Photomultiplier characterisation and its impact on background for SABRE South

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Abstract

SABRE (Sodium iodide with Active Background REjection) South is a NaI(Tl) based dark matter direct detection experiment located at the Stawell Underground Physics Laboratory (SUPL) [1,2]. It is designed to detect an annual modulation of WIMP recoils as an independent replication of the long-standing DAMA/LIBRA modulation signal. SABRE South will have a low energy threshold of 1 keV in the NaI(Tl) crystal detector and a low experimental background. This requires precise characterisation of the photomultipliers used to understand both their sensitivity at low thresholds and their contribution to the background. We report on the photomultiplier characterisation test bench developed for the crystal detector photomultipliers including studies of the single photon response, transit time, and dark noise. A specific focus is on estimating the contribution to the experimental background of coincident photomultiplier noise due to its predominance at low energy and inability to be modelled using traditional MC simulation.

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1 Introduction

The DAMA experiments have detected a modulating signal of nuclear recoils in NaI(Tl) compatible with dark matter for 20 years, with a combined significance of 12.9 σ [3]. The claimed dark matter interpretation of this signal is in tension for a spin independent WIMP with null results from large noble gas experiments. This has motivated several NaI(Tl) based independent replication efforts including ANAIS [4], COSINE [5] and SABRE [1]. So far both ANAIS and COSINE have not been able to confirm or refute the DAMA modulation signal with significant sensitivity. SABRE is a upcoming experiment with twin detectors in the Northern [6] and Southern hemisphere [2]. SABRE South is currently under construction in SUPL, with a projected commissioning commencing in 2023. A complicating factor in these searches is that the lower threshold of the DAMA region of interest, 1 keV_{ee}, corresponds to low number of detected photons, between 8 and 14 depending on the experiment, spread across hundreds of nanoseconds. This signal has can be easily mimicked by noise from the photomultipliers used to measure the crystals. This noise is a significant component of the low energy background model that is difficult to include in time dependent background models as it cannot be modelled in Monte Carlo simulations. To understand this background requires accurate measurement of the low energy noise. This also allows for the development of techniques to minimise this background.

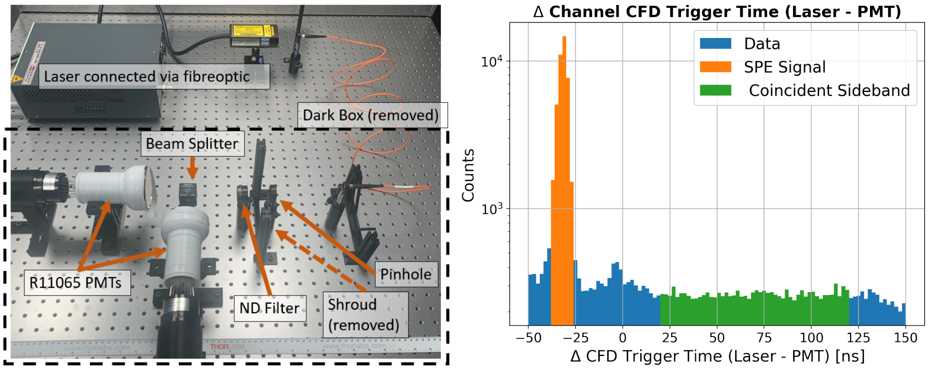
We report on the photomultiplier characterisation test bench developed for the crystal detector photomultipliers for the SABRE South experiment, a detector designed to test the DAMA modulation. This includes studies of the single photon response, quantum efficiency, dark noise and the linearity of the PMT response at high energies. A specific focus is on correlated dark noise between two photomultipliers above the random coincidence rate, due to its significant contribution to the low energy background. We have also begun development of signal versus noise classifiers for low energy scintillation events base on a set of pulse shape variables. We present the results of the photomultiplier characterisation and its impact on the low energy performance of the SABRE South experiment.

2 PMT characterisation

A PMT test bench has been setup at the University of Melbourne to characterise the 18 R5912 veto PMTs, and the 14 R11065 crystal PMTS. This bench is shown in figure 1a. The light source is a Hamamatsu pulsed laser (PLP-10) with a peak wavelength of 405 nm and < 100 ps pulse width. This is then passed into a aluminium dark box via a multimode fibre optic before passing through a neutral density filter and a 500 μm spatial aperture. A reflective neutral density filter with a metallic coating was used for its consistent performance for visible/near UV light. The filter used has an optical density of 4.0, ensuring a low average photon occupancy. Whilst the aperture ensures that the beam is sufficiently collimated. Using the time difference between a synchronisation signal from the laser and the PMT signal, a cut is made to select PMT events that are in time with a laser pulse. This is shown in figure 1b which shows the time difference distribution, the cut region for the “SPE signal”, and a “coincident sideband” where the detected PMT pulse occurs sufficiently after a laser signal. The coincident sideband region provides a sample of dark events that are randomly coincident with an empty laser pulse and can be used to estimate the number of noise events within the SPE Signal range. Based on the in time region for the sample shown in figure 1b we obtain a sample of single photoelectrons composed of 96.2% laser caused pulses, with a well defined sideband from the out of time region to provide detailed information on the 3.8% contamination.
The data acquisition (DAQ) system used for these tests is a scaled down version of the planned DAQ for the SABRE South experiment. This consists of a CAEN V1730 digitiser with 500 MS/s readout linked via fibre optic readout to a high performance PC running a custom EPICs based DAQ developed by SABRE South.

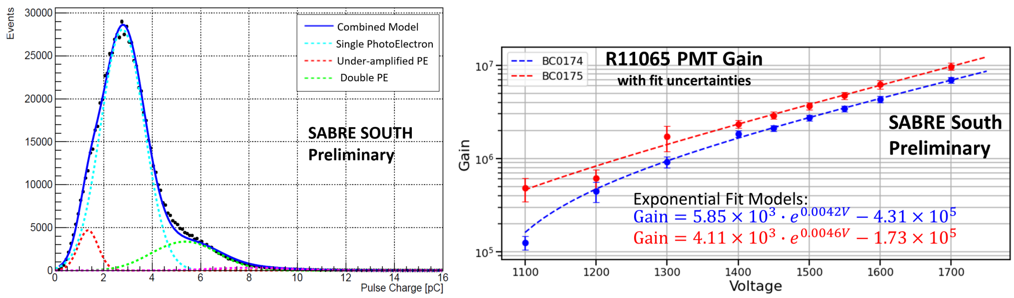
2.1 SPE response

The single photoelectron (SPE) response is an important property used to measure the PMT gain, and to reconstruct the measured signals. Additionally this is used to generate synthetic waveforms from Monte Carlo simulations which allow for development of machine learning classifiers (see section 4). The SPE charge model for SABRE South is based on Ref. [7] with



(a) Annotated image of SPE test bench (b) SPE timing cut

Figure 1: **(a)**:Annotated image of Single PhotoElectron (SPE) test bench showing key components with darkbox removed. **(b)**: Histogram of the timing difference.



(a) Fitted R5912 PMT SPE charge spectrum (b) R11065 Photomultiplier Gain

Figure 2: **(a)**:Fitted SPE charge spectrum from a R5912 veto photomultiplier **(b)**: R11065 PMT gain as a function of voltage for two SABRE South PMTs with an exponential best fit model applied.

the background terms removed due to the use of a low amplitude trigger ($\sim 0.1\times$ SPE peak height) for the acquisition. An additional component is added to describe under-amplified events, where the electron avalanche is not complete either due to the initial photoelectron bypassing the first stage or due to events where a fraction of the electron avalanche misses the next dynode and is lost. The model used is:

$$\text{pdf} = \sum_{n=1}^{4} p'_n \cdot \text{Gaussian}(nQ_{\text{PE}}, \sqrt{n}\sigma_{\text{PE}}) + \text{Pr}_\text{U} \cdot \text{Gaussian}(\delta Q_{\text{PE}}, \delta\sigma_{\text{PE}}), \tag{1}$$

where p'_n is the Poissionian probability term of seeing pulses containing n photoelectrons, corrected to account for the fact we only use $n = 1, 2, 3, 4$ terms. The parameter Pr_U is the probability of the under-amplified signal while δ scales the under-amplified distribution relative to the single PE. From this model we can extract the mean single photoelectron charge Q_{PE} and use it to measure the gain. Figure 2a shows this model applied to a SPE charge spectrum from a R5912 Veto PMT, this fit describes a data set with a higher mean occupancy than typically used to show the adaptability of the model.Figure 2b shows the gain as a function of voltage for two R11065 PMTs.

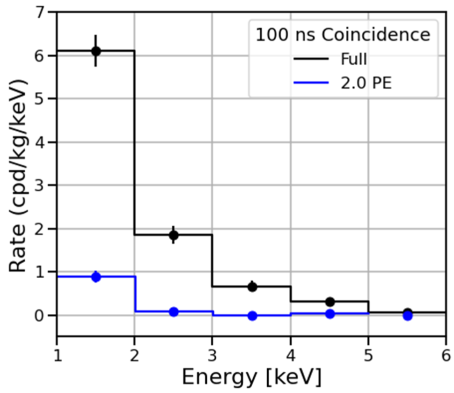


Figure 3: Upper limit on background from uncorrelated coincident dark rate in a 7kg crystal detector unit; With (blue) and without (black) a conservative asymmetry requirement of two photoelectrons of charge (~ 0.18 keV) in both PMTs. No further selections have been made on the data.

3 Coincident noise

An estimate of the background rate due to uncorrelated coincident noise in the R11065 PMTs has been produced by combining "dark" noise events (called dark as the signal is not caused by detecting light) from two PMTs to produced a synthetic data set that is re-scaled to match the expected rate of random coincidences given by:

$$r_{\text{coincident}} = r_A(1 - e^{-r_B \cdot t_c}) + r_B(1 - e^{-r_A \cdot t_c}). \tag{2}$$

Uncorrelated coincident events in the 1-6 keV region of interest are mostly asymmetric. With ~ 1 PE of charge detected in one PMT and the rest of the charge in the other. These asymmetric events can be removed from the eventual background by rejecting events with < 2 PE's (~ 0.18 keV) of charge in each PMT. This provides a significant decrease in the background rate from these random coincidences. This rejection of asymmetric events is significantly more permissive than that used by DAMA [3], or ANAIS [4] and SABRE South will likely adopt a more sophisticated selection. Figure 3 shows the background contribution from these uncorrelated coincident events with a 7 kg crystal. This background is 0.2 cpd/kg/keV averaged across the 1-6 keV_{ee} region of interest. This is prior to any cut based selection (aside from a relaxed asymmetry cut) or a signal to noise classifier. As such it is reasonable to expected that this contribution can be reduced to below 0.1 cpd/kg/keV with high ($> 50\%$) 1 keV signal efficiency.

4 Digitisation process

Digitisation is the process of emulating detector and DAQ effects for Monte Carlo simulations to produce pseudo data that can be analysed using the regular processing framework. We have developed a python based softward package DOOM (Digitastion Of Optical Monte carlo) that takes photon arrival times, individual PMT parameters (SPE Charge model, QE, Transit Time, + more) and DAQ information (sample rate, resolution) to simulate individual waveforms. This tool is currently being validated on tagged data sets from quenching factor studies [8] and NaI(Tl) calibration measurements. DOOM is now generating data sets with known event origin (position and energy) that will be used in the development of particle ID and localisation tools for the NaI(Tl) and Veto detectors. Additionally, it will be used to estimate the signal efficiency of the PMT noise classifer before it is confirmed with tagged NaI(Tl) data.

5 Conclusion

We have developed a photomultiplier characterisation system that is being used to characterise all 32 (+ 4 spare) photomultipliers for the SABRE South liquid veto and crystal detectors. The single photoelectron test bench uses a pulsed laser system with mean occupancy <0.05 photons per pulse producing a data set that contains >95% single photoelectron pulses. This was used to develop a single photoelectron model that can be used to measure the PMT gain.

Finally an estimate of the uncorrelated coincident photomultiplier noise contribution has been made. With basic selection criteria we find that the R11065 PMT has a preliminary upper limit of 0.2 cpd/kg/keV in the region of interest. We ultimately expect to reduce this to <0.1 cpd/kg/keV by applying a multivariate classifier.

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