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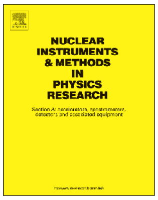

Pulse shape discrimination performance of stilbene coupled to low-noise silicon photomultipliers

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ABSTRACT

Pulse shape discrimination (PSD) techniques can be used to discern between neutron and gamma-ray interactions in certain organic scintillators. Traditionally, photomultiplier tubes (PMTs) have been used in organic-scintillator assemblies. However, silicon photomultipliers (SiPMs) have great potential to be used in many applications in which PMTs have been predominantly used, including those utilizing PSD techniques. To evaluate the current state of the art of the SiPM technology, SensL's 6-mm B-Series and C-Series SiPMs were compared to a fast Hamamatsu PMT in conjunction with a $6 \times 6 \times 6$-mm^3 stilbene organic scintillator to assess the PSD performance of the detector assemblies. Measurements with a Cf-252 source were performed and a figure of merit (FOM) for discriminating between neutron and gamma-ray pulses between 100 keVee and 200 keVee was calculated for each assembly. A digital charge-integration PSD technique was used to process all measured data. The FOM for the B-Series SiPM, PMT, and C-Series SiPM was 1.37, 1.93, and 2.13, respectively. The C-Series SiPM was shown to perform as well as the PMT in the experiments.

1. Introduction

Silicon photomultipliers (SiPMs) are solid-state light sensors with similar light-conversion and amplification capabilities to photomultiplier tubes (PMTs) [1,2]. When coupled to a scintillating medium, these devices have been used in a variety of radiation detection and spectroscopy applications including dosimetry [3,4], medical imaging [5–8], high-energy physics [9–11], and homeland security [12–14]. Additionally, organic crystals with pulse shape discrimination (PSD) capabilities coupled to SiPMs have been shown to be capable of fast-neutron detection [15–17]. Previous approaches used complex PSD algorithms and exhibited poorer PSD performance with SiPMs when compared to PMTs. Recently, however, improvements in SiPM technology have significantly reduced the amount of noise produced [18]. This noise reduction opens up the potential for improved PSD performance of SiPMs coupled to organic scintillators. SiPMs already have a number of attractive features when compared to PMTs, including low sensitivity to magnetic fields, low voltage requirements, small size, and competitive cost. If the PSD performance of SiPMs matched that of PMTs, SiPMs could present a viable alternative to PMTs in applications where PSD performance is critical. PSD-capable organic scintillators are used in a variety of applications, including nonproliferation and safeguards applications [19–21], fusion experiments [22], and geological studies [23]. This work investigates the PSD performance of stilbene read-out with the new generation of SiPMs and compares it to the performance of the previous SiPM generation and a fast PMT.

2. Silicon photomultipliers

SiPMs are composed of numerous Geiger-mode avalanche photodiodes (APDs), referred to as microcells [1]. In particular, the SiPMs used in this work are each composed of 18,980 35-μm microcells [24,25]. The outputs of the microcells are summed up, producing a signal proportional to the number of microcells discharging at any time [1]. While a single APD gives a binary response indicating whether or not a photon was detected, SiPMs are capable of producing a signal proportional to the incident photon flux. Furthermore, when sensing scintillation light of low enough intensity such that all of the microcells do not trigger at once, a time profile of the light production is retained in the output signal of the SiPM. The preservation of the temporal distribution of scintillation light production, originating in a PSD-capable scintillator, allows PSD to be performed.

The SiPMs used in this work have peak sensitivity at approximately 420 nm [24,25]. In comparison, stilbene's wavelength of maximum emission is approximately 410 nm [26]. This peak-sensitivity similarity makes these SiPMs a good option for measuring scintillation from stilbene.

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3. Method

Three light sensors were evaluated: a Hamamatsu H10580 PMT assembly (R9800 PMT), a SensL MicroFB-60035 SiPM, and a SensL MicroFC-60035 SiPM. A single $6 \times 6 \times 6$-mm^3 stilbene crystal from Proteus, Inc. [27] was coupled to each of the light sensors. Eljen Technology EJ-550 silicon optical grease was used to couple the stilbene crystal to each of the light sensors. The stilbene crystal coupled to the PMT and the B-Series SiPM is shown in Figs. 1 and 2, respectively. During experiments, each detector assembly was contained within a custom-designed, opaque, 3D-printed coupler, which prevented external light from reaching the light-sensitive portions of the assemblies. A CAEN V1730 digitizer was used to digitize and collect the pulses from the PMT and B-Series configurations and a CAEN DT5730 was used to digitize pulses from the C-Series configuration. Both digitizers have 14-bit resolution and a sampling frequency of 500 MHz [28]. The different digitizers were used because of limited availability and comparison measurements were performed to confirm that their performance is similar enough to justify their use. The resulting figures of merit, described in Section 4.2, agreed within approximately 10%.

Each detector configuration was calibrated using 478-keVee Compton edge measured with 662-keV gamma rays from a Cs-137 source. Then, each configuration was used to acquire pulses while placed 5 cm from a bare Cf-252 spontaneous fission source, with source strength of approximately 150,000 neutrons per second. A 50-keVee threshold was used for each measurement.

PSD was performed using a digital charge comparison technique in which the ratio of the integral of the pulse tail to the total integral of each pulse is calculated to identify the type of incident radiation [29,30]. Three parameters were varied for each detector configuration in order to obtain the optimum particle discrimination: the time before the pulse peak at which the total integral begins, the time after the pulse peak at which the tail integral begins, and the time after the pulse peak at which both integrals end. To optimize these values, each combination of plausible values was used to calculate a figure of merit (FOM) using an automated MATLAB script. The FOM quantifies the quality of particle discrimination, as discussed in Section 4.2. The combination for each detector configuration that produced the largest figure of merit was used. These optimal values are listed in Table 1 for all three configurations. It is worth noting that for the C-Series SiPM, the integral end time is significantly longer than that of the B-Series SiPM. This is because of the lower noise in the tail of the pulses, as discussed in Section 4.1.

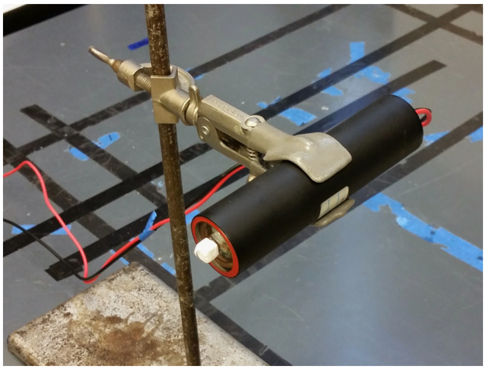

Fig. 1. Photograph of a stilbene crystal coupled to a Hamamatsu H10580 PMT assembly.

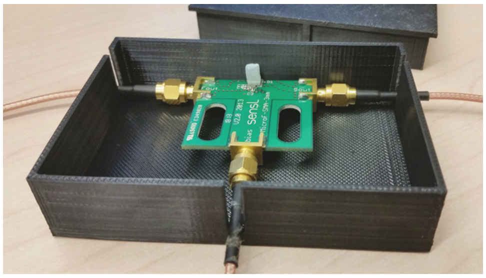

Fig. 2. Photograph of a stilbene crystal coupled to a SensL MicroFB-60035 (B-series) SiPM.

4. Results

4.1. Waveforms

A digitized neutron and a gamma-ray pulse acquired using the PMT configuration is shown in Fig. 3. While the two example waveforms have approximately the same pulse height, the neutron pulse has a larger tail than the gamma-ray pulse. This expected phenomenon is exploited to perform PSD.

Because of the fast timing properties of the PMT, the digitized signal closely represents the timescale in which the light decay occurs within the stilbene crystal. This is in contrast to the longer response of the B-Series SiPM, which, like the C-Series SiPM, has a microcell recovery time of 210 ns [24,25], as exemplified by the pulses shown in Fig. 4. Nonetheless, the tail of the neutron pulse acquired with this device is still substantially larger than that of the corresponding gamma ray, allowing PSD to be performed to distinguish between the two particle types.

Fig. 5 shows pulses acquired using the C-Series SiPM; these appear similar in shape to the B-Series SiPM pulses but exhibit less noise in their baseline, allowing for more accurate discrimination

Table 1
Optimized PSD parameters.

Configuration	Total start time (ns)	Tail start time (ns)	Integral end time (ns)
PMT	2	18	200
B-Series SiPM	2	34	520
C-Series SiPM	0	44	1100

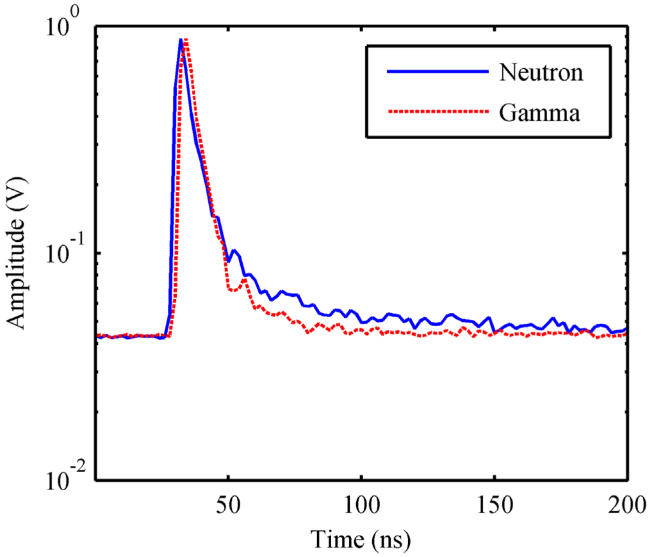

Fig. 3. Digitized 1-MeVee neutron and gamma-ray pulses measured using stilbene coupled to a PMT.