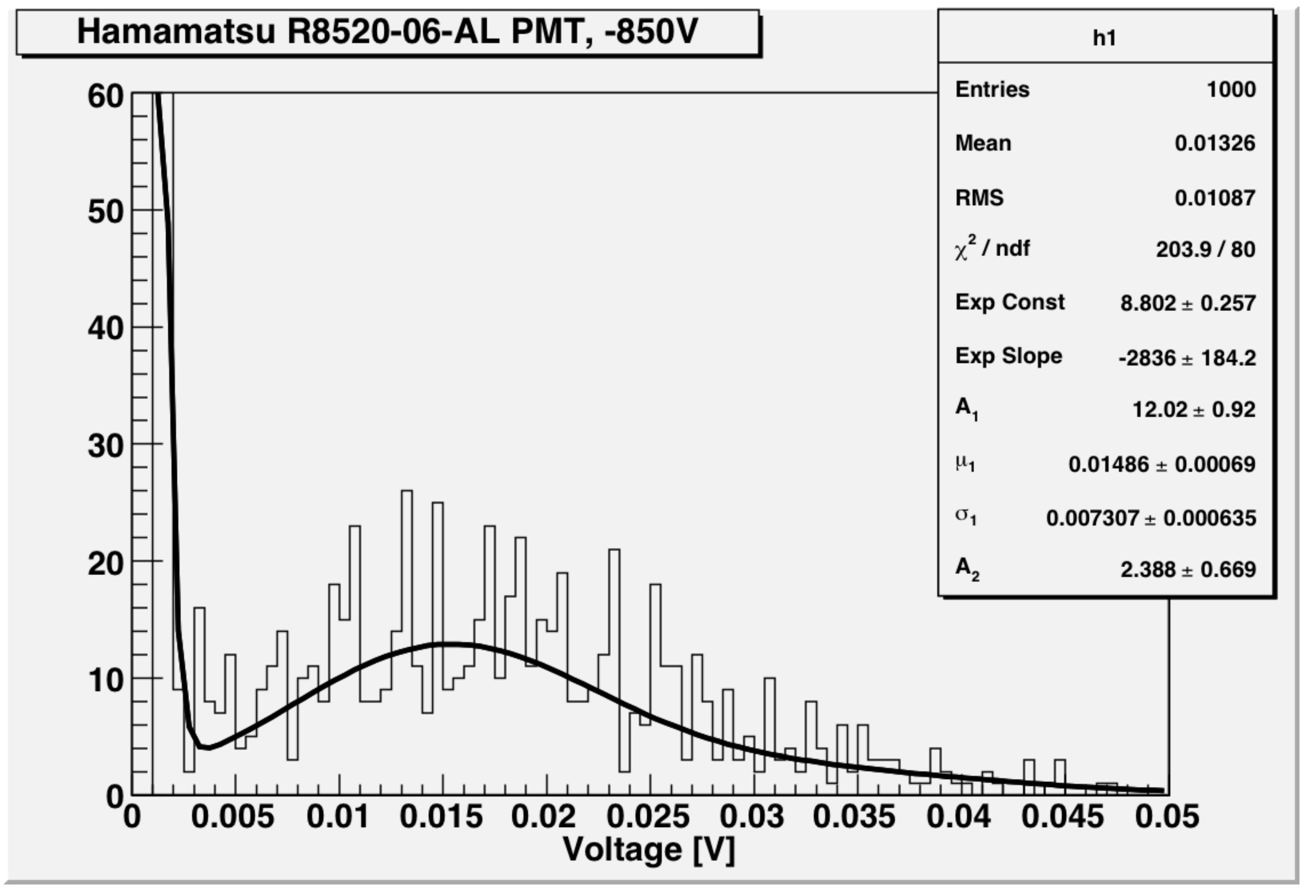

Fig. 4 SER spectrum for Hamamatsu R8520-06-AL PMT

Relative measurements of this gain are important when PMT is later cooled, as the gain will almost certainly change.

4 Discussion

The signal to noise ratio is much improved since switching to the photon counting method. With the Keithley, the measured background level was around 200 μA, and the signal-to-noise ratio was generally in the range of 3 or 4. As shown in Figure 3, the background level for the photon counting method is orders of magnitude lower than the signal, allowing for much better observation of the diffuse and spectral lobes.

However, we are still refining the measurements that are being taken with the photon counting method. Figure 3 is a plot of the measurements taken at 65°, so we would expect the specular peak at 65°, but instead we see it around 85°. One possible reason for this is that the teflon sample and the beam may not be lined up in the way we originally thought. The vacuum chamber has rotational feed-throughs that allow for adjustment of the x and z position of the teflon sample, so these can be varied in order to deduce the position of the beam. It may be that the PTFE is blocking more of the beam than was expected, which could result in the specular peak appearing at an unexpected angle. Measurements sweeping the range of x and z positions will be taken with and without the PTFE sample to more accurately understand the position of the beam with respect to the PMT.

In the diffuse region, we also see some abnormal behavior. There appears to be a peak in the region around -30°, which is not expected. One possibility is that reflected light is from the PTFE is also being reflected by the stainless steel inside of the vacuum chamber. To investigate this possibility, the inside of the chamber will be coated with black flocked paper.

Another measurement of interest is the quantum efficiency of the PMT. Quantum efficiency is the probability that a photon incident on the PMT window will produce an electron-hole pair, thereby triggering the electron cascade in the dynode system. We are interested in relative measurements for the QE, comparing hot and cold temperatures. As of now, a data acquisition method still needs to be established for these measurements.

5 Acknowledgments

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