Measurement of the Quantum Efficiency of Hamamatsu R8520 Photomultipliers at Liquid Xenon Temperature

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Abstract: Vacuum ultraviolet light sensitive photomultiplier tubes directly coupled to liquid xenon are being used to efficiently detect the 178 nm scintillation light in a variety of liquid xenon based particle detectors. Good knowledge of the performance of these photomultipliers under cryogenic conditions is needed to properly characterize these detectors. Here, we report on measurements of the quantum efficiency of Hamamatsu R8520 photomultipliers, used in the XENON Dark Matter Experiments. The quantum efficiency measurements at room temperature agree with the values provided by Hamamatsu. At low temperatures, between 160K and 170K, the quantum efficiency increases by ∼ 5–11% relative to the room temperature values.

Keywords: Monochromators, photomultipliers

1. INTRODUCTION

Liquid Xenon (LXe) detectors are currently a favored choice for rare event search experiments, from dark matter direct detection to neutrinoless double beta decay [1] [2] [3] [4]. In particular, the XENON100 dark matter experiment [5] [6] uses 242 Hamamatsu R8520-06-Al photomultiplier tubes (PMTs) [7] to detect the scintillation light produced by Weakly Interacting Massive Particles (WIMPs) as they scatter off Xe nuclei.

These compact metal-channel PMTs were specifically designed to work at 177 K, close to the temperature of LXe, and at a pressure up to 5 atm. They have a quartz window and a bialkali photocathode, for high sensitivity and low dark current in the UV regime [8]. Recently, a new version of the same PMT (R8520-406) with improved sensitivity at 178 nm, the scintillation wavelength of LXe, was produced by Hamamatsu and procured for an upgrade of the XENON100 experiment.

The quantum efficiency (QE) is one of the most important characteristics of a PMT. The QE is defined as the ratio between the number of photoelectrons emitted from the photocathode and the number of incident photons. The energy absorbed from the incident photons is transferred to the valence band of the photocathode. Since the photoemission process has a probabilistic nature, not all of the electrons that absorb energy from the incident photons are emitted as photoelectrons [8].

A quantity related to the QE is the radiant sensitivity (Sk), used to express the spectral characteristics and especially the relationship between the photocathode response and the incident light wavelength. The radiant sensitivity is defined as the photoelectric current generated by the photocathode, IK, divided by the incident radiant flux at a given wavelength, LP:

\[ \text{Sk} = \frac{I_K}{I_P} \]  

The relationship between the QE and the Sk is given by [8]

\[ \text{QE} = \frac{h \cdot c}{\lambda \cdot e} \cdot \text{Sk} \approx \frac{1240}{\lambda} \cdot \text{Sk} \cdot 100 \% \]  

where \( h \) is Planck’s constant, \( c \) is the speed of light in vacuum, \( \lambda \) is the wavelength of the incident light in nm, \( e \) is the electron charge, and Sk is the radiant sensitivity in A/W.

The radiant sensitivity is often provided by the manufacturer for each PMT. More generally, the blue sensitivity index (sometimes called cathode blue sensitivity), Skb, which is the photoelectric current generated from the photocathode with a blue filter interposed in the same setup, is specified. However, this value is usually measured only at room temperature. Hence, a quantitative study of the QE as a function of temperature is necessary for an improved understanding of LXe experiments.

2. EXPERIMENTAL SETUP

A schematic of the setup is shown in Figure 1. It consists of a deuterium lamp and two independent vacuum chambers. The first chamber contains a monochromator used to select a narrow wavelength range from the spectrum of the deuterium lamp. The second chamber hosts the PMT being tested.

A deuterium lamp (McPherson, Model 632) emits light between 115 nm and 400 nm and is particularly useful for measurements in the vacuum ultraviolet (VUV) and deep
UV. The output spectrum between 380 nm and 165 nm is continuous [9]. Below 165 nm, molecular lines predominate. The light emitted from the lamp is transmitted by a MgF$_2$ window and passes through an entrance slit into a vacuum monochromator (McPherson, Model 218) where a narrow wavelength range from the lamp is selected. The monochromator is composed of a snap-in diffraction grating that is optimized for wavelengths between 150 nm and 300 nm, and two Al+MgF$_2$ coated mirrors that have a reflectivity of $\sim$75% at 178 nm [9]. The diffraction grating can be remotely adjusted with a stepper motor control unit. After the monochromator, the light with the selected wavelength propagates through an exit slit to the next vacuum chamber. The size of both the entrance and the exit slits can be adjusted from 10 $\mu$m to 2 mm in order to modify the flux of the beam and the reciprocal linear dispersion. For this work, the size of both slits was set to 2 mm. The MgF$_2$ window that separates the monochromator and the vacuum chamber has an optical transmissivity of $\sim$80% [10] for light with a wavelength of 178 nm. Independent vacuum pumping stations are used to prevent impurities from the monochromator side, such as oil from the stepper motor, from reducing the optical transparency of the PMT window. A Pfeiffer HiCube 80 Eco pumping station on the monochromator and a Pfeiffer TMU071P turbomolecular pump with a dry backing pump on the second vacuum chamber keep the pressure at about 1.5 x 10$^{-5}$ mbar and below 10$^{-6}$ mbar, respectively.

The vacuum chamber is equipped with a motion feedthrough that allows for linear motion in three dimensions as well as rotation. The photodetector — either a PMT or a photodiode for calibration purposes — is mounted on this rotator, which can in addition be translated in both the horizontal and vertical directions. A customized collimator is installed on the port of the vacuum chamber where the light goes through. This reduces the size of the beam to $\sim$ <1 cm and allows for more controlled and parallel beam shining on the photodetector.

To cool down the PMT from room temperature to a value close to that of LXe ($\sim$165 K), an Iwatani PDC08 Pulse Tube Refrigerator (PTR) is coupled to the vacuum chamber. Two copper braids are connected to the PTR and attached to each side of a copper box, which is in direct contact with the case of the PMT. One of two Pt100 thermometers is mounted on an aluminum piece that supports the PMT as can be seen in top of Figure 2. Another Pt100 is attached to the PMT wall, allowing a direct measurement of the PMT temperature (not shown in the Figure). The case of the PMT is connected to a positive voltage while the PMT base is at the negative voltage. For electrical insulation of the PMT due to the polarity used in the PMT base, the PMT was wrapped around with PTFE tape that also helped hold the Pt100 in place. The signal of the Pt100 is fed into a customized LabView program and used for a PID control system that regulates the temperature, via resistive heating of 6.2 V Zener diodes. The pressure inside the chamber is kept below 10$^{-6}$ mbar for the duration of all measurements.

An Ortec HV supply provides the high voltage on the PMT. A modified voltage divider allows a fixed voltage difference to be set between the photocathode and the first dynode in the recommended linearity range between 50 and 300 V [8]. The current from the photodetectors is measured by a Keithley 6485 picoammeter with a precision of 0.01 pA. Individual measurements of the current, each set to take 1 second, are stored by a dedicated routine provided by Keithley. For each temperature setting, 100 measurements are taken consecutively within 2 minutes and are used to determine the mean of the photocurrent and its fluctuations.

The four PMTs used in the measurements are Hamamatsu R8520-406 with bialkali photocathodes and dimensions of 25.7 $\times$ 25.7 $\times$ 28.2 mm$^3$, with an effective photocathode area of 20.5 $\times$ 20.5 mm$^2$. The QE and the Skb, at room temperature was provided by the manufacturer for each of these PMTs. The average QE value is $\sim$31% at 178 nm Xe scintillation light [7]. Table I shows some specifications of this PMT.

A calibrated silicon photodiode of type AXUV-100G from NIST is used as a reference detector to measure the light flux at the position where the PMT is located. The photodiode has an active area of 10 $\times$ 10 mm$^2$. The detector is sensitive to UV light from 5 nm to 254 nm, and its QE has been determined by NIST between 116 nm and 254 nm [11]. This allows us to directly measure the QE of the PMT.

3. CALIBRATION AND DATA TAKING PROCEDURE

The monochromator has been calibrated by scanning the wavelength region of a Hg/Cd lamp and comparing...
the output spectrum with the one provided in the literature [12]. The relationship between the actual wavelength and the value seen from the monochromator can be described by a simple linear function and was taken into account for selecting the wavelength of interest:

$$\lambda(\lambda_{MP}) = (11.8 \pm 2.2) \AA + (0.9996 \pm 0.0005) \AA \cdot \lambda_{MP}$$  (3)

where $\lambda_{MP}$ is the wavelength indicated on the scale of the monochromator and $\lambda(\lambda_{MP})$ is the actual wavelength as a function of $\lambda_{MP}$.

A calibration with the Na-D lines was done with a slit size of 20 $\mu$m each. The resolution of the monochromator is dependent on the size of the entrance and exit slits as well as the wavelength. This configuration of the monochromator is expected to yield a resolution of 1 $\AA$.

To measure the QE at room temperature, the number of photoelectrons measured by the PMT was compared to the number of photoelectrons measured by the calibrated photodiode. The ratio between the current read from the PMT and the photodiode is directly proportional to the ratio of the QE of the PMT to the one of the photodiode, written as:

$$QE_{PMT} = QE_{\text{photodiode}} \times \frac{I_{PMT}}{I_{\text{photodiode}}}$$  (4)

where $I_{PMT}$ and $I_{\text{photodiode}}$ are the currents measured by the picoammeter for the PMT and the photodiode.

The current from the PMT’s photocathode is measured when a voltage is applied between photocathode and the first dynode. The dependence of the signal size on the voltage is shown in Figure 3. To correctly estimate the signal of the PMT, the dark current, due to electron emission from the photocathode not related to light absorption [8], has to be subtracted. This is measured at each configuration of the measurement by turning off the lamp and measuring the current from the PMT. The filled circles in Figure 3 corresponding to the corrected signal show that the photocurrent is flat for voltages above 20V. A value of 50V, well within the range of the plateau, was chosen for the final measurements.

To make sure that the beam size at the position of the PMT is smaller than the area of the photodiode, so that no geometrical corrections for the flux are needed, the beam profile was scanned in two orthogonal axes parallel to the surface of the photodiode. The entering slit from the monochromator is equipped with a customized aperture to define the opening of the light beam. Figure 4 shows scans along one of the axes. When the photodiode is translated 10 mm away from its center, which is

TABLE I: Specifications of R8520-406 PMTs provided by Hamamatsu.

| Parameter                  | Description                  |
|----------------------------|------------------------------|
| Spectral Response          | 160 to 650 nm                |
| Window Material            | Synthetic silica             |
| Photocathode Material      | Bialkali                     |
| Radioactivity              | 15 mBq/PMT Max               |
| Operating Ambient Temperature | -110 to +50 deg.C             |
| Maximum Supply Voltage     | 900 V                        |
| Pressure-resistance        | 5 atm                        |
| Gain                       | $1.0 \times 10^6$            |
| Dynode-stage               | 10                           |

which allows the two Na transition lines, from $\lambda(P_{3/2})$ at 5890 $\AA$ and $\lambda(P_{1/2})$ at 5896 $\AA$, to be separated. From the output of the monochromator, two peaks at $\lambda_{MP} = 5788 \AA$ and $\lambda_{MP} = 5794 \AA$ can be resolved.

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FIG. 3: Photocathode currents measured as function of the applied voltage: photocathode current deuterium lamp on (triangles), dark current (squares, deuterium lamp off). The circles show the photocurrent induced by the UV photons as the difference of the photocathode current with deuterium lamp on and off.

the width of the photodiode, there is no current reading. Thus, the light flux shining on the photodiode and the PMT is the same, and a geometrical correction is not required to compare these measurements.

The stability of the emission of the deuterium lamp was monitored for ~12 hours, and the variations of the signal throughout the measurement were found to be smaller than 1%. Thus, it is unnecessary to correct the signals from the photodiode and the PMT, which are taken within a few minutes, for such variations.

To reduce the material outgassing, the entire system was baked for several days while the PMT and the PMT base were kept outside. Because of some soldered components within the chamber, the temperature was kept below 473 K. Since the chamber had to be opened several times to change the PMTs, it was either baked again after the opening at a temperature of ~473 K overnight or was flushed with ultra-high purity N₂ during the opening of the chamber.

To measure the response of the PMTs at low temperature, it is important to keep a good vacuum in the chamber in order to prevent both the absorption of UV as well as the condensation of molecules on the cold PMT quartz window. The main contribution to UV absorption are water molecules with a cross section of \( \sigma_{H_2O} = 2 \times 10^{-18} \text{cm}^2 \) for wavelengths near 178 nm [13]. The contribution from other contaminants, such as oxygen, is 3 orders of magnitude smaller (\( \sigma_{O_2} = 4 \times 10^{-21} \text{cm}^2 \)) [14] at the same wavelength and therefore negligible.

During the cool-down of the chamber, the body of the PMT is the coldest surface inside the vacuum chamber and water from the residual gas may condense on its surface and cause light absorption. At our lowest temperature of \( T_{min} = 160 \text{ K} \), the saturation pressure of water decreases down to \( \approx 10^{-6} \text{ mbar} \) [15]. Since we kept the total pressure inside the vacuum chamber always below \( 10^{-6} \text{ mbar} \) and the partial pressure of water in the chamber was even lower, no condensation of water could have happened at the quartz window of the PMT. Of course, these arguments only hold for condensing of a bulk film, which would be governed by the adsorbate-adsorbate (water-water) interactions. The arguments do not contradict a possible monolayer of water on the quartz window of the PMT, which would be governed by adsorbate-substrate (water-quartz) interactions. But even a monolayer of water would not have influenced the QE measurement significantly. Using the typical surface density of a monolayer of \( nd = 10^{15} \text{ cm}^{-2} \), the absorption probability amounts to \( P_{abs} = nd \cdot \sigma_{H_2O} = 2 \cdot 10^{-3} \) only and would have changed out QE determination by 0.2%. This possible systematic effect is a factor 10 smaller than the other uncertainties.

For a better understanding of the impurities in the system, an Extorr XT300 Residual Gas Analyzer (RGA) was installed to monitor the water peak as the system was cooled down, and a cryopump was added to effectively trap gas that could affect the measurements at low temperature. The residual gas content was monitored by computer with a continuous scan of the whole mass range. The amount of water decreased below ~270K, which can be explained by water freezing around that temperature. Although the dark current drops below 270K, the signal, i.e., the difference between photocurrent and dark current, does not change within the measured fluctuations. If water were sticking to the PMT window, a decrease in the response to the light would have been observed. This demonstrates that the impact
of water on our results is negligible.

4. RESULTS AND DISCUSSIONS

4.1. QE measurements at room temperature

As a first step, the QE at room temperature is measured for the four PMTs and the results are compared with the values provided by Hamamatsu. Using as a reference the NIST photodiode, as explained in the previous section, the photocurrent from each PMT is measured and transformed into a QE according to Eq. 4. Table II shows the values provided by Hamamatsu and the values measured with the present setup. For both the photomultipliers and the reference photodiode, the standard deviation of the fluctuations in each dataset was taken as the uncertainty on the measurements.

| PMT S/N | Hamamatsu QE [%] | Measured QE [%] |
|---------|-------------------|-----------------|
| LV1002  | 30.5              | 31.1 ± 2.7      |
| LV1009  | 30.0              | 31.3 ± 5.0      |
| LV1013  | 30.9              | 31.6 ± 1.5      |
| LV1014  | 30.3              | 31.3 ± 3.6      |

4.2. QE measurements at low temperature

To measure the QE of the PMT as a function of temperature, the PMT casing is cooled down with the PTR. The temperature is kept at its set point by heating with the Zener diode. Since the geometry inside the chamber remains unchanged, the amount of light incident on the PMT window stays the same and the QE at low temperature can be inferred from the room temperature measurement according to:

$$QE(T) = \frac{I(T_0)}{I(T)} \cdot QE(T_0)$$  \hspace{1cm} (5)

Thus, no further comparison to the photodiode is necessary. Current measurements were performed from room temperature down to 160 K, the lowest operation temperature of the PMTs, as indicated by the manufacturer. Figure 5 shows the ratio between the QE at low and room temperature for the four PMTs studied, as a function of temperature. Note that the room temperatures for each PMT are slightly different, as shown by the rightmost points in each curve, thus shifting the reference point for each.

For all the PMTs, the sensitivity increases up to ∼10% at the lowest temperature that was measured. No hysteresis effect was observed while warming back up to room temperature in any of these measurements. The uncertainties reflect the standard deviation values of 100 current measurements at each temperature. The larger error bars for PMT LV1013 are due to electronic noise from running the turbo pump during that measurement.

5. CONCLUSION

We have designed a system to measure the QE of R8520-406 PMTs, which have special bialkali photocathodes capable of providing a good performance at temperatures down to 160 K. Four PMTs were measured with this setup. Their absolute QEs at room temperature were measured by comparing their response to that of a calibrated photodiode, and the values obtained match those quoted by the manufacturer within the uncertainties.

The QE of the PMTs was also measured for temperatures down to 160 K, the temperature of LXe at which these PMTs are usually operated. A relative increase at low temperatures of up to ∼10% is measured for all four PMTs. This constitutes an important measurement for detectors based on LXe scintillation since it will help to more accurately determine the number of photons observed from the number of photoelectrons detected. The setup can be adopted to enable testing of other types of PMTs being considered for next generation experiments based on liquid noble elements.
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