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Response of photomultiplier tubes to xenon scintillation light

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ABSTRACT

We present the precision calibration of 35 Hamamatsu R11410-22 photomultiplier tubes (PMTs) with xenon scintillation light centred near 175 nm. This particular PMT variant was developed specifically for the LUX-ZEPLIN (LZ) dark matter experiment. A room-temperature xenon scintillation cell coupled to a vacuum cryostat was used to study the full-face PMT response at both room and low temperature (∼ −100 °C), in particular to determine the quantum efficiency (QE) and double photoelectron emission (DPE) probability in LZ operating conditions. For our sample with an average QE of (32.4 ± 2.9)% at room temperature, we find a *relative* improvement of (17.9 ± 5.2)% upon cooling (where uncertainty values refer to the sample standard deviation). The mean DPE probability in response to single vacuum ultraviolet (VUV) photons is (22.6 ± 2.0)% at low temperature; the DPE increase relative to room temperature, measured here for the first time, was (12.2 ± 3.9)%. Evidence of a small triple photoelectron emission probability (∼ 0.6%) has also been observed. Useful correlations are established between these parameters and the QE as measured by the manufacturer. The single VUV photon response is also measured for one ETEL D730/9829QB, a PMT with a more standard bialkali photocathode used in the ZEPLIN-III experiment, for which we obtained a cold DPE fraction of (9.1 ± 0.1)%. Hence, we confirm that this effect is not restricted to the low-temperature bialkali photocathode technology employed by Hamamatsu. This highlights the importance of considering this phenomenon in the interpretation of data from liquid xenon scintillation and electroluminescence detectors, and from many other optical measurements in this wavelength region.

1. Introduction

Despite recent advances in vacuum ultraviolet (VUV) silicon sensor technology, photomultiplier tubes (PMTs) with quartz windows remain the sensor of choice to detect the VUV scintillation light generated in xenon radiation detectors. Specific models developed for high radiological purity are employed in two-phase (liquid/gas) xenon time projection chambers (LXe-TPCs), which are a leading technology for direct dark matter searches [1]. In these detectors, a significant number of PMTs sense both the prompt scintillation and the electroluminescence signals emitted from the liquid and gaseous phases, respectively. The 3-inch Hamamatsu R11410 PMT is a popular model, offering high quantum efficiency (QE) to xenon VUV light, good low-temperature performance due to a low-resistivity bialkali photocathode (with added bismuth) [2], besides extremely low radiological background. Several studies related to its performance in xenon detectors can be found in the literature [3–9]. These are also the sensors adopted for the LUX-ZEPLIN (LZ) dark matter experiment [10], which motivated the study presented here—specifically, the '−22' variant was developed for LZ.

We describe in this article the precision calibration of 35 Hamamatsu R11410-22 PMTs with xenon scintillation light, both in ambient conditions and at low temperature (approximately −100 °C). We also measured a single unit of another PMT model: the ETEL D730/9829QB, used in the first science run of ZEPLIN-III [11,12]; significant characterisation data exist for this model also [13,14], and it is interesting to include in this study a different photocathode technology (standard bialkali) from another leading manufacturer. A full acceptance testing programme is being carried out in parallel by LZ collaborators to characterise all (494) R11410 LZ PMTs at room and low temperature using visible light (cf. Section 3.4.1 in Ref. [10]).

There are several technical motivations for this work. Firstly, Hamamatsu measure the VUV response of these phototubes only at room temperature, while the photocathode response for short wavelengths is known to improve upon cooling, and the same is

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true of the multiplication gain (see, e.g. Ref. [5,13] for this PMT model).

Secondly, the manufacturer's VUV QE calibration is conducted with a small, 5-mm diameter spot size on the photocathode, with illumination provided by a deuterium lamp filtered through a monochromator to a central wavelength of 175 nm (and other relevant values), with a FWHM of only 4 nm [15]; a systematic error of 10% is indicated for this calibration. The scintillation emission spectrum from liquid xenon is centred at 174.8 nm with a significantly larger FWHM of 10.2 nm [16]; the electroluminescence spectrum from gaseous xenon peaks at a somewhat shorter wavelength of 171 nm with a FWHM of 12 nm [17] (it is noted that this is a room temperature measurement). Therefore, a calibration is required that is more representative of the scintillation emitted by liquid and gaseous xenon incident over the whole photocathode.

Finally, and perhaps most importantly, it has been recognised recently that more than one 'photoelectron' can be emitted in response to a single VUV photon in some PMT models, including the R11410 [18]. Although this phenomenon has been known for decades [19,20], the impact of this double photoelectron emission (DPE) in LXe-TPCs had not been fully appreciated until recently.[1] Hamamatsu report a DC measurement, whereby the QE is determined by dividing the steady photocathode current by the incident VUV photon flux. This QE^{DC} does not represent the probability that a VUV photon will produce a detectable response (QE^{P}). The latter is the quantity required in experiments which must estimate without bias the stochastic distribution of scintillation photons emitted in particle interaction events. Understanding and quantifying this phenomenon led to a significant improvement in response linearity and in energy resolution in the LUX experiment [21].

The response of these detectors to very low energy electronic and nuclear recoils cannot be correctly interpreted without this understanding. The single photon response for each PMT must be determined accurately, including the DPE emission fraction ($\sim$20%, as measured in Ref. [18]) and its temperature dependence, which has not been studied previously.

By testing to percent level a sufficient sample of the LZ phototubes, we aim to establish a good correlation between these response parameters and those specified by the manufacturer. Naturally this information will permit cross-calibration of all (494) units in the LZ TPC and it will be useful to other liquid xenon experiments and beyond. To this end we employed a xenon gas scintillation cell maintained at room temperature illuminating a vacuum cryostat containing seven PMTs, which are cooled to $-97.4\,^{\circ}$C, the nominal LZ operating temperature. We measured precisely the absolute QE for xenon scintillation as well as the response to single scintillation photons of the same wavelength, which may involve the generation of one or two photoelectrons and other phenomena.

This paper is organised as follows: we introduce our PMT response model in Section 2; we describe the experimental methodology in Section 3; we then present the results for the single photon response and the response to the main scintillation pulse in Section 4; and we discuss our results in Section 5. Conclusions are presented in Section 6.

2. PMT response model

When a photoelectron (phe) is produced by a photon incident on the PMT photocathode, it may diffuse to the surface of the sensitive layer and be emitted into the vacuum inside the PMT if it has sufficient energy to overcome the work function of the photosensitive layer. The probability that these three steps are successful is termed the quantum efficiency (QE) of the photocathode [22]. The emitted electron accelerates in the electric field created by the potential $V_{\text{k-dy1}}$ applied between the photocathode and the first dynode. The collection efficiency (η) represents the probability that the photoelectron reaches the first dynode and successfully multiplies through the dynode chain to produce a measurable electronic signal at the PMT anode. This efficiency η depends on the electric field distribution and strength, the geometry and the materials of the electron multiplier, and in particular the design of the first stages of electron multiplication. Occasionally, for sufficiently short photon wavelengths, the primary photoelectron can lead to the emission of a second electron via impact ionisation in the photocathode, which may result in DPE. In either case, each 'photoelectron' can contribute to the signal. The ratio between the charge collected at the anode and the input charge is the gain of the PMT, and it depends on the dynode voltage distribution and electrostatic design.

Various models have been proposed to describe the gain fluctuations experienced by a single photoelectron (SPE) emitted by the photocathode—characterised by the distribution of charge, q, measured at the PMT anode for a mean gain g and standard deviation σ, $P(q; g, \sigma)$. This charge is often obtained by integrating a digitised waveform and given in pVs. For the Hamamatsu R11410 this distribution is generally found to be well described by a Gaussian function for a sufficiently high gain. In the case of the ETEL D730/9829QB, the SPE distribution is better described by a Polya function [14]. In DPE events the gain fluctuations are well modelled assuming that the multiplication of the two electrons is uncorrelated. Quite generally, the single photon response distribution can be described by

$$\mathcal{P}(q) = (1 - f^{\text{DPE}})\, P(q; g, \sigma) + f^{\text{DPE}}\, P(q; 2g, \sqrt{2}\sigma) + c\, P(q; 3g, \sqrt{3}\sigma) \tag{1}$$

for $q > 0$, where f^{DPE} is the DPE *fraction*[2] and c accounts for the small fraction of events consistent with triple photoelectron emission (TPE). Neglecting the very small 3 -phe contribution, the mean pulse area obtained in response to single VUV photons is

$$\mu = \langle \mathcal{P}(q; c = 0) \rangle = \int_0^{\infty} q \cdot \mathcal{P}(q; c = 0)\, dq\,, \tag{2}$$

which, in the case of a sizeable DPE fraction, will clearly differ from the mean SPE pulse area, μ_1:

$$\mu_1 = \langle \mathcal{P}(q; f = 0, c = 0) \rangle. \tag{3}$$

To measure the absolute photocathode QE a source of known photon flux and wavelength is necessary. The DC measurement provided by Hamamatsu ($QE_{\text{H}}^{\text{DC}}$) is subject to several systematic effects when applied to PMT operation in photon-counting mode, including that due to the presence of DPE emission, which generates twice the anode charge for a fraction of photons. This is unlikely to be important for applications where PMTs are used in DC mode, but it is a major effect in photon counting experiments, where the number of detected photons is estimated by explicitly counting the number of pulses in the waveforms. Thus, $QE_{\text{H}}^{\text{DC}}$ can only be used in combination with μ_1 when calculating the number of photons incident on the photocathode. If the DPE fraction for the spectrum of incident light is known, $QE_{\text{H}}^{\text{DC}}$ can be used to derive the true

[1] Note that only the primary electron directly released by the photon can be termed the 'photoelectron', with the second one being produced by subsequent impact ionisation within the photocathode layer; we use the term 'double photoelectron' loosely, mostly to distinguish these electrons from others generated in the multiplication process.

[2] The DPE fraction is thus defined in this study as the number of DPE events divided by the sum of SPE and DPE events. We exclude higher multiple emission from the ratio as it is expected to be very small; our definition of DPE is more readily applicable and has already been used in other experiments [18,21,23].