

# Demonstration of photomultiplier tube operation at 29 K

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We describe measurements of gain, dark current, and quantum efficiency obtained while cooling a Hamamatsu R5912-02-MOD photomultiplier tube from room temperature to 29 K. We found that the PMT operated normally down to 29 K, with a reduced gain and quantum efficiency at the lowest temperatures. Furthermore, we found that the dark count rate increased as the temperature decreased. We conclude that these PMTs appear to be adequate for the requirements of the CLEAN experiment.

## INTRODUCTION

The CLEAN detector is designed to collect scintillation light from solar neutrinos and dark matter particles interacting in liquid neon [1]. The engineering design of CLEAN is greatly simplified by operating the photomultiplier tubes (PMTs) directly in liquid neon at 27 K. While there are experiments that use PMTs in liquid xenon (165 K) [2, 3], liquid argon (87 K) [4], and liquid nitrogen (77 K) [5], there are no published measurements of the characteristics of PMTs below 77 K.

In this paper we present measurements of the gain, dark count rate, and quantum efficiency of a Hamamatsu R5912-02-MOD PMT as a function of temperature between 300 K and 29 K. This PMT has fourteen dynodes, four more than the standard R5912, and it has a platinum underlay on the photocathode to improve performance at low temperatures. When standard PMTs are operated at low temperatures, the electrical conductivity of the photocathode decreases as the photocathode is cooled, resulting in space charge buildup and a reduced quantum efficiency. The platinum underlay corrects this situation by allowing charge to flow to any point on the photocathode regardless of the photocathode conductivity. The disadvantage is a small loss of light transmission due to the extra layer of material on the PMT face. According to manufacturer specifications, the room temperature quantum efficiency of the Hamamatsu R5912 decreases from 22% to about 16% at 390 nm after the addition of the platinum layer [7].

## EXPERIMENTAL DETAILS

Figure 1 is a schematic of the test cell used to cool and illuminate the PMT. The vessel was a stainless steel can with feedthroughs for the PMT signal, PMT high voltage, thermometers, gas service, and an optical fibre. The incoming gas was cooled by a pulse tube refrigerator [8], and the temperature of the PMT was monitored by direct readout of two silicon diodes [9] attached to its exterior with thermal grease. We used dry nitrogen exchange gas at 1100 mbar for temperatures between room

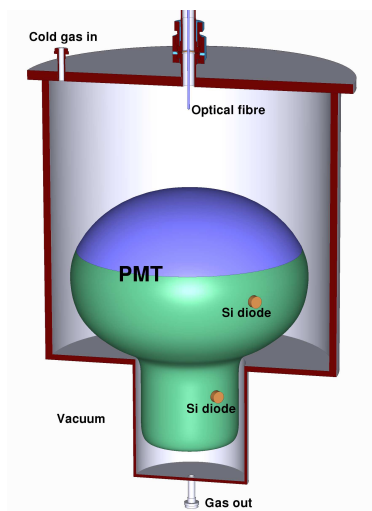


FIG. 1: Schematic representation of the PMT test cell.

temperature and 100 K, and neon gas at 1500 mbar for temperatures below 100 K. We used nitrogen at high temperatures because neon can potentially diffuse through the PMT glass causing after-pulsing in the tube, as has been observed in helium [6]. By introducing the neon gas only below 100 K, the diffusion rate was sufficiently suppressed to eliminate this risk.

The cooling and heating rates were kept below 2.5 K/hour between 100 K and 300 K, and below 4.5 K/hour between 29 K and 100 K. The vessel was kept at 29 K for approximately 9 days before warming.

We introduced from the top of the cell a single optical fibre, ground to a point to illuminate as much of the photocathode surface as possible. One end pointed towards the PMT while the other end of the fibre was illuminated by an LED pulser at room temperature. This pulser consisted of four blue LEDs [10] with a peak wavelength of 430 nm glued into an acrylic block mounted to a photodiode. The fibre connectors were mounted to the side of the block so that only a small fraction of the light illuminating the photodiode entered the fibre and reached the PMT. The photodiode monitored the gross light output from the LEDs to ensure consistent illumination of the PMT.

We used a voltage divider design recommended by Hamamatsu for the R5912-02-MOD PMT with separate cables for high voltage and signal. The capacitors and resistors for the divider were individually tested in liquid nitrogen to check for temperature-dependent variation before assembly. The PMT anode voltage was set to +1500 V.

The LEDs were powered by a digital pulse generator [11] and their light output was monitored with the photodiode. The LEDs were pulsed with either 5.8 V or 6.2 V at a rate of 20 Hz and a pulse width of 32  $\mu$ s. The coupling between the LED pulser and the fibre was weak enough that the signal from the PMT consisted of discrete single photoelectron events spread over the duration of the LED pulse.

## EXPERIMENTAL RESULTS

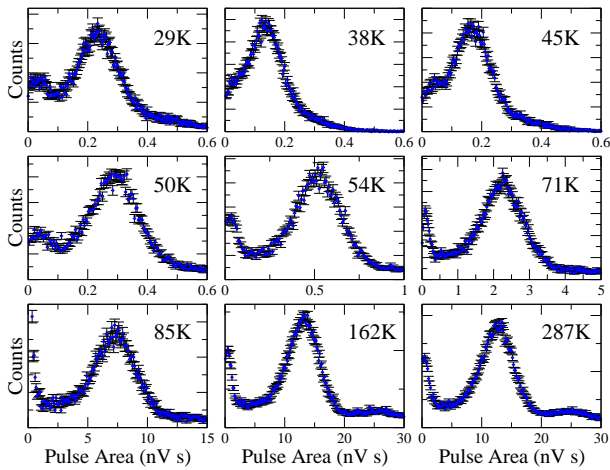


FIG. 2: Plots of the single photoelectron spectra at various temperatures.

By measuring the value of the single photoelectron peaks, we were able to obtain the PMT gain as a function of temperature. The PMT voltage trace was divided into 150 ns regions where the trace crossed an experimentally determined threshold of about 1/5 of a photoelectron. These regions were integrated to obtain the pulse area. Fig. 2 shows a series of histograms of the pulse area at various temperatures. By making Gaussian fits to the peaks, we obtained curves for the absolute gain as a function of temperature, shown in Fig. 3.

There is currently no quantitative model that explains all of the structure seen in Fig. 3. Possible explanations include thermal contraction of the PMT components or a variation in emissivity of the dynodes. Measured changes in the voltage divider component values were much too small to account for the observed variation of the gain.

To determine the dark count rate, we counted the number of single photoelectrons in a fixed interval while the

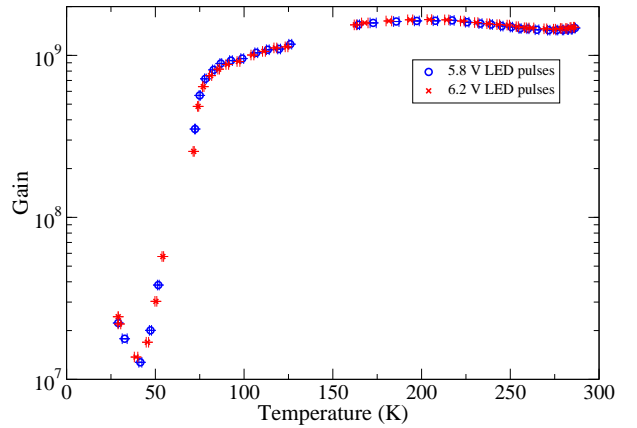


FIG. 3: Plot of the single photoelectron peak position vs. temperature.

PMT was not externally illuminated. The single photoelectron spectra were integrated and rounded off into integer multiples of the single photoelectron peak area for counting, then divided by the LED pulse length to obtain the rate. At room temperature, we measured a dark count rate of approximately 300 counts per second (cps).

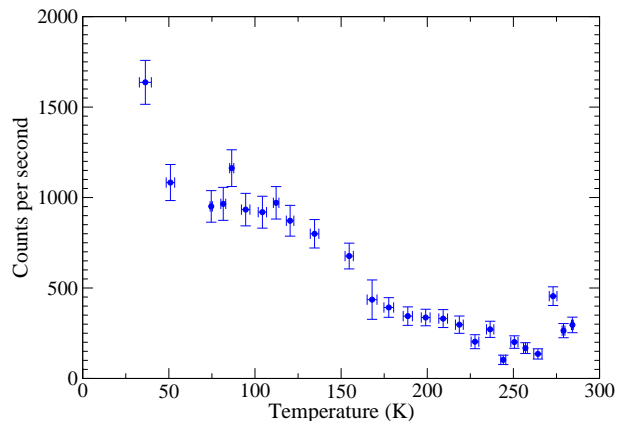


FIG. 4: Plot of the dark count rate as a function of temperature.

Fig. 5 is a plot of the dark count rate as a function of temperature. The uncertainties are dominated by photoelectron counting statistics. We think that the contribution from scintillation in the gases was low as the nitrogen and neon were swapped at 100 K with less than a 14% change in the dark count rate.

The PMT quantum efficiency was estimated by counting the number of photoelectrons observed during the 32  $\mu$ s LED pulse duration. At room temperature, the count rates were  $6.5 \times 10^4$  cps and  $2.8 \times 10^5$  cps when the LEDs were powered at 5.8 V and 6.2 V respectively. The repetition rate was kept at 20 Hz so the room temperature time average for the pulsed signal was 42 cps

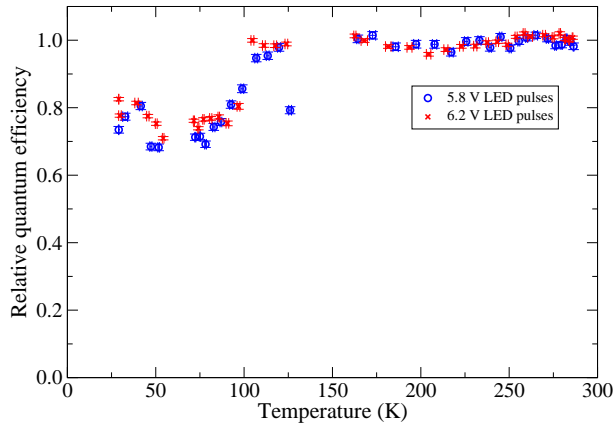


FIG. 5: Plot of the quantum efficiency as a function of temperature relative to the room temperature value.

and 170 cps above the dark rate for 5.8 V and 6.2 V respectively.

To check for depletion in the second half of the pulse, we compared the first and last 16  $\mu\text{s}$  of each pulse. The ratio of signal in the first half of each pulse to the total signal in the pulse was measured to be  $0.504 \pm 0.009$  and  $0.48 \pm 0.01$  at room temperature and 29 K respectively, suggesting the absence of charge depletion over the duration of individual pulses at both temperature extremes.

As we did not know the absolute photon flux onto the PMT, we measured the quantum efficiency relative to the room temperature value, shown in Fig. 5. We do not have a definitive explanation for the change in the measured quantum efficiency at 100 K.

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