SPE analysis of high efficiency PMTs for the DEAP-3600 dark matter detector

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Abstract. The **D**ark matter **E**xperiment using **A**rgon **P**ulse-shape discrimination is a collaborative effort to develop a next-generation, tonne-scale dark matter detector at SNOLAB. The detector will feature a single-phase liquid argon (LAr) target surrounded by an array of 266 photomultiplier tubes (PMTs). A new high-efficiency Hamamatsu R877-100 PMT has been delivered to the University of Alberta for evaluation by the DEAP collaboration. The increase in efficiency could lead to a much greater light yield, but other experiments have reported a slower rise time [1],[2]. We have placed the PMT in a small dark box and had a base and preamplifier designed to be used with either an oscilloscope or a multi-channel analyzer. With this setup we have demonstrated the PMT's ability to distinguish single photo-electrons (SPE) and characterized the PMT by measuring the SPE pulse height spectrum, the peak-to-valley ratio, the dark pulse rate, the baseline, time resolution and SPE efficiency for varying the high voltage supplied to the PMT.

1. Introduction

The DEAP programme consists of two detectors: DEAP-1 and DEAP-3600. The former is a prototype, operating underground at SNOLAB since 2007, while the later has a one tonne fiducial mass and is under construction. The DEAP-3600 detector will consist of an acrylic sphere (2m diameter) containing 3600kg (1000kg fiducial) of liquid argon (LAr) as a target, and will be surrounded by 266 8" PMTs separated from the sphere by acrylic light guides to attenuate neutron radiation from the PMT glass. The experiment has ultra-low backgrounds and uses a single phase target. We are observing spin-independent weak interactions between the Ar nuclei and hypothetical WIMPs, generic dark matter candidate particles that solve the dark matter problem. When energy is deposited in the LAr, excited or ionized Ar nuclei form dimer pairs, which release photons during recombination. The number of photons observed is proportional to the amount of energy deposited, which can tell us about the mass and speed of the incident particle. The Ar dimers combine into either singlet or triplet states with differing recombination times. Lighter particles, βs and γs, create more triplet states and, hence, slower light signatures than heavier particles such as αs, neutrons and WIMPs [3]. This time difference allows us to distinguish among possible sources of a recorded event using pulse-shape discrimination (PSD) [4–6]. PSD uses the F_{prompt} ratio as an observable: the ratio of prompt light from an event to the total light, defined as:

$$F_{\mathrm{prompt}} = \frac{\mathrm{PromptPE}\,(150\,\mathrm{ns})}{\mathrm{TotalPE}\,(9\,\mu\mathrm{s})}$$

where PromptPE is the number of photoelectrons (pe) in the first 150 µs and TotalPE is the number of pe in the entire pulse (9 µs). Figure 1 shows an electronic recoil event with high F_{prompt} and a nuclear recoil with low F_{prompt}, with the prompt region highlighted. The objective of DEAP-1 is to demonstrate that the PSD method is accurate enough to reject electromagnetic backgrounds to a level at which we are capable of performing a WIMP search, as determined by theoretical calculations of the rate of WIMP interactions. Further discrimination can be done by studying the amount of energy deposited (such as for αs). PSD at a level of 10^{-9}, the fraction of electronic recoils mistakenly misidentified as a nuclear recoil, is required to reject the radioactivity from ^{39}Ar in natural argon.

DEAP-1 is an operational prototype with a cylindrical LAr target (7kg) and two PMTs. It has been used extensively to study the background sources we will face when operating DEAP-3600. In DEAP-1 all of the light from an event is collected by only the two PMTs. In DEAP-3600 the same amount of light from a similar event will instead be divided among the entire array of PMTs, resulting in low light pulses from each PMT. The success of DEAP-3600 depends on the accuracy of our PSD, which, in turn, depends on the calculations made from event pulses. Thus, among our development goals are to maximize the amount of light we collect from an event and to accurately quantify the light by being able to distinguish and count the number of SPE. To achieve the latter, the PMTs response to SPE must be well understood.
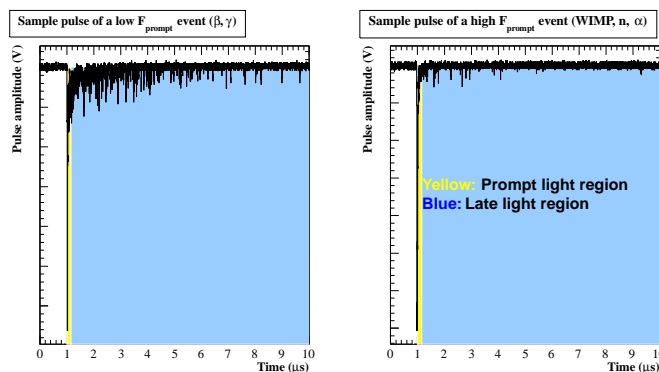

Figure 1. We calculate the F_{prompt} ratio: the ratio of prompt light from an event to the total light. The amount of light in each region is a calculation of the number of photoelectrons in the pulse.

1.1. PMTs in use

DEAP-1 was originally deployed with a pair of Electron Tubes 9390B with a 5" flat-faced geometry and with 28% quantum efficiency (QE). Hamamatsu recently unveiled a new line of PMTs using a new photocathode material which dramatically increased the QE of their detectors, dubbed either super or ultra bialkali. The DEAP collaboration tested the high efficiency PMTs to see whether they could improve detector light yield without unwanted side effects, such as increased noise, after-pulsing, or a poor return to baseline after a pulse. This study focuses on the Hamamatsu R877-100 super-bialkali (SBA) PMT, which has matching geometry to the original Electron Tubes PMT and could be installed on DEAP-1 with minimal difficulty. Hamamatsu reports that this PMT is capable of 35% QE [7]. At 5", this is the largest

SBA PMT offered by Hamamatsu. The DEAP-3600 detector will feature 8" hemispherical PMTs, and after a survey of PMTs this size from various manufacturers, DEAP has chosen the Hamamatsu R5912. For testing, Hamamatsu has delivered a set of high QE versions of this PMT; these are PMTs that surpassed Hamamatsu's specifications when tested after manufacture. The R5912-HQE PMTs that we are testing have ≈ 32% QE compared to a normally specified QE of 25% [8]. Since we wish to fully understand the response of these PMTs, they have been installed on DEAP-1 at SNOLAB and are currently taking data.

2. Results

The new high-efficiency Hamamatsu R877-100 SBA PMT was compared to previously deployed Electron Tubes PMTs. The Hamamatsu super-bialkali R877-100 PMT behaves well for a wide range of operating voltages. The PMT obeys an exponential relationship between operating high voltage and both dark pulse rate and gain. The range of dark pulse rates observed is between 2.04 ± 0.02 and 13.2 ± 0.3 kHz and is greater than for the R1408 SNO PMTs, which had a range less that 5 kHz [9]. The SNO PMTs have a lower QE and are indicative of how QE affects PMT characteristics. At the nominal operating voltage and below the R877-100 PMT stays within a noise threshold below 10 kHz. The Electron Tubes 9390B PMT is much quieter, with a range of 1.29 ± 0.01 to 6.70 ± 0.05 kHz. The increased efficiency of the Hamamatsu PMT should offset the larger noise by providing an increase in light collection capability [10].
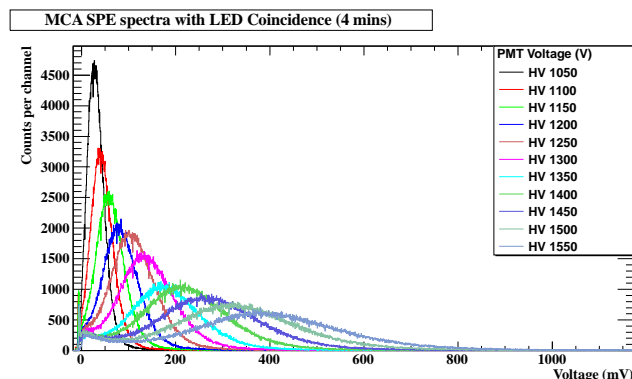
Figure 2. With the SPE trigger setup and an LED flasher, the pulse height spectra from the Hamamatsu R877-100 SBA PMT for different operating voltages.

The spectra of pulse amplitudes due to SPE and noise were measured at different operating voltages. From the SPE spectra we determine the average SPE amplitude and corresponding width. The Electron Tubes PMT has larger peak-to-valley ratios and its noise is of lower amplitude independent of the supplied high voltage (HV). The spectra due to SPE for the Hamamatsu R877-100 SBA PMT is shown in Figure 2. From the dark spectrum we determine the peak-to-valley ratios to be ≈ 1.4 compared to ≈ 2.5 for the Electron Tubes PMTs

A measurement of the gain of both PMTs at different HV was made by integrating averaged waveforms to determine the charge of an SPE. The oscilloscope traces are the time-dependent voltage $V(t) = I(t)R$ of the averaged pulse and are related to current $I = dQ/dt$. The average charge produced in a PMT due to an SPE is calculated by integrating the averaged waveforms:

$$Q = \int \frac{V(t)}{R} \, dt \tag{1}$$

The gain is the number of electrons output by the PMT due to an SPE that are needed to produce the observed charge:

$$G_{PMT} = \frac{\int V(t)\,dt}{eRG_{amp}} \tag{2}$$

where e is the electric charge and G_{amp} is the gain of any amplifiers used: 1 for the Electron Tubes PMT and 16.14 for the linear amplifier required when using the lower gain Hamamatsu PMT.
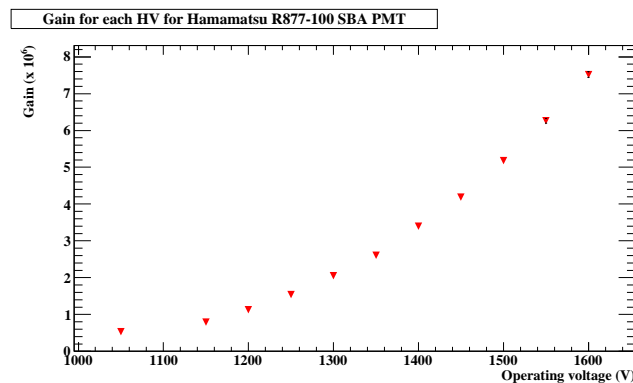

Figure 3. Gain of the Hamamatsu R877-100 SBA PMT for different operating voltages.

For the Hamamatsu PMT the gain was found to be $7.52 \pm 0.08 \times 10^6$ when operating at 1600 V. The Electron Tubes PMT had a gain of $5.45 \pm 0.05 \times 10^7$ at 1750 V. As expected there is an order of magnitude difference. The gain variation with HV was determined by measuring the average SPE amplitude and is shown in Figure 3 for the Hamamatsu R877-100 PMT. Hamamatsu reports a typical gain of 3.1×10^5 [7] at 1250 V which is about one fifth of our measurement of 1.5×10^6 at the same HV. Electron Tubes reports a typical gain of 2.7×10^6 for its 9390B PMT when operating at 1000 V [11]. Our measurements do not reach such a low HV, but our measurement suggests that the gain will be $< 4.6 \times 10^6$, the measurement at our lowest HV of 1300 V. Both of the reported values for gain are lower than those we measured but within a small enough range to be acceptable.

The pulse tail and baseline are critical parameters for F_{prompt}. To study these parameters for each PMT pulse, waveforms for SPE were averaged and analyzed, shown in Figure 4. The electronics were designed to create as close to a Gaussian-shaped pulse as possible for the Hamamatsu PMT. The longer fall time of the Electron Tubes PMT is due to greater overall charge stored in the PMT and transferred to the electronics, a result of the high gain. The baselines were studied to determine the contributions from electronics and the contributions inherent to the PMT. Proper measurement of the baseline due to SPE allows for accurate subtraction during analysis, where several SPE pulses contribute. An ideal pulse tail will follow an exponential trend, allowing for easy and accurate compensation. Neither of the pulse tails observed for the Hamamatsu and Electron Tubes PMTs can be fit well with an exponential curve (Figure 5). However, close analysis of features reveals similarities between the two PMTs, suggesting that the electronics common to both test may be the cause, and these features may be removed in future implementations.

The Electron Tubes PMT has a faster response time, on the order of 100 ns. The response time is the difference in time between the event (LED flash) and the PMT response. The Hamamatsu PMT has a response time around 200 ns when operated near its optimal HV. At higher operating voltages the PMTs respond quicker but have lower energy resolution characterized by wide peaks
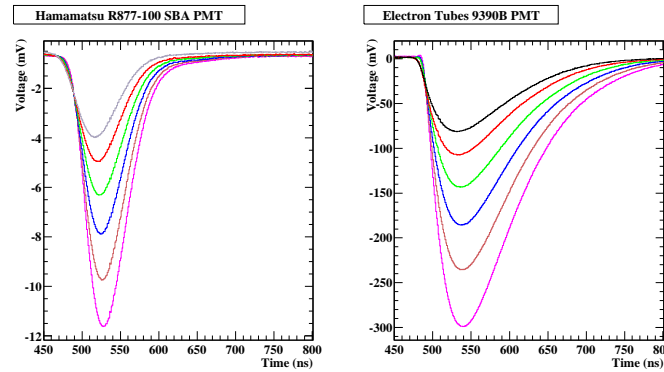
Figure 4. A sample of the average waveforms due to SPE taken with the oscilloscope for increasing HV. The Electron Tubes PMT exhibits a much longer fall time than the Hamamatsu PMT and has a long tail. The risetime is dominated by the preamplifier and the fall time is dominated by the PMTs.
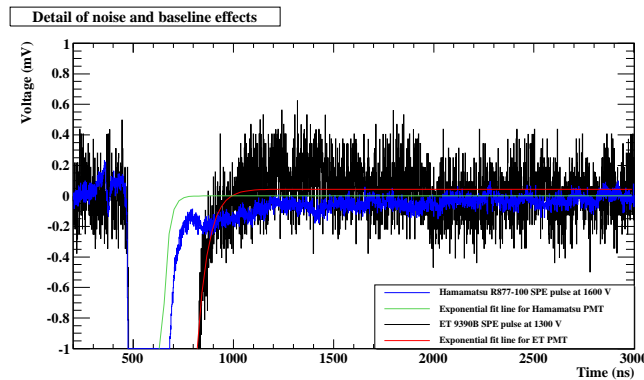

Figure 5. A comparison of the SPE waveforms and exponential baseline fits of the Hamamatsu (blue) and Electron Tubes (black) PMTs. Features preventing reliable fits are clearly visible in the waveform collected for the Hamamatsu PMT.

in their spectra. The differences are well understood, however, and the slower response of the Hamamatsu R877-100 PMT should not be a problem for the applications we are considering. This PMT follows a strongly linear relationship between the magnitude of the source and its output voltage. The higher efficiency will improve the sensitivity and light yield of our detectors and should not present many difficulties in its operation and analysis.

3. Conclusion

The accuracy of DEAP-3600 will depend on maximizing our rejection power, which will be improved by high efficiency PMTs and well understood responses to SPE:

- Accurate baseline corrections improve PSD
- Increased light yield improves calculations
- Understanding SPE response improves both

DEAP-3600 will be capable of detecting WIMP scattering with a cross section sensitivity of 10^{-46}cm^2. We predict that this will require a PSD fraction of 10^{-10}. A prototype detector

(DEAP-1, 7kg LAr) has achieved $< 6 \times 10^{-8}$ [12].

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