Neutron-gamma discrimination via PSD plastic scintillator and SiPMs

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Neutron-gamma discrimination via PSD plastic scintillator and SiPMs

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Abstract. The reduction in availability and inevitable increase in cost of traditional neutron detectors based on the ^{3}He neutron capture reaction has resulted in a concerted effort to seek out new techniques and detection media to meet the needs of national nuclear security. Traditionally, the alternative has been provided through pulse shape discrimination (PSD) using liquid scintillators. However, these are not without their own inherent issues, primarily concerning user safety and ongoing maintenance. A potential system devised to separate neutron and gamma ray pulses utilising the PSD technique takes advantage of recent improvements in silicon photomultiplier (SiPM) technology and the development of plastic scintillators exhibiting the PSD phenomena. In this paper we present the current iteration of this ongoing work having achieved a Figure of Merit (FoM) of 1.39 at 1.5 MeVee.

1. Introduction

It is well-known that the emission from organic scintillation detectors comprises both fast and slow components. For the vast majority of applications it is the prompt emission that is most useful. However, pulse shape discrimination is a special case in that it is the slow component of emission which is of greatest importance. For scintillators exhibiting the PSD phenomena the delayed fluorescence can be directly related to the type of incident radiation[1], i.e. it can be used to distinguish between pulses caused by neutrons and gamma rays in a way that other scintillators cannot. Thus a PSD system can help end the reliance on a dwindling supply of ^{3}He for national nuclear security.

PSD is most strongly observed within the category of organic liquid scintillators such as EJ-309[2, 3, 4]. The chemical properties of these materials make them undesirable for mass deployment, especially in situations where they would require regular maintenance by personnel. Conversely, plastic scintillators are known for their stability and ruggedness, making them a far more suitable prospect for a long-term deployment with possible public exposure. With the development of EJ-299-33 [5], a plastic scintillator exhibiting PSD properties, there appears to be a solution to the absence of neutron detection capability.

All scintillators require a coupled sensor to detect the emission of light, a role generally filled by the photomultiplier tube (PMT). Unfortunately, PMTs usually require a high voltage power supply, presenting an electrical hazard to their deployment, as well as the nature of their operation being such that they remain unsuitable for use with magnetic fields[6]. The silicon photomultiplier (SiPM) is an alternative which solves these issues[7], and with recent technological improvements the high dark current of previous generations has been greatly reduced[8].

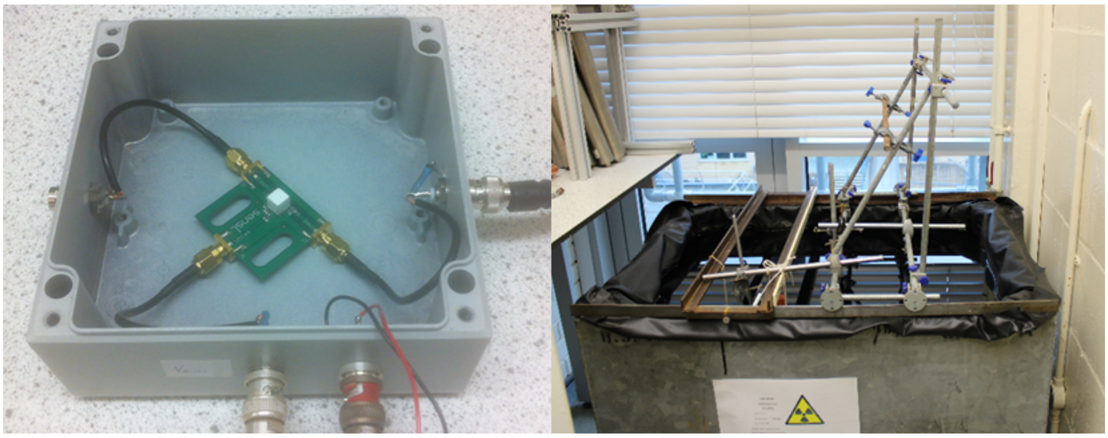

Figure 1. The EJ-299/SiPM detector system (left), the AmBe neutron source tank (right).

The use of digital electronics via fast waveform digitisers enables the raw SiPM pulse to be processed and subsequently analysed. Ongoing development work in the field of digital electronics has allowed a study on the relative importance of various pulse processing factors, specifically Analogue-to-Digital Conversion (ADC) resolution[9]. This paper concerns the ongoing development of a digitised plastic scintillator-SiPM PSD system and we present new Figures of Merit (FoM) in comparison to those established with our previous generation data acquisition (DAQ)[10].

2. Experimental Summary

The detector combined a small (6x6x6 mm^3) piece of EJ-299 plastic scintillator and a SensL MicroFC-SMA-60035 C-series SiPM. To maximise light transmission the scintillator had been highly polished, painted with EJ-510 titanium-oxide paint, and optically coupled to the SiPM with standard silicon grease. In addition, the scintillator's wavelength of peak emission corresponds well to the peak response of the SiPM, which are both at 420 nm[8, 11].

The detector setup consisted of a sealed, light-tight metal box with surface mount BNC ports for access to the fast/slow outputs of the SiPM, the bias supply, and an additional connector to monitor the temperature via a PT100 platinum thermistor. The detector housing is shown in Figure 1. The SiPM selected was the largest single-cell device currently manufactured by SensL at 6x6 mm^2 with 18980 microcells at a 64% fill factor, which enables the detector to be sensitive over a greater dynamic range than smaller devices. The breakdown voltage (Vbr) was found to be in accordance with datasheet values at 24.8 V (at 26°C) using a Keithley 487 picoammeter driven by LabView operating software. The operating voltage was selected as Vbr + 2.5 V and was provided by an Ortec 710 Quad Bias Supply.

Although access to both outputs of the SiPM was available, only the slow output was used, which was connected to a Caen digitiser. Two digitisers were used, a 10-bit V1751 (bandwidth 500 MHz and sample rate of 1 GS/s), and a 14-bit V1730C (bandwidth 250 MHz and sample rate 500 MS/s); previous work at the University of Surrey has established ADC resolution to be one of the most important factors for achieving good quality PSD with digital systems[9]. Pulses were processed either through the on-board Digital Pulse Processing (DPP) PSD algorithms, allowing the digitisers Field Programmable Gate Array (FPGA) to perform the charge integration, or the waveform was simply recorded for post-processing with external, in-house analysis software.

The mixed radiation field produced by a 17.57 GBq AmBe source was used to test the PSD capability. The use of fast neutrons was enabled through insertion of an air-tube into the 1 m^3 water tank shielding the AmBe source. The detector was placed 50 cm from the source, but

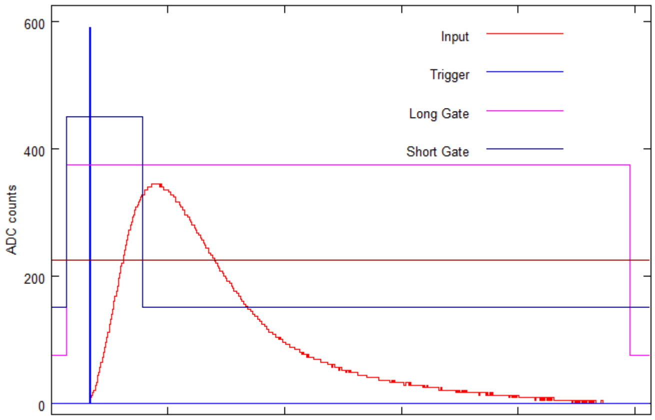

Figure 2. A typical radiation waveform (red), with the trigger, short gate, and long gate overlaid.

less than 1 cm of water shielding remained. The AmBe source has a significant gamma-ray flux, therefore 5 cm of lead was placed between the source and detector to avoid over-saturation due to gamma signals. The setup can be seen in Figure 1.

2.1. Charge integration

The charge integration technique for PSD involves the application of two time gates to each pulse and establishing the ratio between them. As it is the slow component that contains the information regarding the nature of the incident radiation[1] it is the relative strength of this that allows neutron-gamma discrimination to take place.

The application of the two time gates is depicted in Figure 2, with the charge collected from each integration used to determine the PSD parameter as given by:

$$PSD = 1 - \frac{Q_s}{Q_l} \tag{1}$$

where Q_s and Q_l are the charge integrated in the short and long gates respectively. The optimum short gate was found to be 66 ns with the V1751 while the long gate encompassed the entire record length (700 ns) of the pulse. For direct comparison, these settings were maintained for the V1730C measurements.

3. Results

The standard method of determining the quality of neutron-gamma discrimination is via a 2-D histogram of total integrated charge versus the respective PSD parameter of that pulse. The PSD parameter is calculated by equation 1, and the integrated charge is simply the Q_l value of that equation. This histogram for the C-series/V1730C system is shown in Figure 3, and exhibits the characteristic PSD shape of two, well-defined regions, where the upper region contains neutron events and the gamma pulses are confined to the lower region.

The quantitative performance of PSD for a given detector system is defined by a Figure of Merit (FoM). The FoM details the neutron-gamma discrimination for a given energy threshold, and is a function of both the separation and resolution of peaks in the PSD parameter, i.e. a projection of the y-axis of Figure 3. The widely used FoM calculation[12] here is in common with other recent works [10, 13], and is given by:

$$FoM = \frac{S}{\Gamma_1 + \Gamma_2} \tag{2}$$

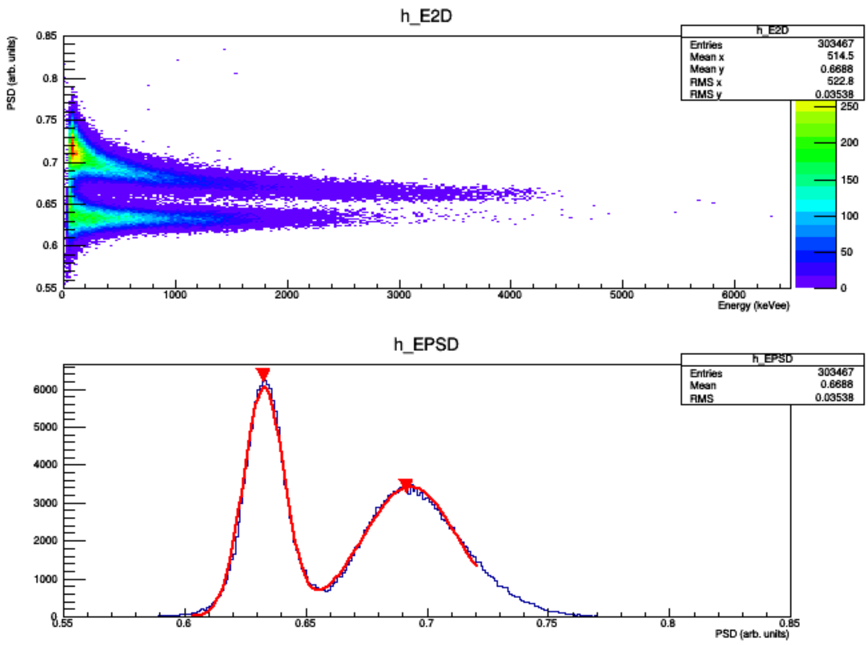

Figure 3. The standard PSD histogram for the C-series SiPM with V1730C digitiser. The PSD projection has had a double Gaussian function fitted to enable extraction of the parameters for the calculation of the Figure of Merit.

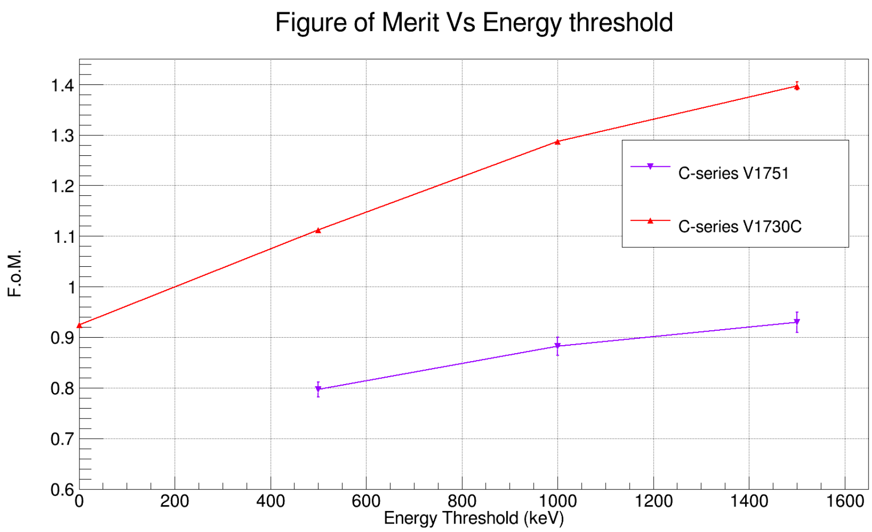

Figure 4. Figures of Merit versus energy for C-series SiPM.

where S is the separation between the neutron and gamma peaks and Γ_1 and Γ_2 are their full widths at half maximum.

There is generally a strong correlation between the FoM and increasing neutron/photon energy. At the lowest energies the FoM is significantly reduced due to overlap between neutron and gamma ray PSD distributions. The FoM as a function of energy threshold is shown in Figure 4.

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4. Conclusion

The presented system has achieved significant separation of the neutron and gamma ray pulses from an AmBe source, achieving a FoM of 1.39 at 1.5 MeVee. In particular we have shown the substantial improvement to be made when increasing the resolution of the signal pulse height as determined by the digitiser specification. The variation in neutron and gamma pulses with EJ-299-33 is subtle, and the amplitudes are small. The V1730C 14-bit digitiser has a resolution of $\sim$0.03 mV/ADC unit. A typical difference between neutron and gamma pulses obtained by the V1730C would be $\sim$100 ADC units over each sample of a pulse, corresponding to $\sim$3 mV. Similar pulses processed by a V1751 10-bit digitiser would be separating based on a difference of $\sim$3 ADC units per sample. We believe that it is this fundamental difference that produces superior PSD for the V1730C over the V1751. Furthermore, the advanced technologies implemented at this stage have shown that a plastic scintillator/SiPM system can compete in terms of performance with alternative PSD systems. The work of Liao and Yang[13] highlighted the potential of an EJ-299-33/SiPM system, quoting FoMs of 0.59 and 0.76 at 1 MeVee for a charge integration and complex algorithm respectively. The system in [13] however, used an older B-series device. Contrastingly, Cester *et al.*[14] confirms the superior PSD qualities of PMT-based systems and makes use of a V1751 10-bit digitiser achieving a FoM of 1.3 at 1 MeVee. For comparison to other scintillation materials, Yanagida *et al.* quote a FoM of 1.53 for an anthracene/PMT system[15], with Woolf *et al.* suggesting that a liquid scintillator system has a FoM of around 2[16].

At present the SiPM technology is undergoing continued development and new versions of the sensor are available. It is likely that the J-series device will see further improvements in its signal-to-noise ratio and that the FoM will increase as a result. The next stage of work will be to repeat the investigation presented here with the J-series SiPM, and then to investigate the tolerance of PSD performance with respect to the sample rate of the digitiser by down-sampling the waveform. It has already been shown that the increased resolution of the V1730C (which allows for the subtleties between the neutron and gamma pulses to be more readily discerned) more than compensates for the reduction in sample rate from the V1751, but the limitations of this trade-off are yet to be determined.

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