Assessment of photon detectors for a handheld gamma-ray and neutron spectrometer using Cs$_2$LiYCl$_6$:Ce (CLYC) scintillator

M.B. Smith$^a$, M. McClish$^b$, T. Achtzehn$^a$, H.R. Andrews$^a$, M.J. Baginski$^c$, D.J. Best$^c$, B.S. Budden$^d$, E.T.H. Clifford$^a$, N.A. Dallmann$^d$, C. Dathy$^e$, J.M. Frank$^e$, S.A. Graham$^a$, H. Ing$^a$, L.C. Stonehill$^d$

$^a$ Bubble Technology Industries, PO Box 100, Chalk River, ON, Canada, K0J 1J0
$^b$ Radiation Monitoring Devices, 44 Hunt Street, Watertown, MA 02472, USA
$^c$ SCI Technology Inc., a Sanmina Company, 13000 S. Memorial Parkway, Huntsville, AL 35803, USA
$^d$ Los Alamos National Laboratory, Los Alamos, NM 87545, USA
$^e$ Saint-Gobain Crystals, 17900 Great Lakes Parkway, Hiram, OH 44234, USA

ABSTRACT

The coupling of Cs$_2$LiYCl$_6$:Ce (CLYC) scintillator to silicon photon converters has been evaluated with the goal of investigating replacements for the traditional photomultiplier tube (PMT) in small handheld spectrometers. Energy spectra produced under irradiation by a range of gamma-ray and neutron sources were collected with CLYC mounted to several avalanche photodiodes, PIN photodiodes, and silicon photomultipliers. The performance for both gamma rays and neutrons was compared to that obtained by coupling CLYC to PMTs. None of the silicon devices evaluated provide comparable performance to that of a PMT with CLYC. This is attributed to the photon-detection efficiency of the silicon detectors over the wavelength range of CLYC emissions, as well as the noise characteristics of the devices.

1. Introduction

The detection of photons produced by the interaction of ionizing radiation in scintillator materials has traditionally been performed using a photomultiplier tube (PMT). The PMT offers excellent performance for scintillator-based spectrometers because of its low noise characteristics and high quantum efficiency over the wavelength range appropriate for many scintillators. These properties result in good energy resolution and the ability to measure gamma and X-rays down to approximately 20 keV with many scintillator materials. However, the PMT has disadvantages for some applications (such as small handheld spectrometers) because of its large size, sensitivity to magnetic fields, and high voltage requirements. Consequently, recent developments in silicon photon detectors are of interest for these applications. Silicon photon-to-electron converters include avalanche photodiodes (APDs), silicon photomultipliers (SiPMs), PIN photodiodes, and silicon drift diodes. These devices have varying specifications (relative to PMTs) in areas such as noise and spectral response, which may impact their suitability for use with scintillator materials. Many silicon devices have peak photon-detection efficiency at wavelengths higher than the typical wavelength range of emission associated with commonly-used scintillator detectors. However, in some applications, these disadvantages are offset by factors such as smaller size, lower voltage requirements, insensitivity to magnetic fields, and lower cost. Some silicon devices have been shown to provide energy-resolution performance approaching that of a PMT with certain scintillator materials, e.g., CsI:Tl [1] and LaBr$_3$:Ce [2,3].

The elpasolite scintillator Cs$_2$LiYCl$_6$:Ce (CLYC) has gained significant interest because of its ability to simultaneously perform neutron detection and gamma-ray spectroscopy with good energy resolution for a scintillator [4–10]. Recent work [11,12] has shown that CLYC also has potential for fast-neutron spectroscopy, based on neutron reactions with the Cl component of the material. This discovery was subsequently validated by independent experiments [13]. The scintillation response of CLYC for thermal neutrons is very bright, producing approximately 70,000 photons per neutron, and the resulting thermal-neutron capture peak appears at gamma-equivalent energy (GEE) of approximately 3.2 MeV. The response of CLYC to gamma rays (approximately 20,000 photons/MeV) is not as bright as that of many other scintillators commonly used in gamma-ray spectroscopy. However, the excellent proportionality of CLYC enables energy resolution as good as 4% (full-width at half-maximum, FWHM) for 662-keV gamma rays. Non-proportionality is known to degrade the energy-resolution performance of other scintillators (e.g., NaI:Tl) despite their high light output.

Pulse-shape discrimination (PSD) of neutron and gamma-ray events in CLYC is enabled by different time characteristics of

* Corresponding author. Tel.: +1 613 589 2456; fax: +1 613 589 2763. E-mail address: smithm@bubbletech.ca (M.B. Smith).
neutron- and gamma-induced pulses. CLYC emits visible light in the wavelength range of 250–450 nm by a variety of processes including prompt Ce\(^{3+}\) luminescence, Ce\(^{3+}\) luminescence via self-trapped excitons (STEs), and core-valence luminescence (CVL). Prompt Ce\(^{3+}\) luminescence has a typical decay time of 50 ns and Ce\(^{3+}\) STE luminescence typically has a decay time of 1 μs. The fastest of the processes (CVL, with a decay time of a few nanoseconds) only occurs under gamma-ray excitation. The absence of fast decay components under neutron excitation enables PSD with CLYC. The dual-mode (gamma-neutron) detection property of CLYC makes it an excellent candidate as a detector material for handheld radiation-detection devices.

In this work, the possibility of coupling CLYC to a small photon converter suitable for handheld spectrometers has been investigated by evaluating a number of silicon devices. Several APDs, SiPMs, and PIN photodiodes were evaluated with CLYC crystals. The performance (particularly the energy resolution and low-energy threshold) for gamma-ray and neutron sources is compared to that obtained with PMTs of various sizes. A number of properties of the photon detector which influence energy-resolution performance are considered and discussed, including the statistics of the detected photons, dark current, excess noise (in detectors with gain), and readout noise. Packaging, wrapping, and optical coupling of the scintillator to the photon detector (all considerations which strongly influence energy resolution) are also discussed.

2. Measurements and results

The evaluation of silicon photon detectors was performed using several CLYC crystals, each with dimensions 12.7 × 12.7 × 25.4 mm\(^3\). The crystals were grown by Radiation Monitoring Devices (RMD) and provided to our team as Government-furnished material by the United States Department of Homeland Security, Domestic Nuclear Detection Office. The Li component of each crystal was enriched to 95% in \(^{6}\)Li to maximize thermal-neutron detection efficiency. Crystal packaging was performed by Saint-Gobain Crystals. The crystals were polished on all sides and individually packaged into a thin aluminum housing with an epoxy interface between the crystal and a quartz optical window. For all measurements, BC-630 [14] silicone optical grease (which has an index of refraction \(n = 1.47\)) was used to couple the CLYC crystal [\(n = 1.81\) at 405 nm [15]] to the photon detector.

The energy resolution of the crystals for 662-keV gamma rays from a \(^{137}\)Cs source was determined to be in the range of 5.0–6.0% (the FWHM, determined using peak-fitting analysis software, is used as a measure of energy resolution throughout this paper) using large (2” and 3” diameter) super-bialkali (SBA) PMTs. The energy resolution obtained with these crystals using PMTs is worse than the 4% stated in Section 1. This is because the crystals used in this work were not of the highest quality, exhibiting defects such as chips, cracks, and bubbles. The performance measured with PMTs was compared to that obtained by coupling the CLYC samples to a number of APDs, SiPMs, and PIN photodiodes. The energy resolution of the crystals used does not affect the conclusions of this work because comparisons between PMTs and silicon devices were always performed using the same CLYC crystals.

A summary of the properties of the photon detectors evaluated in this work is provided in Table 1. This information was provided by the manufacturers of the devices from their web sites and by private communication. Photon converters manufactured by Detection Technology [16], Hamamatsu [17], SensL [18], and RMD [19,20] were evaluated. A summary of energy-resolution measurements performed in this work is provided in Table 2.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Device</th>
<th>Type</th>
<th>Size</th>
<th>Noise properties</th>
<th>Efficiency (%)</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamamatsu</td>
<td>R6231-100</td>
<td>PMT</td>
<td>2’ diameter</td>
<td>Dark current (-10) nA(^a)</td>
<td>(-33) (^d)</td>
<td>2.3 × 10(^7)</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>R6233-100</td>
<td>PMT</td>
<td>3’ diameter</td>
<td>Dark current (-10) nA(^a)</td>
<td>(-33) (^d)</td>
<td>2.3 × 10(^7)</td>
</tr>
<tr>
<td>RMD</td>
<td>S1315-P</td>
<td>APD</td>
<td>14 × 14 mm(^2)</td>
<td>Dark current (-1) μA</td>
<td>(-50) (^d)</td>
<td>300–1000</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>3204-08</td>
<td>PIN diode</td>
<td>18 × 18 mm(^2)</td>
<td>Dark current (-6) nA (typical); 20 nA (maximum)</td>
<td>(-15) (^e)</td>
<td>1</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>5390-18</td>
<td>PIN diode</td>
<td>10 × 10 mm(^2)</td>
<td>Dark current (-4) nA (typical); 10 nA (maximum)</td>
<td>(-27) (^e)</td>
<td>1</td>
</tr>
<tr>
<td>Detection Technology</td>
<td>PDC 100s-CR</td>
<td>PIN diode</td>
<td>10 × 10 mm(^2)</td>
<td>Dark current (-0.98) nA(^c)</td>
<td>(-15) (^e)</td>
<td>1</td>
</tr>
<tr>
<td>SensL</td>
<td>SPMArray4</td>
<td>SiPM</td>
<td>12 × 12 mm(^2)</td>
<td>Dark count rate (~8) MHz per pixel</td>
<td>(-12) (^e)</td>
<td>1 × 10(^6)</td>
</tr>
<tr>
<td>RMD</td>
<td>P011</td>
<td>SiPM</td>
<td>10 × 10 mm(^2)</td>
<td>Dark current (~100) μA(^c)</td>
<td>(-7) (^e)</td>
<td>1 × 10(^6)</td>
</tr>
</tbody>
</table>

\(^a\) After 30 min.
\(^b\) With guard ring.
\(^c\) Quantum efficiency at 400 nm.
\(^d\) Detection efficiency at 400 nm.

2.1. Avalanche photodiodes

Silicon APDs provide internal gain, fast time response, and high sensitivity in the ultraviolet to near infrared region. Electron–hole pairs, created by incident photons, are accelerated through the silicon crystal lattice by an electric field, producing secondary electrons by impact ionization. High voltage is required to create the electric field which produces the electron avalanche responsible for the device's internal gain.

The performance of CLYC with a 14 × 14 mm\(^2\) S1315-P APD [19], manufactured by RMD, is summarized in Fig. 1. These measurements were made using NIM electronics, including a spectroscopy amplifier with a shaping circuit. The electronics did not include
the capability to separate gamma-ray and neutron events using PSD. The optimal energy resolution for CLYC with a PMT is usually obtained using long shaping times, typically 4 \( \mu s \) or more, because of CLYC's long decay components. However, the characteristics of silicon devices typically necessitate the use of shorter shaping times in order to minimize undesirable noise contributions. Selecting a shaping time for each measurement therefore involves a balance between integrating a substantial fraction of the output signal and reducing noise.

For the room-temperature (22 \(^\circ\)C) measurements with the APD, the high voltage and shaping time were varied in order to optimize performance. Various bias settings were used from 1710 V to 1820 V, with shaping times ranging from 0.25 \( \mu s \) to 2 \( \mu s \). The optimal performance was found using 0.25 \( \mu s \) shaping (Fig. 1(a)) with a bias of 1800 V. Using these settings, the energy resolution for 662-keV gamma rays from \(^{137}\)Cs was determined to be 12.0% at 22 \(^\circ\)C. For comparison, the energy resolution of this crystal was determined to be 6.0% at 662 keV using a 3\( "\) diameter Hamamatsu R6233-100 SBA PMT and NIM electronics with a shaping time of 4 \( \mu s \) and bias voltage of 900 V.

When the APD was cooled to \(-20 \, ^{\circ}\)C, the best energy resolution was determined for a shaping time of 1 \( \mu s \) and bias of 1680 V. The APD has better noise properties when cooled, making it possible to use a longer shaping time than at room temperature. At \(-20 \, ^{\circ}\)C, the energy resolution was measured as 9.4% at 662 keV (Fig. 1(b)). The APD energy resolution is improved at \(-20 \, ^{\circ}\)C because the APD gain increases (for a given bias) at lower temperatures, and because the leakage current (which is the dominant noise source) decreases. In combination, this increases the signal-to-noise and improves the energy resolution. The 662-keV peak appears at a higher channel number in Fig. 1(b) than in Fig. 1(a) because of the longer shaping time used, and because the APD gain increases at lower temperature. The electronic gain for the two measurements was the same. The low-level discriminator was adjusted in each measurement to keep the dead time reasonably low. Because of the higher APD gain and the longer shaping time used to perform the measurement at \(-20 \, ^{\circ}\)C, the discriminator threshold was higher for this measurement than for the measurement at room temperature. The electronic gain was not the same for the gamma-ray and neutron measurements. The electronic gain was the same for the gamma-ray measurements (panels (a) and (b)), but was different for the gamma-ray and neutron measurements presented in panels (c) and (d).

### Table 2

Summary of energy-resolution measurements performed in this work.

<table>
<thead>
<tr>
<th>Photon detector</th>
<th>Type</th>
<th>Readout electronics</th>
<th>Shaping time or integration time (( \mu s ))</th>
<th>Special conditions</th>
<th>Resolution (FWHM) for 662 keV (%)</th>
<th>Resolution (FWHM) for thermal neutrons (GEE (\sim)3.2 MeV) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamamatsu R6231-100</td>
<td>PMT</td>
<td>Custom BTI</td>
<td>2</td>
<td></td>
<td>6.0</td>
<td>Not measured</td>
</tr>
<tr>
<td>Hamamatsu R6233-100</td>
<td>PMT</td>
<td>Standard NIM</td>
<td>4</td>
<td></td>
<td>6.0</td>
<td>4.3</td>
</tr>
<tr>
<td>RMD S315-P</td>
<td>APD</td>
<td>Standard NIM</td>
<td>0.25</td>
<td>Cooled to (-20 , ^{\circ})C</td>
<td>12.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Hamamatsu 3204-08</td>
<td>PIN diode</td>
<td>Standard NIM</td>
<td>4</td>
<td>No photo-peak</td>
<td>9.4</td>
<td>3.5</td>
</tr>
<tr>
<td>Hamamatsu S3590-18</td>
<td>PIN diode</td>
<td>Standard NIM</td>
<td>0.5</td>
<td>No photo-peak</td>
<td>13.8</td>
<td></td>
</tr>
<tr>
<td>Detection Technology</td>
<td>PIN diode</td>
<td>Standard NIM</td>
<td>4</td>
<td>No photo-peak</td>
<td>17.0</td>
<td></td>
</tr>
<tr>
<td>Sensl SiPMArray4</td>
<td>SiPM</td>
<td>Standard NIM</td>
<td>1</td>
<td>With 2-mm wavelength shifter</td>
<td>No photo-peak</td>
<td>33.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>With 4-mm wavelength shifter</td>
<td>No photo-peak</td>
<td>34.7</td>
</tr>
<tr>
<td>RMD P011</td>
<td>SiPM</td>
<td>Standard NIM</td>
<td>1</td>
<td>No photo-peak</td>
<td>13.9</td>
<td></td>
</tr>
</tbody>
</table>

![Fig. 1. Spectra recorded using a RMD APD with CLYC. Panel (a) shows a \(^{137}\)Cs spectrum collected at 22 \(^\circ\)C and panel (b) shows a \(^{137}\)Cs spectrum collected at \(-20 \, ^{\circ}\)C. The 662-keV peak is labeled with its energy. The peak indicated by “Pulser” arises from a test pulser. Panels (c) and (d) present data for an AmBe source at (c) 22 \(^\circ\)C and (d) \(-22 \, ^{\circ}\)C. The thermal-neutron peak is indicated by “Thermal” in these panels. Note that the electronic gain was the same for the gamma-ray measurements (panels (a) and (b)), but was different for the gamma-ray and neutron measurements. The electronic gain was not the same for the two neutron measurements presented in panels (c) and (d).](image-url)
temperature. While cooling the system reduces the effects of noise in the APD and improves the energy resolution for gamma rays, the performance of the APD with CLYC is still considerably worse than that obtained with a PMT.

For thermal neutrons, which have GEE of approximately 3.2 MeV, the energy resolution was determined to be 4.5% at 22 °C (Fig. 1(c)) and 3.5% at −22 °C (Fig. 1(d)). These energy-resolution results (and all thermal-neutron energy-resolution results reported in this work) were determined by fitting the thermal-capture peak in the total (gamma-ray and neutron) energy spectrum. A moderated AmBe source was used to produce thermal neutrons. These measurements were performed using the same CLYC crystal and the same electronics as used for the gamma-ray measurements. However, it should be noted that the gain of the electronics was different for the gamma-ray and neutron measurements, and was different for the two neutron measurements at different temperatures. The energy resolution for thermal neutrons was measured as 4.3% for this CLYC crystal coupled to the R6233-100 PMT with a shaping time of 4 μs. The performance with the APD is only slightly worse than that with a PMT at room temperature, and better than the PMT performance at −22 °C. The APD has superior energy resolution to the PMT when cooled to −22 °C because, for the high light output of thermal neutrons, the APD has better signal-to-noise than the PMT. This is due to the higher detection efficiency of the APD (Table 1) and because cooling reduces the APD’s dark-current noise and increases the APD gain. While gamma-ray spectroscopy using CLYC with this APD would be difficult, there is some potential for using this type of device for thermal-neutron detection.

2.2. PIN photodiodes

A PIN photodiode is similar to a PN junction but features a larger depletion region because of an intrinsic area between the n-type and p-type semiconductors. The voltage required to operate a PIN photodiode is low, but the device does not have internal gain. PIN photodiodes have good sensitivity to photons with wavelengths around 1 μm, which drops as the wavelength decreases into the visible region.

Several PIN photodiodes (each of thickness ~1 mm) have been evaluated using a 12.7 × 12.7 × 25.4 mm² CLYC crystal. The energy resolution of this crystal (different from the crystal used in the APD evaluation) was determined to be 6.0% for 662-keV gamma rays using a 2″-diameter Hamamatsu R6231-100 PMT with a SBA photocathode. This measurement used custom electronics, developed by Bubble Technology Industries (BTI), based on a gated-integrator circuit with a 2-μs integration time.

The PIN-diode measurements used NIM electronics (without PSD) with a fast-spectroscopy amplifier. The bias voltage, electronic gain, and shaping time were varied in an attempt to minimize noise and optimize the CLYC response to both neutrons and gamma rays. Data collected with an 18 × 18 mm² Hamamatsu 3204-08 PIN photodiode (with a shaping time of 4 μs) are shown in Fig. 2. It is known that PIN photodiodes are sensitive to low energy gamma and X-rays, through direct interactions (without a scintillator). In some cases, these interactions can interfere with the spectrum collected by a scintillator crystal coupled to the device. Fig. 2(a) shows the spectrum collected for a 241Am source with the bare PIN diode. The peak around channel 200 in the spectrum is due to 60-keV gamma rays from 241Am decay interacting directly with the PIN diode. Fig. 2(b) presents a spectrum of 241Am with the CLYC crystal mounted to the PIN diode. This is similar to the spectrum for the bare photodiode, although the direct response of the PIN diode to 60-keV gamma rays is lower because of shielding by the CLYC crystal. The similarity of the two spectra illustrates the interference of the bare-diode response with the CLYC response. The response of CLYC to the low-energy 241Am gamma rays is not observable in Fig. 2(b) because it is below the noise threshold of the measurement.

Fig. 2(c) shows a spectrum due to 60Co for the CLYC crystal coupled to the PIN photodiode. Data for 137Cs were also collected, but are not presented here because the response to this source was barely visible. While there is an observable response to the 60Co gamma rays, evidenced by counts above channel 100 in the spectrum, the photon-detection efficiency of the PIN photodiode is insufficient to create clear photo-peaks in the energy spectrum. Consequently, no energy-resolution measurement is provided for 137Cs or 60Co. Fig. 2(d) shows the thermal-neutron spectrum from a moderated PuLi source recorded by CLYC with the PIN diode. For the PuLi source, a peak was observed (indicated by “Thermal” around channel 320 in the spectrum) and the energy resolution for thermal neutrons was measured to be 9.5%.

Similar results were obtained using the Hamamatsu S3590-18, and the Detection Technology PDC 100s-CR. Both these PIN diodes have 10 × 10 mm² active area. The energy resolution measured for thermal neutrons with CLYC coupled to the S3590-18 device was 13.8% using a shaping time of 0.5 μs. For CLYC mounted to the PDC 100s-CR device, energy resolution of 17.0% was determined for thermal neutrons (with a shaping time of 4 μs). The energy resolution measured with the PIN photodiodes is worse than that measured using a PMT because the PIN diode exhibits a worse signal-to-noise ratio. The PIN diode is inherently noisier than the PMT and has no internal gain. Both these factors decrease the signal-to-noise of the PIN diode and degrade the observed energy resolution. The PIN photodiodes evaluated show little promise for 100s-CR device, energy resolution of 17.0% was determined for 241Am with the CLYC crystal mounted to the PIN diode. This is similar to the spectrum for the bare photodiode, although the direct response of the PIN diode to 60-keV gamma rays is lower because of shielding by the CLYC crystal. The similarity of the two spectra illustrates the interference of the bare-diode response with the CLYC response. The response of CLYC to the low-energy 241Am gamma rays is not observable in Fig. 2(b) because it is below the noise threshold of the measurement.

Fig. 2(c) shows a spectrum due to 60Co for the CLYC crystal coupled to the PIN photodiode. Data for 137Cs were also collected, but are not presented here because the response to this source was barely visible. While there is an observable response to the 60Co gamma rays, evidenced by counts above channel 100 in the spectrum, the photon-detection efficiency of the PIN photodiode is insufficient to create clear photo-peaks in the energy spectrum. Consequently, no energy-resolution measurement is provided for 137Cs or 60Co. Fig. 2(d) shows the thermal-neutron spectrum from a moderated PuLi source recorded by CLYC with the PIN diode. For the PuLi source, a peak was observed (indicated by “Thermal” around channel 320 in the spectrum) and the energy resolution for thermal neutrons was measured to be 9.5%.

Similar results were obtained using the Hamamatsu S3590-18, and the Detection Technology PDC 100s-CR. Both these PIN diodes have 10 × 10 mm² active area. The energy resolution measured for thermal neutrons with CLYC coupled to the S3590-18 device was 13.8% using a shaping time of 0.5 μs. For CLYC mounted to the PDC 100s-CR device, energy resolution of 17.0% was determined for thermal neutrons (with a shaping time of 4 μs). The energy resolution measured with the PIN photodiodes is worse than that measured using a PMT because the PIN diode exhibits a worse signal-to-noise ratio. The PIN diode is inherently noisier than the PMT and has no internal gain. Both these factors decrease the signal-to-noise of the PIN diode and degrade the observed energy resolution. The PIN photodiodes evaluated show little promise for the CLYC response. The response of CLYC to the low-energy 241Am gamma rays is not observable in Fig. 2(b) because it is below the noise threshold of the measurement.
gamma-ray spectroscopy with CLYC. However, like the APD, they could be used with CLYC in systems for thermal-neutron detection.

2.3. Silicon photomultipliers

The SiPM is an array of many small APDs operated in Geiger mode. These devices provide high gain ($\sim 10^6$) with low operating voltage and have good sensitivity to light with wavelengths around 500 nm. The efficiency for the wavelengths of CLYC emissions is lower than at 500 nm, as presented in Table 1.

A SPMArray4 SiPM, manufactured by SensL, was evaluated with the same NIM electronics used for the PIN-diode measurements. The SPMArray4 is a $4 \times 4$ array of $3 \times 3$ mm$^2$ pixels. Each pixel consists of many Geiger-mode APDs with only 200 μm dead space between pixels. All 16 elements were summed together by connecting the individual output pins to one wire. Parameters such as the shaping time, bias voltage, and electronic gain were varied, in order to optimize performance.

The response of CLYC with the SPMArray4 is presented in Fig. 3. A shaping time of 1 μs was used for the measurements depicted. As for the PIN diode, there is some response to $^{60}$Co (Fig. 3(b)) when compared to the background spectrum shown in the top panel. However, there is not enough light collected to produce clear photo-peaks in the spectrum, and so an energy-resolution measurement was not possible. The $^{137}$Cs response was also investigated but was less pronounced than that of $^{60}$Co. The PuBe spectrum (lower panel) exhibits a peak, labeled with “Thermal”, and the energy resolution was determined to be 33.3% for thermal neutrons.

An attempt was made to improve the detection efficiency of the SiPM by placing BC-482A wavelength-shifting material between the CLYC crystal and the SiPM. Two different thicknesses of BC-482A material (2 mm and 5 mm) were used, both having the same dimensions as the SiPM (approximately $15 \times 15$ mm$^2$). Optical grease (BC-630) was used on each side of the BC-482A layer, but no reflective material was placed around the wavelength-shifting material. BC-482A [14] is an organic polymer with a decay time of 12 ns, a light-attenuation length of 400 cm, density of 1.03 g/cm$^3$, and refractive index of 1.59. Its absorption peak is at 420 nm (close to the wavelength of maximum emission of CLYC) and its emission occurs at 540 nm (where the efficiency of the SiPM is high). Data recorded with a PuLi source, without the wavelength shifter and with the 2-mm and 5-mm layers, are presented in Fig. 4. The peak due to thermal-neutron capture is apparent in all three spectra. No improvement in the energy-resolution performance was observed using the wavelength shifter. The energy resolution for thermal neutrons degraded slightly to 34.7%, with 2 mm of BC-482A, and to 35.2% with the 5-mm wavelength shifter. Furthermore, the thermal-neutron peak moves to a lower channel in the spectrum as wavelength-shifting material is added. Both the degraded energy resolution and the movement of the peak to lower channels are interpreted as being due to light losses (absorption and reflection) caused by introducing the wavelength-shifting layer.

A P011 SiPM manufactured by RMD [20] was also evaluated with CLYC. This device is a $2 \times 2$ array of $5 \times 5$ mm$^2$ pixels (similar to the SPMArray4) with overall dimensions $10 \times 10$ mm$^2$. For the RMD SiPM measurements, a $12.7 \times 12.7 \times 25.4$ mm$^3$ CLYC crystal was cut in half and further processed to produce two $9 \times 9 \times 10$ mm$^3$ crystals. These smaller crystals provided a better match to the dimensions of the SiPM. NIM electronics were employed with a 1-μs shaping time. Under these conditions, energy resolution of 13.9% was measured for thermal neutrons from AmBe. The performance of SiPMs with CLYC is approximately equivalent to that of the APDs and PIN photodiodes. The SiPM devices could be used with CLYC in thermal-neutron detectors, but show little promise for spectroscopic gamma-ray measurements at the present time.

3. Conclusion

It is concluded that none of the silicon devices evaluated are suitable to replace PMTs in spectrometers which aim to use CLYC for dual gamma-ray and neutron detection. This is primarily because the
energy-resolution performance, particularly for gamma rays, is inferior to that obtained with a PMT (see Table 2). Furthermore, the low-energy threshold for resolving gamma and X-rays is higher with these silicon devices than it is with a PMT. The performance of the silicon photon detectors (in comparison to PMTs) can be explained by the properties of the silicon devices and those of CLYC.

Some of the silicon devices evaluated have relatively low photon-detection efficiency at 400 nm, which is the typical wavelength of CLYC light emissions. All of the silicon detectors are considerably noisier than the PMT. These issues are compounded by the properties of CLYC, particularly the relatively low light output and long decay times. Other scintillators, such as LaBr₃, which have shown better performance with silicon devices, emit light with similar wavelengths to CLYC emissions. However, LaBr₃ is a considerably brighter scintillator than CLYC and its decay is faster. These properties of LaBr₃ help to overcome the detection efficiency and/or noise issues of silicon devices.

None of the silicon devices evaluated provide the gamma-ray spectroscopy performance required for handheld spectrometers based on CLYC scintillator material. However, it might be possible to use CLYC with some of these devices in a system designed to detect thermal neutrons. Such a system would need to take advantage of the excellent PSD offered by CLYC. The PSD performance of CLYC with silicon devices was not investigated in this work, because the measurements presented are sufficient to conclude that the devices evaluated are not suitable for a handheld gamma-ray and neutron spectrometer using CLYC. However, data on PSD performance would be an important part of any future assessment of the viability of a photon detector to be used with CLYC. Future improvements to silicon photon detectors are anticipated, in particular increasing their sensitivity to lower wavelengths where possible. These enhancements may increase the viability of silicon devices for dual-mode detection with CLYC.

Acknowledgments

This work has been supported by the US Department of Homeland Security, Domestic Nuclear Detection Office, under competitively awarded Contract HSHQDC-10-C-00178. This support does not constitute an express or implied endorsement on the part of the Government.

References
