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Evaluation of a Silicon Photomultiplier Array as a Photomultiplier Tube Replacement[1]

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Abstract

Silicon photomultipliers (SiPMs) offer a replacement technology for traditional photomultiplier tubes (PMTs) and have advantages such as lower voltage requirements and a compact package. Some current projects at Sandia National Laboratories that use sodium iodide (NaI) crystals paired with PMTs, could benefit from the replacement of PMTs with SiPMs, but must maintain similar detection performance. This study looks to replicate the performance of a 2”x2” cylindrical NaI(Tl) detector paired with a traditional bialkali PMT by using a CsI(Tl) crystal of the same size paired with a SiPM array. For the required applications, important properties to evaluate were energy resolution, energy linearity, and dark current effects, all across a range of temperatures. Energy spectra were evaluated at temperatures of -30 to 70°C using standard calibration sources. Results showed that at temperature ranges of -30 to 40°C, the SiPM array paired with CsI(Tl) offered energy resolution that was comparable to that of the PMT and NaI(Tl). Adequate linearity was also maintained throughout the -30 to 40°C temperature range. The dark current did not provide a significant contribution until temperatures of 40°C and above. At these temperatures the ability to detect gamma-rays at lower energies is reduced and dead times are significantly increased.

Introduction

For gamma radiation detection applications, NaI(Tl) detectors paired with PMTs have become the industry standard, due to their low cost and relatively good performance. However, the need for high voltages and the larger package of a PMT can be hinderances in field applications. In these situations, a silicon photomultiplier array has the advantage of a smaller footprint with a voltage requirement of less than 30 volts. Voltages in this range are much safer and energy efficient than the 400+ volts needed to operate a photomultiplier tube.

CsI(Tl) was selected to pair with the SiPM because the emission spectrum of scintillation light peaks around 550 nm and is detected with relatively high efficiency in a SiPM array. NaI(Tl) has an emission spectrum that peaks at a shorter wavelength, around 400 nm, which lines up well with the peak detection efficiency of a bialkali PMT (both PMT models used in this study utilize bialkali photocathodes).

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[1] SANDXXXX-XXXX

[2] Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA-0003525.

A major concern with SiPMs is the effect of dark current noise on lower energy resolutions and system deadtimes. Compared to PMTs, SiPMs are susceptible to significantly higher rates of random electron-hole pair production. The rate of random electron-hole pair production increases significantly with temperatures. A major objective of this study was to determine the temperature range for which the SiPM and CsI(Tl) combination offered similar performance to the PMT and NaI(Tl) combination.

Measurements

For this study, a 2”x2” CsI(Tl) crystal was paired with the sensL ArrayJ-600035-64P SiPM pixel array and the sensL ArrayX-BOB6-64S summing board. This system was tested and compared with that of a 2”x2” NaI(Tl) crystal paired with a Bicron 2M2/2 PMT. Baseline measurements were also taken using the same CsI(Tl) crystal paired with an ET 9266KB PMT. All PMT measurements were made using an Ortec 660 Dual 5kV Bias Supply and Ortec 113 Preamplifier. Both PMT and SiPM measurements utilized an Ortec 671 Amplifier and Ortec 927 Aspec Multichannel Analyzer. The SiPM Array was powered using a B&K Precision 1623A 60V Power Supply.

Baseline Measurements

Figure 1 shows the configuration used to collect energy spectra in both PMT systems. The NaI(Tl) and CsI(Tl) crystals were used to determine the effect of temperature on the resolution of the 662 keV peak in Cs-137 and the channel drift at various temperatures. Both systems were evaluated at temperatures from -30 to 70°C in 10° increments, allowing adequate soaking times between each step. Prior to measurements with Cs-137, the detector gain was adjusted to correct for detector drift at a new temperature by aligning the 2614 and 238 keV peaks from U-232 to desired positions, such that the dynamic range of the detector remained constant.

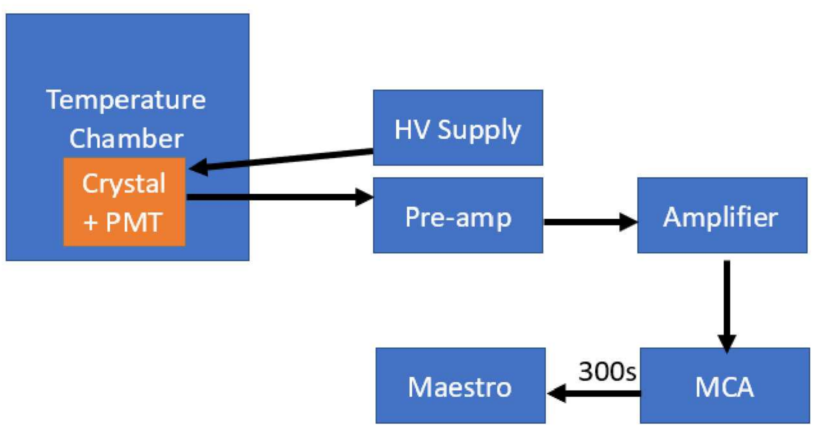

Figure 1: Diagram of experimental set up for PMT systems

CsI(Tl) and SiPM Measurements

The goal of CsI(Tl) and SiPM system measurements were to compare resolution to the PMT systems described prior and to determine if, and when, dark current noise became detrimental to dead time and lower energy resolution. Another goal was to determine if a linear calibration function could be used to adequately generate and calibrate a 120 keV to 3 MeV energy spectrum, for gamma ray detection. Similar to the previously mentioned PMT systems, U-232 was used to adjust for drift at each new temperature. However, instead of adjusting gain to account for drift, bias voltage was adjusted in the CsI(Tl)/SiPM system and gain was held constant at 500. Cs-137 was then measured to determine the system resolution for the 662 keV energy peak.

In addition to Cs-137 and U-232 gamma sources, The CsI(Tl) and SiPM pair were used to measure Am-241, Co-57 and Y-88 gamma sources. These sources, in addition to Cs-137 and U-232, provided a wide range of peaks from approximately 60 keV to 2614 keV to determine energy linearity from -30 to 70°C. Am-241 and Co-57, with energy peaks of 60 keV and 122 keV respectively, were used to monitor the effects of increasing dark current with increasing temperatures that affects the lower energy portion of the spectrum.

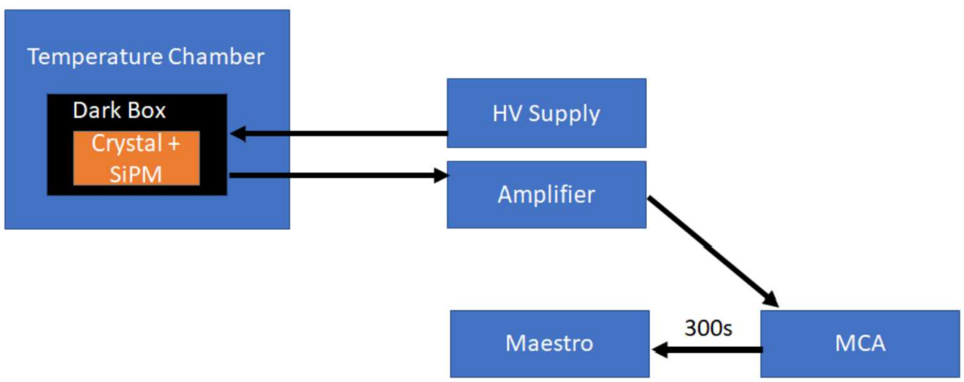

Figure 2: Diagram of experimental set up for SiPM system

Data

Resolution of 662 keV peak comparisons for the three systems are shown below in Figure 3. The resolution values were calculated using a gaussian peak-fitting algorithm. Gain adjustments relative to temperature change for the PMT systems are shown in Figures 4 and 5. Finally, Figure 6 shows changes to bias voltage versus temperature change for the CsI(Tl)/SiPM system.

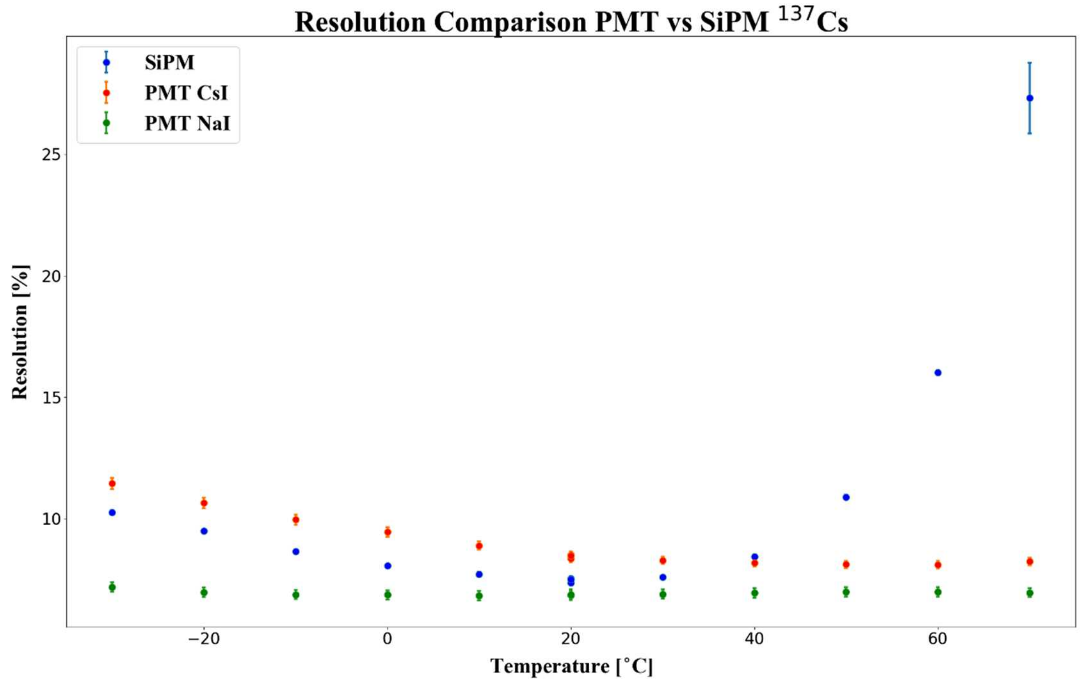

Figure 3: Resolution at 662 keV peak comparisons for all three systems versus temperature changes

NaI(Tl)/PMT Gain vs Temperature

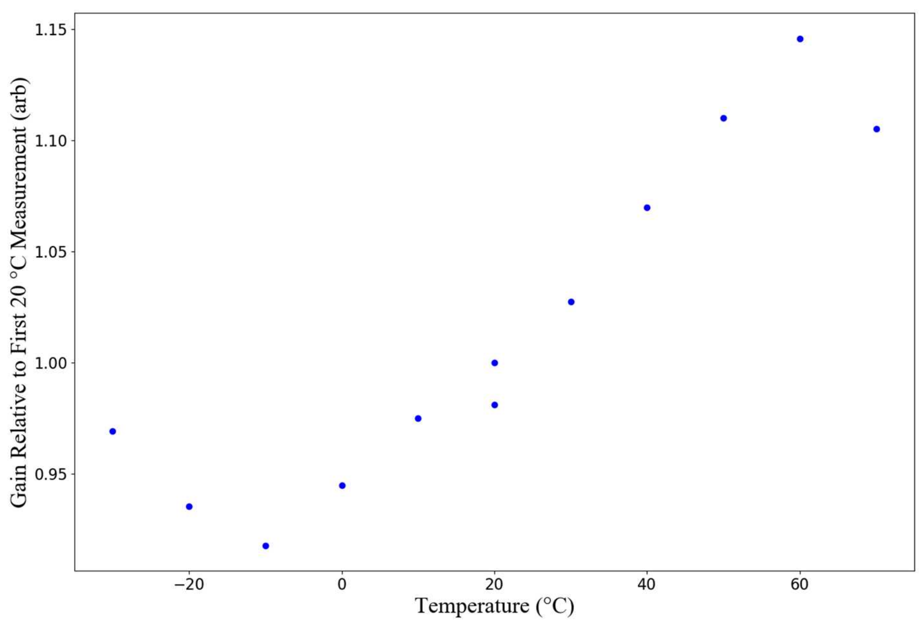

Figure 4: Gain adjustments relative to gain at initial 20°C to account for temperature drift in NaI(Tl) and PMT system

CsI(Tl)/PMT Gain vs Temperature

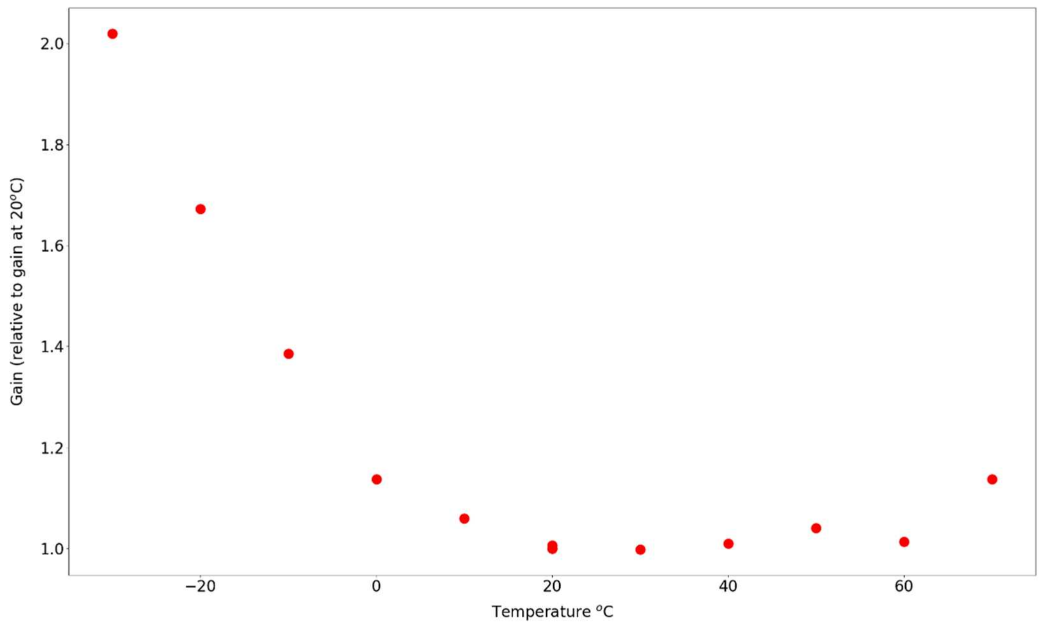

Figure 5: Gain adjustments relative to gain at initial 20°C to account for temperature drift in CsI(Tl) and PMT system

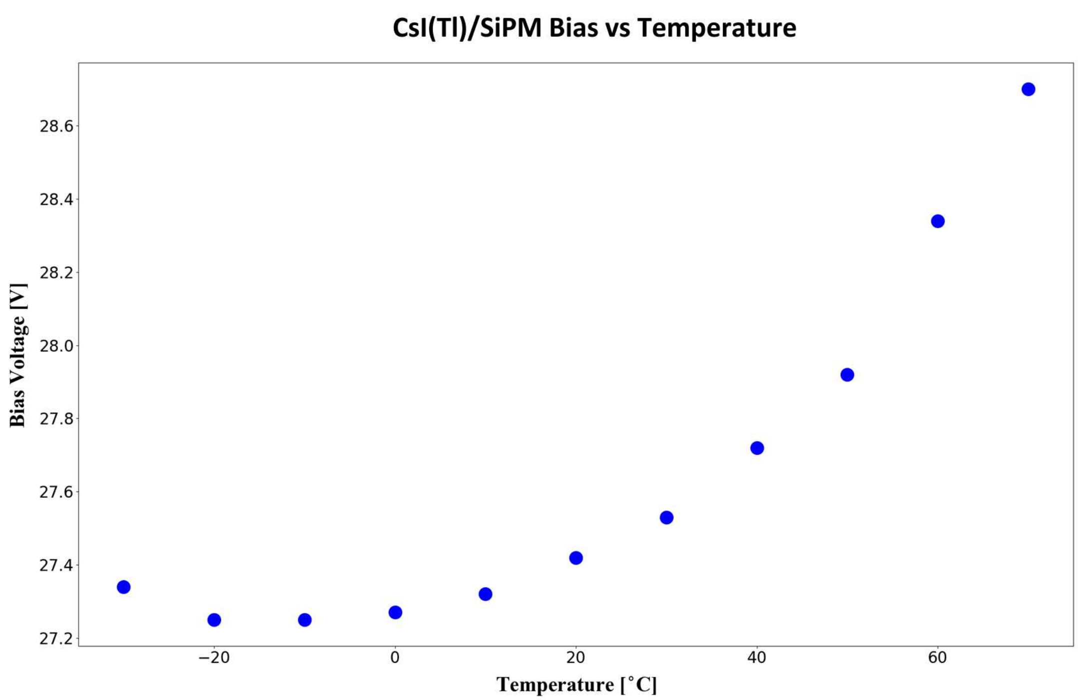

Figure 6: Bias adjustments to account for temperature drift in CsI(Tl) and SiPM system

Analysis

As shown in Figure 3, NaI(Tl) paired with a PMT offers the best resolution over the entire measured temperature range. However, the CsI(Tl)/SiPM offers similar resolutions from -30 to 40°C. The contents of Table 1 were calculated by applying linear fits to the CsI(Tl)/SiPM spectra at each temperature to determine the energy linearity at each temperature. Delineation from the fit equation of the actual peak location was determined using percent error calculations. For example, an observed peak location of 670 keV for the Cs-137 peak would result in a percent error of approximately 1.3% using equation 1, shown below.

$$Percent\ Error\ (\%) = \frac{Observed\ Energy - Actual\ Energy}{Actual\ Energy} * 100 \qquad \textbf{Equation 1}$$

Table 1: Average percent error calculations of deviation from linear fits at all measured temperatures

Peak Energy (keV)	Percent Error (%) Individual calibration equations for each temperature	Percent Error (%) Single calibration equation taken from average of all equations used in previous column	Percent Error (%) Single calibration equation taken from average of the three calibrations generated at 20°C
59.54	11.84	11.84	13.04
122.06	3.93	2.55	2.73
238.63	1.50	2.25	2.18
661.66	3.19	4.03	4.11
898.04	2.32	3.07	3.12
1836.06	1.73	1.94	2.02
2614.53	1.98	2.08	2.16

Conclusion

While NaI(Tl)/PMT systems seem to provide the better overall performance, this study shows that there is little trade-off in switching to a CsI(Tl)/SiPM system at certain temperatures. Especially in applications between -30 and 40°C, resolution of the CsI(Tl)/SiPM system is comparable to that of a NaI(Tl)/PMT system. However, at temperatures above 40°C, dark current counts become a significant detriment to the CsI(Tl)/SiPM system. This change in performance versus temperature change is shown below in Figure 7. For measurements above 50°, the lower level threshold (discriminator) was increased to reduce the dead time that resulted from a significant increase in dark current noise. Prior to the increase of the lower level discriminator, dead times greater than 70 percent were observed. The threshold chosen resulted in a more reasonable dead time near 30 percent for both 60°C and 70°C measurements.

CsI(Tl)/SiPM U232 Spectra vs Temperature

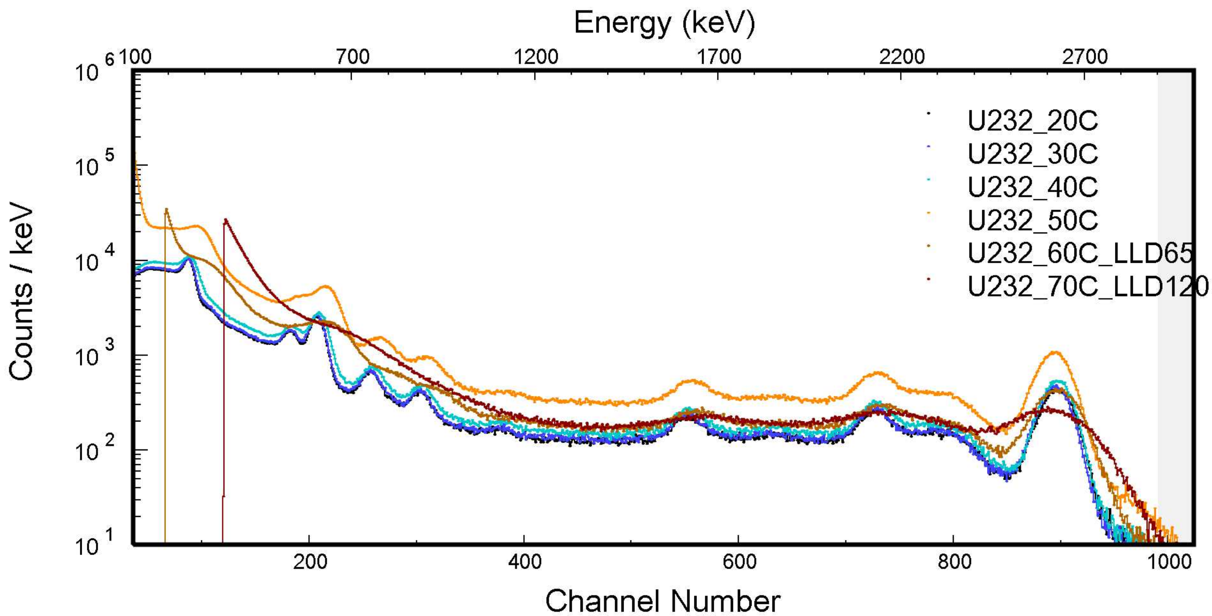

Figure 7: CsI(Tl)/SiPM U-232 spectra vs temperature. (At temperatures above 50°C, lower level discriminator was increased to reduce high dead times resulting from increased dark current.)

As shown in Table 1, adequate linearity is observed across the measured temperature spectrum for CsI(Tl)/SiPM systems. CsI(Tl)/SiPM systems may be increasingly viable in applications that traditionally use NaI(Tl) with a PMT. Field system that favor portability and functionality over fidelity may benefit from the implementation of SiPMs over traditional PMTs.