Investigating the temperature dependence of photomultiplier quantum efficiency when operating in the visible spectrum

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Abstract

The quantum efficiency of a Burle 8850 photomultiplier tube with a potassium-caesium-antimony (bialkali) photocathode was determined by attenuating a 1 mW HeNe laser emitting at 633 nm and measuring the signal frequency when the laser was incident on the photomultiplier. A temperature range of 5 °C − 20 °C was investigated and it was found that the quantum efficiency decreases with temperature, with the signal frequency decreasing at a faster rate than the dark current frequency. Therefore, it was concluded that it would not be beneficial to cool photomultiplier tubes operating in the visible spectrum for use in collinear laser spectroscopy due to a decreasing signal-to-noise ratio. The signal pulse height distribution was also analysed and found to be independent of temperature within the range investigated.

1 Introduction

Photomultiplier tubes (PMTs) operating in both the infrared and visible spectrum are currently used in COLinear Laser SPectroscopy (COLLAPS) at the ISOLDE facility to measure atomic transitions of radioactive isotopes. PMTs are suitable for this purpose as they are sensitive enough to detect low light levels down to the single photon level but the technique is limited by the dark current; noise due to electrons being thermally emitted from the photocathode and dynodes when no photons are incident on the PMT. It has been long known that cooling PMTs reduces the dark current and this is especially important when using infrared PMTs as these are far more susceptible to dark current [1]. For this reason, the infrared PMTs used at COLLAPS are cooled but the visible PMTs are not. The aim of this project was to investigate the temperature dependence of PMTs operating in the visible spectrum and determine whether it would be beneficial to implement cooling for these as well.

2 Theory

When light is incident on the photocathode of a PMT, a photoelectron may be emitted via the photoelectric effect, as shown in Figure 1. The probability of emission is deter-

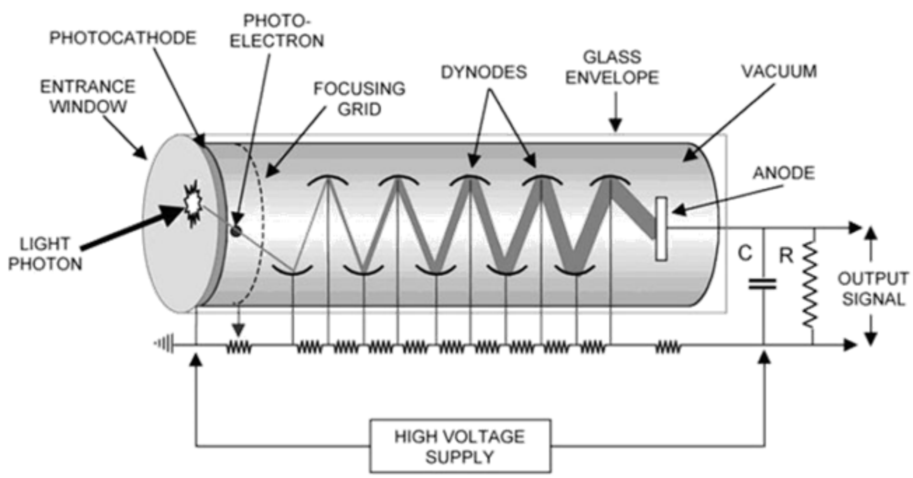

Figure 1: The inner workings of a PMT. A photon incident on the photocathode may cause the emission of a photoelectron into the vacuum tube where it is accelerated by an increasing potential difference. When the electron is incident on the first dynode, it initiates the emission of many secondary electrons which are then accelerated to the next dynode and so on. At the end of the dynode chain, a current pulse is detected at the anode and sent to further electronics for processing and analysis. [Image source: https://www.sense-pro.org/lll-sensors/pmt]

mined by a Poisson distribution. When operating in the single photon counting regime, the quantum efficiency (QE) of a PMT is defined as the ratio of photoelectrons produced at the photocathode for every incident photon [2]. An ideal PMT would have a quantum efficiency of 100 %, i.e. one photoelectron produced for every incident photon. However, in practise, the highest achievable QE is ≈ 30 % and is heavily dependent on the wavelength of radiation being investigated. Little is known how the quantum efficiency of visible PMTs depends on temperature but it is expected to be approximately constant, as found for infrared PMTs. Characteristics of the PMT such as the resolution, signal-to-noise ratio and responsivity are all heavily dependent on the quantum efficiency.

3 Experimental method

The final setup for the experiment is shown in Figure 2. Initially, the laser was not incident on the PMT to investigate the behaviour of the dark current with temperature. A temperature range of -10 °C – 25 °C was investigated but the main experiment focused on the range 5 °C – 20 °C as cooling the PMT near to or below 0 °C causes condensation and ice to form on the PMT, limiting signal intake. After examining the behaviour of the dark

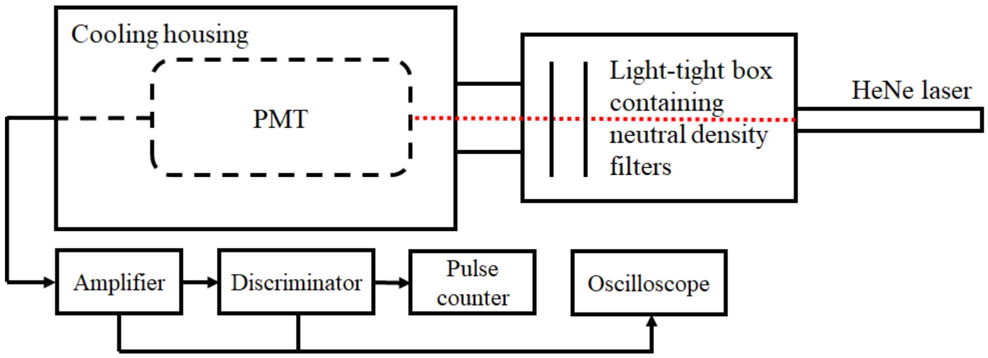

Figure 2: A schematic diagram of experimental setup. The pulse counter was used during measurements of the frequency and the oscilloscope was used to produce histrograms for a pulse height analysis. A potential difference of 2.1 kV was applied across the PMT for all measurements.

current with temperature, the discriminator level was varied to find the level at which the dark current originating from dynode emission could be removed from the analysis. This is possible as the electrons emitted from dynodes, especially dynodes later in the chain, are not subjected to as high of a potential difference and are thus accelerated less than the electrons originating from the photocathode. Therefore, electrons thermally emitted from the dynodes produce a signal with a smaller pulse height which can be removed by discarding all signals below a threshold discriminator level.

Before beginning measurements of the quantum efficiency, the time dependence of the PMT signal was investigated with respect to changing potential difference across the PMT and changing temperature. As the electrical components of the PMT are within a vacuum tube, it takes a significant amount of time for the entire device to settle at the ambient temperature. Therefore, this time delay had to be taken into account when cooling the PMT and before taking measurements.

The high sensitivity of PMTs causes them to become damaged if exposed to significant light levels. A 1 mW HeNe laser operating at 633 nm was used to measure the quantum efficiency, corresponding to $\sim 10^{15}$ photons/s. In order to not damage the PMT, this had to be reduced to $\sim 10^{5}$ photons/s and this was achieved using neutral density filters with transmittance per mm of 0.05 % at the 633 nm [3]. The required optical density, OD, can be calculated via

$$\mathrm{OD} = \log_{10}(I_i/I_f), \quad (1)$$

where I_i is the light intensity incident on the filter and I_f is the intensity after passing through the filter. From the PMT manufacturer data sheet, it was predicted that the quantum efficiency at 633 nm would be significantly less than 1 % [4] and this was also taken into consideration. An oscilloscope was used to carry out a pulse height analysis of the signals. The signal from the discriminator was used to trigger the oscilloscope but it was the signal directly from the amplifier that was measured. The pulse heights were measured in volts and frequencies were collected in bins of width 10 mV.

4 Results and discussion

From investigating the time dependence of the dark current and noise frequency, it was found that the PMT should be left to settle for an hour after each voltage and/or temperature change. Due to time constraints, this limited the number of different temperatures that could be investigated. From Figure 3, it can be seen that the dark current is decreasing

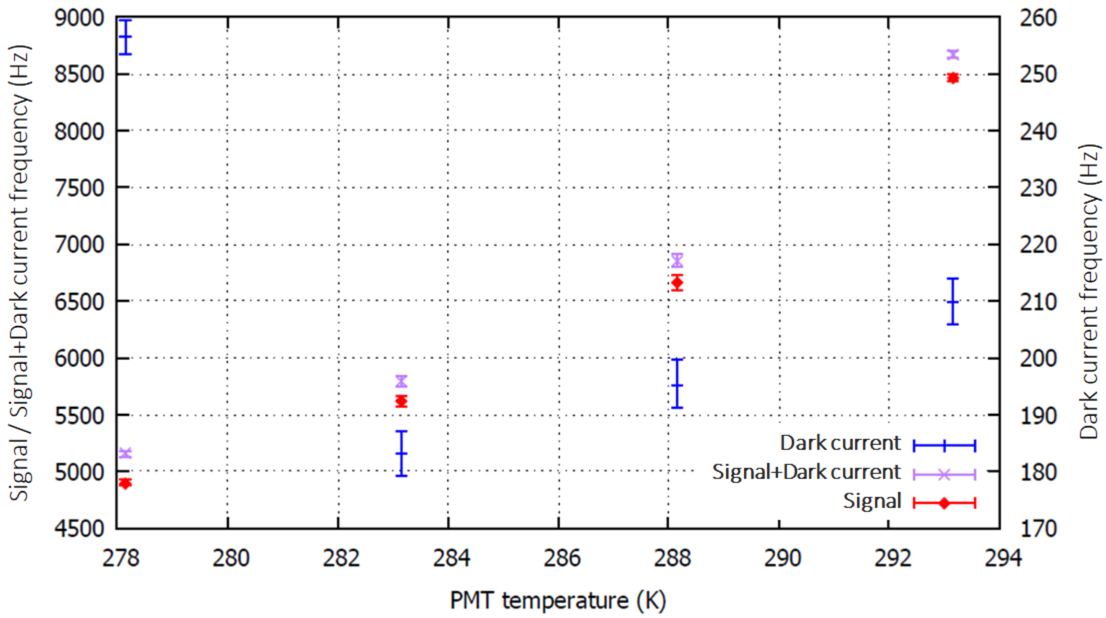

Figure 3: A summary of the signal temperature dependence of the PMT where the signal data was obtained by subtracting the dark current measurements from the measurements when the laser was incident on the PMT.

with temperature, as expected. However, it suddenly increases at 278 K which is thought to be due to a light leak in the black box. As the signal and dark current measurements at each temperature were taken at similar times, this systematic error is removed when subtracting from the signal plus dark current data. The frequencies shown in Figure 3 correspond to a quantum efficiency ranging between 0.045 and 0.08 % which roughly agrees with the manufacturer's data sheet [4]. From these results, it appears that the signal frequency is also decreasing with temperature and at a much faster rate than the dark current. When operating at such low light levels such as those used in collinear laser spectroscopy, an optimal signal-to-noise ratio is crucial. This suggests that it would not be beneficial to cool PMTs operating in the visible spectrum as the signal-to-noise ratio would decrease with temperature also. Figure 3 also suggests that the signal-to-noise ratio would actually improve by heating the PMT although this seems counter-intuitive. In order to determine whether this behaviour is universal, other PMTs should be investigated at a larger temperature range. In order to fully understand the behaviour of the quantum efficiency, other wavelengths should also be investigated so that all achievable quantum efficiencies can be measured.

Figure 4 shows the measured pulse height distribution at varying PMT temperature. It can be seen that the distribution shape is almost identical in every plot and therefore, it can be said the the pulse height distribution is independent of temperature, at least within the temperature range investigated. The only notable difference between the plots is that

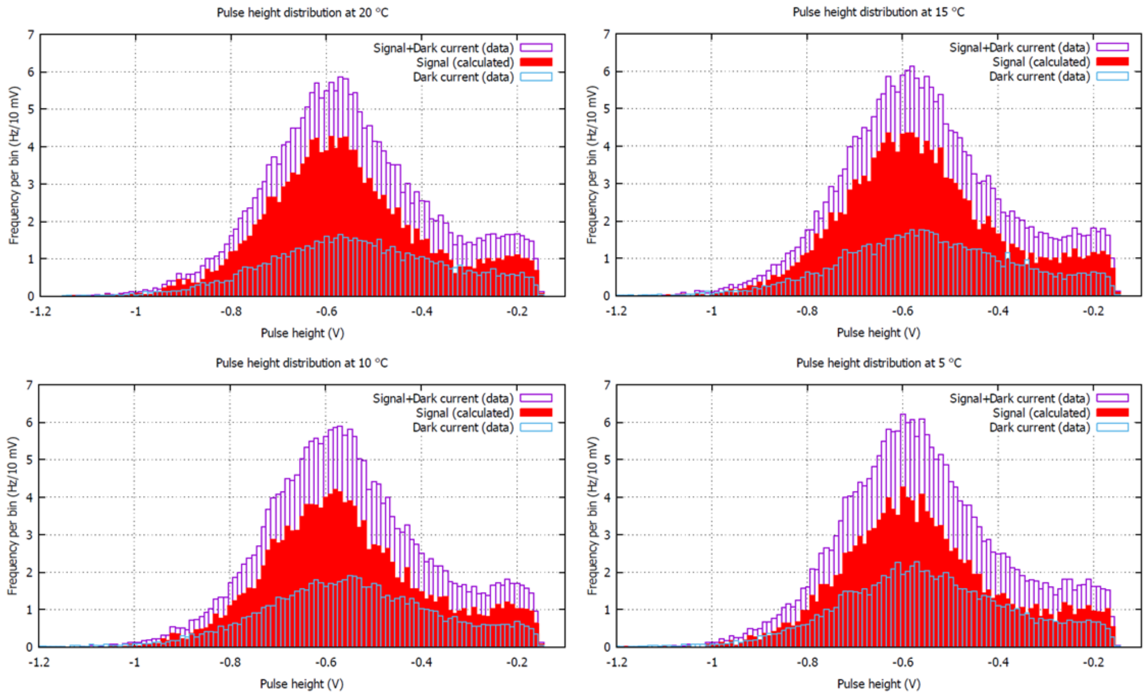

Figure 4: Histograms comparing the pulse height distribution of the HeNe signal at different PMT temperatures. The signal distribution was obtained by subtracting measurements of the dark current from measurements of the signal and dark current when the laser was incident on the PMT.

the total signal frequency, found by summing over all bins, is decreasing as the temperature decreases which is consistent with the results presented in Figure 3.

5 Conclusion

When investigating the temperature dependence of dark current and 633 nm signal frequency of a Burle 8850 photomultiplier tube, it was found that decreasing the temperature decreased the quantum efficiency and also decreased the signal-to-noise ratio. Therefore, the results presented in this report suggest that it would not be beneficial to cool PMTs operating in the visible spectrum for use in collinear laser spectroscopy, where low light levels already produce a low signal-to-noise ratio. This contradicts previous findings of infrared PMT quantum efficiencies which were found to be independent of temperature. In order to verify the findings of this report, the experiment should be repeated with other PMTs operating in the visible spectrum and with different wavelengths. This would allow measurements across the entire range of achievable quantum efficiencies. The temperature range investigated should also be extended to see if there is a critical temperature at which the behaviour changes.

References

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