APPLICATIONS OF SILICON PHOTOMULTIPLIERS IN PERSONAL RADIATION DETECTION AND NUCLEAR IMAGING

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Jamie Sanchez-Fortun Stoker, candidate for the degree of Master of Science in Physics, has presented a thesis titled, Application of Silicon Photomultipliers in Personal Radiation Detection and Nuclear Imaging, in an oral examination held on September 15, 2015. The following committee members have found the thesis acceptable in form and content, and that the candidate demonstrated satisfactory knowledge of the subject material.

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Abstract

Originally developed as the readout for calorimeters in high-energy physics experiments, the silicon photomultiplier (SiPM) has found use in a wide range of fields requiring the detection of low-intensity light. This thesis discusses work on two such applications: in the development of a prototype personal radiation detector (PRD), and in the imaging of a radioactive source.

The ability to detect above-background levels of radiation has received increased attention in recent years, not least from the perspective of national security agencies in, for example, tracking the movement of illicit radioactive materials, or in dealing with potential fall-out from nuclear accidents. In such potentially hazardous environments, there has been an increased demand for improved PRDs for use by emergency workers and first-responders. Motivated by an NSERC-funded partnership with Environmental Instruments Canada Inc. (EIC), the first part of this thesis focuses on a project to develop a small, low-cost, easy-to-use prototype gross-counting gamma-radiation detector based upon SiPM technology. Limited by size and cost requirements, measurements suggested the Hamamatsu S12572-050C model ($3 \times 3 \text{ mm}^2$) as the preferred choice of SiPM, and subsequent work tested several SiPM/light-producing medium combinations. A PTFE (teflon)-wrapped common plastic scintillator
(BC-416), coupled to the SiPM, was identified as the medium providing the most significant sensitivity enhancement with respect to EIC’s existing detection device (incorporating a Geiger-Müller tube as its photosensor), while minimising cost and maintaining the overall physical size of EIC’s detector. An additional project positively assessed the suitability of SiPMs for thermal neutron detection using scintillating fibres coated in successive layers of zinc sulphide and boron carbide.

The second part of this thesis (funded through the Sylvia Fedoruk Centre for Nuclear Innovation) presents a preliminary characterisation of two SensL MatrixSM-9 SiPM array modules, in preparation for their use in a “PhytoPET” plant-imaging system to be built at the University of Regina. Such arrays of SiPMs are now available commercially as part of modular, turnkey readout systems designed specifically for use in high-resolution, state-of-the-art medical-imaging applications. However, PET systems designed to image plants – such as the (operational) PhytoPET system based at Duke University – typically utilise multi-anode photomultiplier tubes. Singles measurements are reported for each SiPM array, coupled in turn to a PTFE-wrapped BC-416 plastic scintillator in several configurations. Pixelated images of noise and various laboratory sources are reconstructed from output data files using dedicated codes, and the array-trigger error of each module is mapped over a wide-range of adjustable array and pixel thresholds.
Acknowledgments

I am immensely grateful to my co-supervisors, Dr. Zisis Papandreou and Dr. Andrei Yu. Semenov, not only for providing me with the opportunity to come to the University of Regina, but also for all of their subsequent help, guidance and advice over the past two years. Many thanks go to Mr. Tegan Beattie for all of his efforts – and patience – in helping me to become more familiar with the equipment found in the SPARRO Group’s Detector Development Laboratory. I would also like to acknowledge both the Natural Sciences and Engineering Research Council of Canada and the Sylvia Fedoruk Canadian Centre for Nuclear Innovation for the financial support I received.

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I am very thankful to members of the SPARRO Group for their discussions and advice, as well as Mr. Derek Gervais for his help in preparing the plastic and PEN scintillators, and Mr. Keith Wolbaum for his electronics expertise. Special thanks go to the summer students who,
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Finally, I’d like to thank my family: my wife, Katrina, for her continued love and encouragement throughout this endeavour, as well as our parents – Shirley and Mike Gibson, and Gerrie and Ken Johnson – for all their prayers, love and support.
For God so loved the world that he gave his one and only Son, that whoever believes in him shall not perish but have eternal life.

John 3:16

For my darling wife, Katrina Louise.
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Chapter 1

Introduction

Over the past decade, the silicon photomultiplier (SiPM\textsuperscript{1}) has emerged as a competitive alternative to traditional radiation detectors such as the photomultiplier tube (PMT) in the detection of low-level light. While possessing many of the properties common to the PMT, such as a high gain ($\sim 10^{5}$–$10^{7}$) \cite{1} and short dead time, the SiPM provides several technical advantages which make it preferable to the PMT in a number of fields. For example, as well as having a low power consumption, low operational voltage ($\sim 20$-60 V \cite{2}) and a virtual immunity to tesla-level magnetic fields up to $\sim 5$ T \cite{2}, the SiPM is a relatively compact device, its small dimensions allowing for a robust design and high granularity.

Initially developed for use in the calorimeters of high-energy physics experiments \cite{3–7}, the SiPM has evolved as the photosensor of choice in many ongoing experimental tests of

\textsuperscript{1}The SiPM (or SPM) is also referred to in the literature by a variety of acronyms, often to provide for distinction between various manufacturers. They are known alternatively as the avalanche photodiode (APD), Geiger-mode avalanche photodiode (GAPD, G-APD, GMAP or GM-APD), Multipixel Photon Counter (MPPC, synonymous with Hamamatsu’s device), micro-channel APD (MAPD), Dead-space-modified avalanche photodiode (DAPD), Metal-resistor-semiconductor (MRS), Pixelated Geiger-mode avalanche photodiode (PPD), Solid-state photomultiplier (SSPM), Single-photon avalanche photodiode (SPAD), AMPP and Hybrid avalanche photodetector (HAPD).
fundamental physics. There is considerable interest in the cryogenic properties of SiPMs immersed in liquid N$_2$ [8–11], He [10, 12], Ar [13–18] and Xe [19]. At such temperatures the single-photon resolution required in, for example, dark-matter searches [19–21] and double-beta decay experiments searching for the majorana neutrino [21, 22], can be achieved.

The SiPM has also found applications in a wide variety of disciplines, ranging from nuclear-waste management [23] and safety in fission reactors (in the detection of thermal neutrons around the reactor core [24]), to geophysics (in the muon radiography of Mount Vesuvius [25–27]), the telecommunication industry [28], military and food safety. As a result of the 2011 nuclear disaster at Fukushima Daiichi, the LANFOS$^3$ radiation-detection system [29] (employing a SiPM) has been developed, a prototype device intended for commercial use, prompted by mounting concern in the Japanese islands over the level of $^{137}$Cs in foodstuffs.

Lidar is a remote-sensing technology which measures the distance to a target by illuminating it with a laser beam and analysing the reflected light. SiPMs have been employed in studies of the terrestrial atmosphere [30, 31], as well as in the tracking of space debris [32, 33], satellites [34] and the Moon [32], and in the automotive industry [35].

In astrophysics, SiPMs have been used in high-speed photometry [36]. Significant attention has been given to several terrestrial- [37–39] and space-based [40, 41] astroparticle experiments designed to detect photons from galactic and extragalactic gamma-ray sources in deep space. For example, the FACT telescope$^4$ is the first Čerenkov telescope [42–45] equipped with a camera incorporating SiPMs, and is used in the monitoring of, for example, highly en-
ergetic (TeV) blazars (very compact quasars) associated with supermassive black holes at the centre of giant elliptical galaxies.

Recent developments in imaging systems used in nuclear medicine, such as PET, MRI and SPECT, as well as time-of-flight PET [50–54] and hybrid multi-modal systems such as PET/MRI [55–65], are dominated by advances in solid-state photodetectors such as the SiPM [66]. In addition to systems for use in human and small-animal patients, PET scanners using position-sensitive PMTs have been developed to image plants [67–71]. Applications of the “next generation” of SiPMs – so-called digital silicon photomultipliers [72–81] – to medical imaging has been the subject of intense investigation by several groups (see, for example, references [52, 82–101].

Technological advances including the SiPM are of interest in biophotonics, with increasingly miniaturised biodiagnostic devices becoming available for use in both clinical [102] and extra-clinical “point-of-care” settings [103]. For example, Mester et al. [102] have utilised SiPMs in a handheld probe for β+-emitting radiotracer detection in operating theatres, while Renna et al. [103] have evaluated a SiPM in a device for implementing integrated fluorescence-based microarrays, which are of use in DNA sequencing and as protein biomarkers in fields such as oncology and pathogen detection.

Over the past decade, the silicon photomultiplier has found commercial use in areas of homeland security such as threat detection (for example, in neutron and gamma detection in cargo scanners [104, 105]) and nuclear hazards [106]. In a 2013 request for information (RFI),

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1Positron emission tomography (PET) [46, 47], Magnetic Resonance Imaging (MRI) [48] and Single-photon emission computed tomography (SPECT) [49] are all well-known imaging modalities used in modern nuclear medicine. A brief overview of PET is given in Section 4.1.

and a subsequent Broad Agency Announcement through its SIGMA Program, the Defense Advanced Research Projects Agency (DARPA) – an agency of the United States Department of Defense – publicly solicited for innovative approaches to the development of inexpensive, mass-producible, high-efficiency, packaged radiation detectors for identifying hidden nuclear and radiological threats. Such an initiative clearly demonstrates the requirement for new personal radiation detector (PRD) technologies. Portable, hand-held radiation detectors – for use by first responders in potentially hazardous environments – have been available commercially for many years. However, the SiPM is beginning to supersede existing radiation sensors used in such devices.

In this thesis, applications of SiPMs are considered in the development of PRDs and in nuclear imaging. Both projects advertise positive links between the SPARRO Group at the University of Regina and other organisations within Saskatchewan.

An NSERC-funded partnership with Environmental Instruments Canada Inc. (EIC), provided an opportunity to advance the development of a low-cost, rugged, small, unobtrusive, easy-to-use prototype PRD based on SiPMs, incorporating a wireless Bluetooth connection.

A second project, funded through the Sylvia Fedoruk Canadian Centre for Nuclear Innovation, uses arrays of SiPMs, available as part of modular, turnkey readout systems described...
signed for use in high-resolution, state-of-the-art medical imaging systems. As a precursor to
the development of a plant-imaging PET program (using SiPMs as the photodetector) at the
University of Regina, results of singles measurements are presented in the imaging of a $^{90}\text{Sr}$
source using two such SiPM array modules coupled to a plastic scintillator.

In Chapter 2 the theory, properties and operation of the silicon photomultiplier are dis-
cussed, before a presentation of the results of the PRD and nuclear-imaging projects in Chap-
ters 3 and 4, respectively. Conclusions of this work are given in Chapter 5.
Chapter 2

Theory & Operation of the Silicon Photomultiplier

While the mechanisms underlying the theory of the photodetector can be traced back to the quantum hypothesis of Planck [108, 109] and the explanation of the photoelectric effect by Einstein [110], the first experimental photodetectors included those of Smith [111], in demonstrating photoconductivity in selenium, Hertz [112] (in the first demonstration of the photoelectric effect) and Thomson [113, 114] (in the discovery of the electron). The past 120 years or so has seen a significant development of increasingly sensitive and more efficient detectors for use in nuclear and particle physics. All such devices operate on same basic principle: a transfer of part/all of the particle’s energy to the detector, which converts it into some measurable property,¹ which constitutes a detection event. Here, the focus is on scintillating detectors, in which the excitation/ionisation of a scintillating material by the incident particle results in the emission of a photon, which is directed into the detector.

¹For example, the electrical resistance of Se in the case of Smith’s experiment, and luminosity in Thomson’s.
Modern photodetectors are electronic devices which, upon the detection of an incident photon, generate an electrical output which is then passed to a data acquisition (DAQ) system. Naturally, the development of photosensors – and their associated electronics and DAQ systems – as well as scintillators have benefited greatly from the significant technological improvements of the past several decades. Advances in the hardware and software capabilities of modern computer systems have had a profound impact on DAQ systems and data analysis, while a new generation of crystal scintillators with good energy-deposition, time-resolution and relatively large light outputs have become available. For example, cerium-doped, silicate-based inorganic scintillators such as Lutetium oxyorthosilicate (LSO) and Lutetium-yttrium oxyorthosilicate (LYSO) are now in widespread use in the medical industry, offering desirable properties such as high stopping power, fast decay time and high light yield (see Table 2.1).

Since its inception in 1935, the PMT was almost unrivalled as the photodetector of choice in most applications. However, significant advances in semiconductor design and manufacture over the past forty years have resulted in solid-state detectors such as the avalanche photodiode, and more recently the silicon photomultiplier. Based upon thin silicon wafers, solid-state technology has enabled photosensors to be developed which, while retaining many of the desirable properties of the PMT, offer additional advantages such as much smaller dimensions and lower cost.

Here, the semiconductor diode – which forms the basis of the SiPM – is considered initially, before discussing the operation and properties of the silicon photomultiplier itself.
<table>
<thead>
<tr>
<th>Inorganic</th>
<th>Light yield (x 10^3 ph./MeV)</th>
<th>Peak emission (nm)</th>
<th>Density (g/cm³)</th>
<th>Refractive index</th>
<th>Decay constant (ns)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGO</td>
<td>2.66-4.56</td>
<td>480</td>
<td>7.13</td>
<td>2.15</td>
<td>300</td>
<td>Bismuth Germanate (Bi₄Ge₃O₁₂)</td>
</tr>
<tr>
<td>LaBr₃</td>
<td>63 [120]</td>
<td>380 [120]</td>
<td>5.29 [120]</td>
<td>~ 2.06 [120]</td>
<td>26 [120]</td>
<td>Lanthanum bromide</td>
</tr>
<tr>
<td>LFS</td>
<td>30.4-32.3</td>
<td>425</td>
<td>7.35</td>
<td>1.81</td>
<td>33</td>
<td>Lutetium Fine Silicate</td>
</tr>
<tr>
<td>LSO</td>
<td>15.2-28.5</td>
<td>420</td>
<td>7.4</td>
<td>1.82</td>
<td>40</td>
<td>Lutetium oxyorthosilicate (Lu₂SiO₅(Ce))</td>
</tr>
<tr>
<td>LYSO</td>
<td>26.6-30.4</td>
<td>420</td>
<td>7.1</td>
<td>1.81</td>
<td>41</td>
<td>Lutetium-yttrium oxyorthosilicate (Lu₂(1-x)Y₃xSiO₅(Ce))</td>
</tr>
<tr>
<td>GAGG</td>
<td>48 [121]</td>
<td>520 [121]</td>
<td>6.63 [121]</td>
<td>N/A</td>
<td>88 [121]</td>
<td>Gadolinium aluminium gallium garnet (Gd₃(Al₁₋ₓGaₓ)₂O₁₂(Ce))</td>
</tr>
<tr>
<td>NaI</td>
<td>38</td>
<td>415</td>
<td>3.67</td>
<td>1.85</td>
<td>230</td>
<td>Sodium iodide (NaI(Tl))</td>
</tr>
<tr>
<td>ZnS</td>
<td>49.4</td>
<td>450</td>
<td>4.09</td>
<td>2.36</td>
<td>110</td>
<td>Zinc sulphide (ZnS(Ag))</td>
</tr>
</tbody>
</table>

Table 2.1: Physical properties of some common inorganic scintillators of interest in this thesis. Data for BGO, LFS, LSO, LYSO and NaI is from the white paper Zecotek Lutetium Fine Silicate (LFS) Scintillation crystals: Enabling the Future of Imaging and Detection, produced by Zecotek Photonics Inc. (http://www.zecotek.com/media/LFS%20White%20Paper.pdf), while that of ZnS is from the ZnS(Ag) Zinc Sulfide Scintillation Material data sheet produced by Saint-Gobain (http://www.hep.ph.ic.ac.uk/fets/pepperpot/docs+papers/zns_602.pdf). The refractive index stated for LaBr₃ is an average value based upon calculations given in Ilitis et al. [120]. Scintillators such as NaI are strongly hygroscopic (i.e., absorb moisture from the surrounding environment, thus damaging the scintillator) while LaBr₃ is very hygroscopic and CsI is only slightly so. The remaining scintillators are non-hygroscopic.
<table>
<thead>
<tr>
<th></th>
<th>Light yield ($10^3$ ph./MeV)</th>
<th>Peak emission (nm)</th>
<th>Density (g/cm$^3$)</th>
<th>Refractive index</th>
<th>Decay constant (ns)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BC-408</td>
<td>10</td>
<td>434</td>
<td>1.032</td>
<td>1.58</td>
<td>2.1</td>
<td>PVT-based common plastic scintillator</td>
</tr>
<tr>
<td>BC-416</td>
<td>6.6</td>
<td>434</td>
<td>1.032</td>
<td>1.58</td>
<td>4</td>
<td>PVT-based common plastic scintillator</td>
</tr>
<tr>
<td>LAB</td>
<td>13.05</td>
<td>425</td>
<td>0.87</td>
<td>1.47</td>
<td>3.5</td>
<td>Linear alkylbenzene (liquid); $\text{C}_6\text{H}_5\text{C}<em>n\text{H}</em>{2n+1}$; $(n = 10 - 16)$</td>
</tr>
<tr>
<td>PEN</td>
<td>10.5 [122]</td>
<td>425 [122]</td>
<td>1.33 [122]</td>
<td>1.65 [122]</td>
<td>N/A</td>
<td>Poly(ethylene-2,6-naphthalene dicarboxylate); $(\text{C}<em>{14}\text{H}</em>{10}\text{O}_4)_n$</td>
</tr>
</tbody>
</table>

Table 2.2: Physical properties of some common organic scintillators of interest in this thesis. Unless otherwise stated, the data is from the Saint-Gobain Crystals data sheet [http://www.crystals.saint-gobain.com/uploadedFiles/SG-Crystals/Documents/SGC%20BC400-404-408-412-416%20Data%20Sheet.pdf].
2.1 The Semiconductor Diode

It is well known that the electrical conductivity of an intrinsic semiconductor can be modified by the introduction of dopant materials, enabling $n$-type (that is, electron-rich, hole-deficient) and $p$-type (hole-rich, electron-deficient) semiconductors and compound devices, such as diodes and transistors, to be produced. The initial formation of a $p$-$n$ junction, in the region between the $p$- and $n$-type materials, is accompanied by a rapid diffusion of oppositely charged carriers towards the opposing region: conduction-band electrons (holes) from the $n$-doped ($p$-doped) region diffuse into the $p$-doped ($n$-doped) region adjacent to the boundary, leaving behind immobile positive (negative) ions. In both regions there is a recombination of electrons and holes, and a steady-state is quickly reached in which further diffusion of charge carriers is inhibited by the intrinsic electric field, \( \vec{E} \), created by the oppositely charged ions. The net effect is an insulating region in the vicinity of the junction, known as the \textit{depletion layer}, in which there is an absence (or depletion) of mobile charge carriers (Figure 2.1.1a).

The behaviour of a semiconductor diode in a circuit is characterised by its current-voltage ($I$-$V$) dependence, the shape of the corresponding $I$-$V$ curve being determined by the mobility of charge carriers through the depletion region. While the \textit{zero bias} voltage $\Delta V = E\Delta x$ across the $p$-$n$ junction (in which $\Delta x$ is the width of the depletion layer) is intrinsic to the diode, an externally applied \textit{forward bias} or \textit{reverse bias} may be used to control the current output (Figure 2.1.1b). In the former, the applied bias $\Delta V > 0$ V generates a field $\vec{E}_f$ opposing $\vec{E}$: as $\Delta V$ is increased, the depletion layer is reduced and the electrical resistance of the diode decreases, allowing a (forward) current of majority charge carriers (electrons and holes) to flow freely.

Semiconductor diodes are more commonly operated using reverse bias ($\Delta V < 0$ V), in
**Figure 2.1.1:** A typical p-n junction. (a) The operation of the junction in thermal equilibrium with zero applied bias voltage. Upper: schematic of the p-n junction, showing how the carrier concentrations vary with distance across the diode. The blue and red lines indicate the electron and hole concentrations, respectively, whereas the grey regions are neutrally charged. Within the space-charge (or depletion) region in the vicinity of the p-n boundary, the light-red and light-blue areas indicate regions of positive and negative charge, respectively. Lower: sketch graphs of the charge, electric field and voltage across the diode. (b) the “full” I-V curve of a p-n junction. Regions of the graph in which $V > 0 \text{ V}$ and $V_{br} < V < 0 \text{ V}$ are referred to as “forward bias” and “reverse bias”, respectively, while the diode breaks down when $V \leq V_{br}$ (see text). $I_s$ is the reverse-bias saturation current. In the SiPM, the I-V behaviour of the diode operating in reverse-bias and breakdown modes is of singular interest. Both figures from *Wikipedia: The Free Encyclopedia*. 
which $\vec{E}$ is enhanced by the applied electric field $\vec{E}_r$. As $|\Delta V|$ is increased, electrons (holes) in the $n$-doped ($p$-doped) region are pulled away from the junction, widening the depletion layer and leading to an increasingly large resistance. Under such conditions, the only current flow is a residual “leakage” current (Figure 2.1.1b) due to minority carriers: conduction electrons (holes) in the $p$-side ($n$-side) are dragged towards the cathode (anode). However, at very large reverse bias (that is, in a very strong electric field), both conduction electrons and holes may acquire enough kinetic energy to trigger a cascade effect in which electron-hole multiplication generates a large current. Beyond a critical voltage the diode suffers reverse breakdown, usually due to either avalanche or Zener breakdown.\(^2\) In both cases the depletion zone breaks down: in the avalanche effect (Section 2.2), beyond the breakdown or peak inverse voltage, $V_{br} > 4E_g / q$ (in which $E_g$ is the band gap and $q$ the charge of the carrier) \(^1\), the diode suffers reverse breakdown in which the minority carriers suddenly generate large numbers of electrons and holes which move away from the $p$-$n$ junction, and a large current begins to flow. In the Zener effect, when the applied reverse bias is $V_{br} < 4E_g / q$,\(^3\) the strong electric field allows electrons to tunnel from the valence band of the $p$-type material to the conduction band of the $n$-type material, increasing the number of free minority carriers and hence the reverse current.\(^4\) The so-called avalanche photodiode (APD) – which forms the basis of the SiPM – is deliberately designed to exploit the avalanche mechanism.\(^5\)

\(^2\)A third mechanism inducing breakdown, known as thermal instability, is a major influence in semiconductors with relatively small band gaps (see, for example, Sze and Ng \[^{123}\]).

\(^3\)In the intermediate region $4E_g / q < V_{br} < 6E_g / q$, the breakdown is due to a combination of both the avalanche and Zener effects \[^{123}\].

\(^4\)In heavily doped $p$-$n$ junctions – in which the depletion layer is extremely thin – the latter phenomenon forms the basis of the Zener diode.

\(^5\)For the remainder of this report, unless otherwise specified the terms “bias” and “current” are used to refer to “reverse bias” and “reverse current”, respectively.
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2.2 The Avalanche Photodiode, Breakdown & The Geiger-mode Mode of Operation

Silicon APDs were first developed by McIntyre [124] and Haitz [125] in the 1960s. Avalanche multiplication in such devices is a multi-stage cascade process in which a photoelectron, produced via the photoelectric effect from an initial photon incident upon a Si atom, is in a sufficiently strong electric field (generated by the external reverse-bias voltage $V$) that it is energetic enough to subsequently induce a chain reaction in the substrate. Due to so-called impact ionisation, successive atom-free electron and/or hole collisions result in the avalanche – that is, an exponential increase in the number of free charge carriers – in a process analogous to the Townsend discharge (or Townsend avalanche) [126] in gases.

Impact ionisation occurs when a charge carrier collides with a bound valence electron, exciting the electron into the conduction band while leaving a hole in the valence band, thus generating a mobile electron-hole pair. For a typical collision, the probability of ionisation ultimately depends upon the strength of the electric field. The ionisation rate for the (pre-collisional) primary electron (hole) may be quantified by the ionisation coefficient, $\alpha$, that is, the number of (post-collisional) secondary electrons (holes) produced via ionisation by the primary charge carrier per unit path length $x$. Mathematically, for electrons (holes), the ionisation coefficients is $\alpha_e = n_e \frac{dn_e}{dx}$ ($\alpha_h = n_h \frac{dn_h}{dx}$), in which $n_e$ ($n_h$) is the electron (hole) density. It is well-known [127] that $\alpha_e$ and $\alpha_h$ depend upon the electric field strength, $E$, and that in Si, for any value of $E$, $\alpha_e > \alpha_h$. That is, the probability of impact ionisation due to an electron is greater than that of a hole.

Consider the depletion layer $x_1 \leq x \leq x_2$ in the semiconductor, in which the applied
electric field is assumed to be constant. The gain $G_e$ of the diode can be expressed empirically as a function of $V$ and the breakdown voltage $V_{br}$ by [128]

$$G_e = \left[ 1 - \left| \frac{V}{V_{br}} \right| \right]^{-n} \quad (2 < n < 6),$$

and so if $E = dV/dx$, a dependence of $G_e$ on the field strength is obtained. In the weak-field regime (the “no-gain” region), $G_e \approx 1$, i.e., the applied field is too weak to initiate impact ionisation. The resulting current collected at the electrodes is then $I = I_{pe}$ (in which $I_{pe}$ is the initial photoelectron current).

In the strong-field regime (the so-called “gain region”), $G_e \gg 1$, and the resulting current $I = G_e I_{pe} \gg I_{pe}$. While the electrons generate an avalanche, the operational mode of the diode depends upon the probability of ionisation of the holes (recall that $\alpha_h < \alpha_e$): if $E \sim 150$ kV/cm, then the impact ionisation ratio $k = \alpha_e/\alpha_h \sim 100$: there is a low probability of ionisation – the holes are not energetic enough to trigger a self-sustaining avalanche. The photodiode operates in so-called proportional or linear mode (see for example, Knoll [129]), and $G_e \sim 10^2 - 10^4$ [130]. Meanwhile, as $V \to V_{br}$ such that $E \sim 500$ kV/cm, $k \sim 2.5$, and the holes are energetic enough to generate an avalanche: $G_e$ increases strongly until at a critical electric field – corresponding to $V_{br}$ – the avalanche diverges rapidly ($G_e \sim 10^4 - 10^6$), and the resulting APD operates in Geiger-mode mode. The multiplication regions due to various initial photoelectrons begin to merge together to form a single avalanche, forming a large output pulse from a single incident photon.
2.3 The Silicon Photomultiplier

The silicon photomultiplier (Figure 2.3.2) is a highly miniaturised and integrated semiconductor device, comprised of a densely packed ($\gtrsim 10^3 \text{ mm}^2$ [131]) rectangular array/matrix of essentially identical microcells (subject to high quality control in all the silicon and deposition stations of the foundry) connected in parallel. Each microcell is a Geiger-mode APD connected in series with a relatively large ($\sim 10^5 \Omega$) quenching resistor $R_Q$ (Figure 2.3.2d). At a large applied voltage $V$ – supplied by an external power source and typically a few volts above breakdown (referred to as the overbias $V_{ob} = V - V_{br}$) – any photons incident upon one or more microcells will cause the microcell to “fire” (that is, generate a corresponding avalanche). In this way each microcell operates as an independent photodetector.

In each microcell, a self-sustaining avalanche can, in principle, propagate indefinitely. However, in practice the avalanche current increases to a maximum value $I_{max} = (V - V_{br})/(R_Q + R_s)$, in which $R_s$ is the resistance of the undepleted regions of the APD [127], before being subsequently quenched by the accompanying resistor of value $R_Q$ (Figure 2.3.3). As the current $I$, given by

$$I = -\left[1 - \exp\left(-\frac{t}{R_s C}\right)\right], \quad (2.3.2)$$

increases (where $C \sim 0.1 \text{ pF}$ [131] is the capacitance of the depletion region of the APD), the voltage $V_R = IR_Q$ across $R_Q$ increases while that across the APD, $V_{APD} = IR_s$, is reduced below $V_{br}$, inhibiting subsequent avalanches. The current then decreases as

$$I = -\exp\left(-\frac{t}{R_Q C}\right), \quad (2.3.3)$$
Figure 2.3.2: The structure of a silicon photomultiplier. (a) The Hamamatsu S12571-050C MPPC series (photosensitive area $1 \times 1$ mm$^2$). (b) The Hamamatsu S12572-050C MPPC series (photosensitive area $3 \times 3$ mm$^2$). (c) Magnified view of a $1 \times 1$-mm$^2$ SiPM (obtained from the National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), showing the $16 \times 16$ arrangement of individual microcells. (d) Schematic of a circuit showing APD microcells. Each microcell consists of a light-sensitive APD operating in Geiger mode connected in series with a quenching resistor. An external power source reverse-biases the array to a voltage that is up to a few volts above the breakdown voltage of an APD. Based on Figure 1b of Platek [127]. Figures (a) and (b) are the SiPM units used in the PRD tests discussed in Chapter 3. Both units are most sensitive to photons in the spectral range 320 nm-900 nm, with a peak spectral response at 450 nm. From the Hamamatsu data sheets for the respective units (see text).
discharging through $C$. When the output current is completely quenched, the APD relaxes to its quiescent state ($I = 0\ A$) with $V_{\text{APD}} > V_{\text{br}}$, ready for the next photon. The operation of the SiPM in this way is known as limited Geiger-mode.

Since the output signal is independent of the number of incident photons – the current maximum always occurs after approximately the same number of avalanches (regardless of their photon or photoelectron of origin) – the resulting output pulse from a fired microcell is always of the same amplitude. Each microcell will provide the same fixed gain $G_e = \frac{Q}{e}$ when fired (in which $Q$ is the total charge accumulated in the microcell), with a charge $Q = C(V - V_{\text{br}}) \approx 10\ fC$ collected at the anode. In this way each microcell effectively operates as a binary device, its “on” (“off”) state indicating the presence (absence) of an avalanche. It can be thought of as a counter of the initial photons – and hence particle detections – incident upon it. Although the output of each microcell is a binary digit of information, summing the charges from all the microcells in the array yields an analogue signal at the common anode.

For low-level light, it is assumed that an avalanche in each of the microcells has been triggered by a single incident photon. Under such conditions, the output current of the SiPM is proportional to the number of incident photons, and the SiPM is said to exhibit a linear response. However, increasing the intensity of the light results in a greater probability of more than one photon triggering a microcell “simultaneously” (that is, within the fall/relaxation time of the output pulse). The response of the SiPM becomes increasingly non-linear, and the current output is disproportionate to the number of incident photons.
Figure 2.3.3: Typical output pulse shapes from a SiPM and APD. (a) Example of a typical oscilloscope trace of a real signal from a Hamamatsu SiPM array due to laser light. From Tahani [132]. (b) Sketch of a typical pulse from an APD, as described in the text. Note the characteristic shape: the asymmetry of the pulse (exaggerated) is due to the relative sizes $R_S C \ll R_Q C$, of time constants in the rise ($R_S C$) and fall ($R_Q C$) regions. Typical rise and fall times of the pulse are $<100\, \text{ps}$ and $\sim 10-100\, \text{ns}$ [133], respectively. Based on Figure 8 of Platek [127].
2.3.1 The Structure of the SiPM

A SiPM microcell is fabricated by initially growing a thin crystalline overlayer (a so-called “epitaxial layer”) on a low-resistance, silicon-wafer substrate, followed by depositing successive layers of p- or n-type dopant of varying concentration in order to create a p-n junction. Figure 2.3.4a shows a simple schematic of a microcell: a $p^-$-type epitaxial layer (of typical thickness $\sim 2 - 4 \mu m$) is deposited upon a $p^+$ wafer/substrate (of thickness $\sim 300 \mu m$), with a shallow diffusion of subsequent $p^+$ layer, as shown, $\sim 0.5 \mu m$ below the surface of the microcell. Finally, a very thin $n^+$ layer is created on the surface. Applying a bias voltage $V \gtrsim V_{br}$ (that is, operating in Geiger-mode), avalanche breakdown resulting from photon-induced an electron-hole pair creation occurs within the photosensitive depletion region of the resulting p-n junction. As shown in Figure 2.3.4a, in order to generate the electric field necessary for avalanche ($E = dV/dx \sim 300 - 500 \text{kV/cm}$), this depletion layer is necessarily thin ($dx \sim 0.7 - 0.8 \mu m$). Such a configuration – known as a n-on-p structure – is particularly sensitive to red light (i.e., long-wavelength, low-energy photons), which will be absorbed within a few microns of the $n^+$ layer. In contrast, short-wavelength (blue) photons must penetrate into the $p$-layer in order to generate photoelectrons which can initiate avalanches [1], and so are less likely to be detected. Electrons generated in the avalanches drift towards the electrode connected to the $n^+$ layer via the quenching resistor, while holes
drift through the low-field substrate and are collected at the other electrode. Guard rings
\( (n^-\text{-type}) \) surrounding each microcell ensure a uniform electric field within the microcell,
preventing lateral breakdown, while each microcell is connected to the rest via a common
aluminium strip, allowing the SiPM signal to be read out. An anti-reflective coating (ARC),
made of materials such as \( \text{SiO}_2 \), increases the spectral response of the microcell in the blue and
near-UV regions of the spectrum.

Due to efforts to minimise the so-called dark current in each microcell (see Section 2.3.3),
commercially available devices are significantly more advanced than the simple structure dis-
cussed above. For instance, Figure 2.3.4b shows the schematic of a device fabricated by STMi-
croelectronics\(^9\) and analysed by Pagano et al. \(^{135}\). Additional features include, for example,
a \( p/p^+ \) epitaxial layer and \( n^- \) substrate, the \( p^+-n^- \) junction preventing photogenerated
carriers in the latter from reaching the former \(^{136}\). The implanted \( p^+ \) material on the epi-
taxial layer enriches the \( p-n \) junction, while the deep optical trenches surrounding the active
region serve to minimise cross-talk (Section 2.3.3) between adjacent microcells.\(^{10}\)

\subsection*{2.3.2 Properties of the SiPM}

While preserving many of the attributes of the PMT, SiPMs also offer several important ad-
vantages in addition to those noted in Section 1. For example, not only are SiPMs relatively
inexpensive compared to the PMT – and easier to manufacture – but their small dimensions
allow for an extremely compact, light and robust mechanical design (while still maintaining
a high photosensitivity), thus making them easily adaptable to different applications.

\(^{9}\)STMicroelectronics N. V., Headquarters: 39, Chemin du Champ des Filles, Plan-Les-Ouates, Geneva CH
1228, Switzerland (http://www.st.com).

\(^{10}\)Not all manufacturers of SiPMs implement optical trenches: for example, Hamamatsu do not include such
components in many of their devices.
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Figure 2.3.4: Schematics of an idealised and realistic SIPM microcell. (a) Left: A sketch of a simple SiPM microcell (not drawn to scale), consisting of an n-on-p structure. Right: The variation of the electric field with depth, \( x \), in the epitaxial layer. From Buzhan et al. [137]. (b) Left: The components of a SiPM microcell fabricated by STMicroelectronics. The dotted line is the boundary of the depletion region, \( L \) is the active area length and \( L_P \) is the perimeter-length extension. The various layers and current components (1)-(5) are discussed in Pagano et al. [135]. Right: Front-side view of the SiPM microcell: \( A_B \) and \( A_P \) are, respectively, the active and perimeter areas of the microcell. Adapted from Pagano et al. [135].
The sensitivity of a photodetector may be characterised by its photon detection efficiency (PDE), a property measuring the capacity of the device to detect radiation incident upon it. Not every photon entering the SiPM fires a corresponding microcell: indeed, depending upon the manufacturer, a typical PDE – defined by the ratio $N_{\text{detect}}/N_{\text{photons}}$ of the number of detected to incident particles – is $\sim 20 - 40\%$, compared to a value of $\sim 20\%$ at 420 nm for typical PMTs.\footnote{Cinti et al. [138] state a typical range of 20 - 30\% for a Hamamatsu MPPC. That of the PMT is from the SensL technical note Introduction to the SPM – retrieved from \url{http://www.sensl.com/downloads/ds/TN%20-%20Intro%20to%20SPM%20Tech.pdf} – who also report a PDE of $\sim 25\%$ at a peak wavelength of 520 nm for a SiPM with 100 $\mu$m microcell size. The PDEs of the Hamamatsu S12571-050C and S12572-050C MPPCs used in Chapter 3 are 35\% (see Table 3.1), while that of the SensL “M” series of SiPM used in Chapter 4 is 20\% (see Table 4.1).} In a SiPM of $N_{\text{total}}$ microcells, the number $N_{\text{fired}}$ firing is related to $N_{\text{photons}}$ by

$$N_{\text{fired}} = N_{\text{total}} \left[ 1 - \exp \left( - \frac{N_{\text{photons}}}{N_{\text{total}}} \cdot \text{PDE} \right) \right], \quad (2.3.4)$$

and the number of avalanche photoelectrons is then $N = G_e \cdot N_{\text{detect}}$, yielding an output current $dQ/dt$ given by

$$I = e \cdot \frac{dN}{dt} = e \cdot \frac{dN_{\text{photons}}}{dt} \cdot \text{PDE} \cdot G_e. \quad (2.3.5)$$

in which $e$ is the charge of an electron.

Equation (2.3.5) assumes that the response of the SiPM is linear. That is, for low-intensity light, in which $N_{\text{photons}} \ll N_{\text{total}}$ a Geiger-mode microcell may be fired by a single incident photon before relaxing back into its quiescent state (recall Figure 2.3.3). However, at high intensities ($N_{\text{photons}} \geq N_{\text{total}}$) the SiPM becomes saturated: the photon flux is so high that multiple photons may be incident upon a microcell, either generating separate avalanches or...
occurring during the deadtime of the detector. In both cases only one photon is detected: in
the former, the avalanches are merged and quenched, while in the latter only the initial, trig-
gering photon is counted. As $N_{\text{photons}} \rightarrow N_{\text{total}}$, the SiPM thus operates in an increasingly non-linear manner, and Equation (2.3.5) is no longer valid.

The PDE can be expressed as

$$PDE = \varepsilon_{\text{geo}} \cdot \varepsilon_{\text{trigger}}(\lambda, V, T) \cdot \varepsilon_{\text{QE}}(\lambda),$$

with the variables are described as follows:

- **Geometric efficiency**, $\varepsilon_{\text{geo}}$: also known as the geometric fill factor, this is the ratio of the active/photo-sensitive area of the SiPM to its total physical area.

- **Triggering probability**, $\varepsilon_{\text{trigger}}$: also known as the Geiger discharge probability, this describes the likelihood that electrons and holes created in the photon interaction initiate an electrical breakdown, generating an avalanche. The triggering probability depends upon the SiPM structure, and in particular the photon absorption length in silicon (which varies from $\sim 0.01 \mu m$ to few micrometres for wavelengths in the range $300 \text{ nm} < \lambda < 700 \text{ nm}$ [140]).

- **Quantum efficiency (QE)**, $\varepsilon_{\text{QE}}$: may be quantified by the ratio $\varepsilon_{\text{QE}}(\lambda) = \frac{N_{e-h}}{N_{\text{photons}}}$ of the number of photogenerated electron-hole pairs, $N_{e-h}$, resulting in the output current to the number of photons incident upon the photosensitive SiPM surface. That is, the QE represents the probability that an incident photon will enter the detector and generate a photoelectron, and so depends upon the photon wavelength $\lambda$. Quantum efficiencies of $\sim 55\%$ have been reported for Hamamatsu MPPCs [138],
while SiPMs manufactured by Ketek\textsuperscript{12} have values of $\sim 80\%$. The latter report the QE of a PMT to be $25 - 40\%$.

### 2.3.3 Noise in Silicon Photomultipliers

It is well known that for low-intensity light the SiPM is capable of single-photon resolution at room temperature (see, for example, the discussion of photopeak spectra in Buzhan \textit{et al.} \textsuperscript{131}). However, although it is desirable that the avalanche current generated by a microcell originates only from an initial photoelectron in the silicon, spurious avalanches can be triggered by other mechanisms within the depletion layer of the semiconductor. The thermal, tunnelling and trapping processes outlined below can all generate free charge carriers which subsequently induce avalanches in the substrate, contributing to an overall noise component superimposed upon the photon-triggered signal. This noise is recognised as an inherent part of the output current, and impairs the sensitivity of the detector \textsuperscript{141}.

The main source of noise in a PMT is due to the so-called \textit{thermionic emission} of electrons emitted by the photocathode (and, to a lesser extent, the dynodes and glass wall of the PMT \textsuperscript{142}). As a random process, the resulting dark current exiting the dynode chain adds a statistically fluctuating component to the overall photoelectron current measured by the PMT. By comparison, as well as an inherent component due to thermally generated electron-hole pairs, the SiPM contains “parasitic” contributions to the noise – known as \textit{crosstalk} and \textit{afterpulsing} – which arise from the primary, photoelectron-induced avalanche. Here, each of

\textsuperscript{12}Ketek GmbH, Hofer Straße 3, 81737 München, Germany (\url{http://www.ketek.net}).

\textsuperscript{13}Note that due to its relatively high gain, the level of electronics noise of a SiPM is negligible, corresponding to less than 10\% of the signal from one photoelectron \textsuperscript{129}.

\textsuperscript{14}For example, a PMT with a 50-mm-diameter photocathode may generate $\sim 10^5$ such electrons per second at room temperature \textsuperscript{142}.
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these components is considered in turn.

2.3.3.1 Thermally Generated (Dark) Noise

Thermally generated conduction-band electrons in the semiconductor substrate are recognised as being the main source of noise which limits the ability to resolve single-photon peaks in the SiPM’s photopeak spectrum. Since a microcell is equally responsive to a thermal electron as it is to a photoelectron, then upon firing, both charge carriers will produce the same avalanche current, adding a random-noise component to the scintillation signal.

Such noise in a SiPM can be reduced in two ways. Using a discriminator in the read-out electronics, it is found that the dark rate decreases significantly with an increase in threshold level. Setting a threshold level corresponding to the simultaneous firing of successive numbers of microcells gives rise to a distinctive staircase function (Figure 2.3.5a). It is seen that an increase in the threshold voltage by an amount corresponding to the one-photoelectron amplitude reduces the dark rate by almost an order of magnitude, while setting the threshold to higher than the four-photoelectron amplitude results in a dark rate below 1 kHz [1].

A second approach is to cool the SiPM: it is well known that the dark rate in a SiPM is temperature dependent. For instance, while a factor of \(2\) reduction in dark rate has been reported for every 8 K drop in temperature [1],\(^8\) decreasing for example from \(1 \sim 2\) MHz/mm\(^2\) at room temperature to \(200\) Hz/mm\(^2\) at 100 K [140].

\(^8\)Both SensL and Ketek report a 50% reduction in dark rate for every 10 K decrease for their respective SiPM devices. See, for example, the SensL technical note Introduction to the SPM (http://www.sensl.com/downloads/ds/TN%20-%20Intro%20to%20SPM%20Tech.pdf) and Ketek documentation at http://www.ketek.net/products/sipm-technology/device-parameters, respectively.
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(a) Dark-rate-versus-discriminator-threshold behaviour in a SiPM.

(b) Primary mechanism: optical crosstalk and "trapped" afterpulsing.

(c) Secondary mechanism: delayed crosstalk and "diffused" afterpulsing.

Figure 2.3.5: Noise mechanisms in a SiPM: (a) The distinctive "staircase function" of the dark-rate-versus-discriminator-threshold for a typical $1 \times 1$ mm$^2$ SiPM (the Hamamatsu S10362-11-050C) operated at a gain of $6.5 \times 10^5$. From Renker and Lorenz [1]. (b) The primary noise mechanism in a SiPM: afterpulsing (AP-traps) is due to carriers trapped in crystal defects within a microcell, while (almost instantaneous) optical crosstalk (CT-opt) is due to secondary photons reaching neighbouring microcells (see text). (c) The secondary noise mechanism in a SiPM: the diffused afterpulsing (AP-diff) and crosstalk (CT-diff) effects due to the action of secondary photons in the silicon substrate (see text). Figures (b) and (c) are from Rosado et al. [143].
2.3.3.2 Inter-microcell Crosstalk & Afterpulsing

It is well known that a reverse-biased p-n junction undergoing breakdown fluoresces [144], and Lacaita et al. [145] have shown that these “secondary” photons (of energy $\gtrsim 1.14$ eV) are created at a rate of about $3 \times 10^{-4}$ per electron crossing the junction. Such photons are strongly correlated to a primary avalanche and, if created in a microcell, are capable of almost instantaneously triggering Geiger discharge(s) in adjacent microcell(s) in a process known as optical crosstalk (Figure 2.3.5b). For a SiPM gain of $10^4 - 10^7$, it is therefore expected that $\sim 3-300$ such photons would be generated by a microcell during breakdown. In a secondary mechanism, those secondary photons which are photoabsorbed in the substrate can generate minority carriers, which either diffuse to the initially fired microcell or to a neighbouring microcell, with the latter effect known as delayed crosstalk (Figure 2.3.5c). Such charge carriers are accelerated in the electric field and energetically capable of inducing avalanches in these locations. Indeed, the triggering of adjacent microcell(s) in this way can even spread in a chain reaction across multiple microcells, contributing appreciably to the SiPM noise.

In afterpulsing, defects and/or impurities in the silicon substrate of the microcell act as a charge trap. During an avalanche, a charge carrier may be trapped in the defect and then released after the microcell has relaxed to its quiescent state, only to trigger subsequent delayed avalanches ($\sim 100$ ns $- 2\mu$s) within the same microcell (Figure 2.3.5b). Due to the various types of trapping mechanisms in a semiconductor, there may be several components to the afterpulsing effect. A second mechanism may occur (Figure 2.3.5c) in which the minority carriers triggered by the secondary photons are themselves trapped in the defect, leading to so-called diffused afterpulsing (see, for example, Rosado et al. [143]). Afterpulsing results in an increased count rate for an incident photoelectron.
The effects of crosstalk and afterpulsing are critical factors in the design and operation of SiPMs. For example, introducing blocking/isolation trenches – comprised of an optically absorbing material – between adjacent microcells (see, for example, Figures 2.3.4b, 2.3.5b and 2.3.5c) is a common strategy in reducing optical crosstalk. However, increasing the width of such trenches reduces the geometric fill factor of the SiPM, thus decreasing the PDE.

Theoretical techniques to model noise are based upon approaches such as Monte Carlo simulations and statistical models, with several physical models dealing with crosstalk and afterpulsing having appeared in the literature (see, for example, references [146–159]).

The theory and operation of the SiPM outlined in this chapter forms the basis of the photosensors used in both applications discussed in this thesis. By applying a reverse bias to the SiPMs of interest, such that it operates in limited Geiger-mode, the detection of an incident photon occurs due to the large gain of the photosensor. However, the resulting signal output is necessarily affected by the inherent, undesirable noise mechanisms outlined in this chapter. In both applications, it is important to find the optimal configuration in which the desired signal frequency can be detected at a level sufficiently far above the noise (or indeed any additional components due to extraneous sources in the surrounding environment) to be attributed (with confidence) solely to the radioactive source alone. Since cooling of the SiPM device is impractical in both applications, an important part of both projects was to investigate the discrimination threshold – or range of thresholds – above/within which the source signal was maximised while that of the noise suppressed. Experimental details of such techniques, and the subsequent analysis, are discussed in the following two chapters.
Chapter 3

Application: Personal Radiation Detector

Recently, several groups have reported on the use of SiPMs in radiation detectors, intended for use by emergency workers and first responders. The first commercially available PRD was the “SENTIRAD” system of Osovizky et al. [160–165], subsequently renamed “PDSGO” [107], a device which the authors claim [107] satisfies the DARPA and SIGMA program requirements discussed in Chapter 1. Their PRD uses a $3 \times 3$ mm$^2$ SensL SiPM (the SPM303 model) coupled to an $8 \times 8 \times 30$ mm$^3$ CsI(Tl) crystal scintillator. Meanwhile, the “MiniSpec” system due to Becker and Farsoni [166] – also employing a SiPM manufactured by SensL (the MicroSL 60035 model) coupled to a CsI(Tl) crystal – has been designed as a low-cost, compact radioisotope identifier, capable of interfacing wirelessly with any cell phone. Ahmadov and co-workers are currently developing [167] a compact $\gamma$-ray detector using a $3 \times 3 \times 0.5$ mm$^3$ SiPM (developed by Sadygov et al. [168]) optically coupled to a teflon-wrapped Lutetium Fine Silicate (LFS) crystal scintillator (Table 2.1).$^3$

$^1$SensL Technologies, Ltd., 6800 Airport Business Park, Cork, Ireland (http://sensl.com/).

$^2$These authors also present results of $\alpha$-particle measurements with LFS, as well as fast-neutron measurements using a teflon-wrapped Stilbene crystal scintillator (Table 2.2).
This chapter is organised as follows: initially, an overview of the project is provided (Section 3.1), followed by a discussion of the SiPM units that are most promising to be adapted to EIC’s requirements. Details of the experimental set-up (Section 3.3) – and subsequent results (Sections 3.4 and 3.5) – in evaluating various SiPM-wrapped scintillator configurations are then presented. In Section 3.6, measurements pertaining to the use of a lead mini-calorimeter as a possible light-producing medium are given. Details of corresponding measurements, obtained when the nuclear electronics housed in the SPARRO Group’s Detector Development Laboratory (DDL) were replaced by their modified EIC counterparts, are discussed in Section 3.7.

A further investigation considers the use of SiPMs in neutron detection (Section 3.8). Neutron radiation can present a serious nuclear and biological hazard, and the ability to detect its presence remains of critical importance in, for example, homeland security. It is hoped that this preliminary study may form the basis of further collaboration between SPARRO and EIC, with the possibility of the latter incorporating a neutron-detection capability into a PRD.

Over time, neutron beams can also inflict appreciable radiation damage at a microscopic level in exposed materials, leading to, for example, their embrittlement or swelling. Degradation in solids via the Wigner effect [169] is of concern in the neutron moderators of fission reactors.

Although the ability to detect neutrons is a DARPA requirement, the PDS-GO PRD [107] does not currently have that capability.
3.1 Project Background

EIC’s existing PRD platform, the CT007 Gamma Detector,\(^5\) employs a Geiger-Müller (G-M) tube (the LND 713 Thin wall beta-gamma detector\(^6\)) as its photodetector. The CT007 device has no buttons or screens: instead, it communicates wirelessly with a smart-phone (or other mobile computing platform) via a wireless Bluetooth\(^\text{TM}\) (BT) connection, allowing radiation-exposure data to be displayed easily to the user and/or transmitted to a remote data repository. Although compact in its dimensions (with an effective length of 27.9 mm and diameter 7.77 mm), the LND device lacks the durability of the SiPM-based detector, as well as requiring a larger operating voltage (~ 450-650 V), and possessing a longer dead time (45 \(\mu\)s) and lower sensitivity to \(\gamma\)-ray photons (7.5 cps/mr/hr for \(^{60}\text{Co}\)) than a typical SiPM-based detector. Furthermore, G-M tubes are incapable of detecting neutrons, and in operating essentially as a gross gamma counter do not provide spectral information (and therefore cannot be used in, for example, radionuclide identification).

The target of the EIC/SPARRO collaboration was to develop a prototype gross-counting gamma counter based on the SiPM (and coupled to an appropriate light-producing medium), which offers a significant enhancement in light sensitivity over that of the CT007 unit, while still minimising cost and retaining the overall physical dimensions (50 x 90 x 15 mm\(^3\)) of the latter. It is hoped that such a device could subsequently be used by EIC as the basis for a commercially available detector, replacing the existing CT007 Gamma Detector.

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\(^5\)See, for example, \url{http://www.eic.nu/CT007.html}, with technical specifications available at \url{http://www.gammawatch.com/pdf/PromoCT007withScreenAndButton.pdf}.

\(^6\)LND Inc., 3230 Lawson Boulevard, Oceanside, New York 11572, United States (\url{http://www.lndinc.com/}).
3.2 Photosensor Selection

The SiPMs of interest in this project, listed in Table 3.1, are from the Hamamatsu\footnote{Hamamatsu Photonics K. K., 360 Foothill Road, Box 6910 Bridgewater, New Jersey 08807, United States (http://www.sales.hamamatsu.com/).} S12571-050C and S12572-050C series (Figure 2.3.2). Units of the former contain a $20 \times 20$ pixelated array, with microcell dimensions $50 \times 50 \mu m^2$, giving an overall effective photosensitive area of $1 \times 1 \text{mm}^2$. Those of the S12572-050C series provide a larger effective photosensitive area of $3 \times 3 \text{mm}^2$,\footnote{For the remainder of this chapter, the S12571-050C/P and S12572-050C series units are often referred to in the text by their sizes – $1 \times 1 \text{mm}^2$ and $3 \times 3 \text{mm}^2$, respectively.} with 3600 microcells arranged in a $60 \times 60$ array with pitch of $50 \mu m$.\footnote{Technical details of the S12571-050C and S12572-050C series are available at http://www.hamamatsu.com/jp/en/S12571-050C.html and http://www.hamamatsu.com/jp/en/S12572-050C.html, respectively.} The individual units are identified by the corresponding serial numbers given in Table 3.1.

In a previous technical report\footnote{Although Tables 2.1 and 2.2 list numerous scintillators with superior light-yields compared to BC-416, the commercial viability of PRDs necessarily requires the use of low-cost materials (a stipulation also outlined in the DARPA RFI discussed in Chapter 1). The cost of several of the scintillators listed in the respective tables makes them prohibitively expensive for use in the current project. Also, while NaI(Tl) (Table 2.1) would be expected to be the preferred choice of scintillator for this project, due to its considerable light yield and relatively low-cost, its strong hygroscopicity (requiring it to be housed in an air-tight enclosure) and relatively long decay time make it unsuitable.} the SPARRO Group presented results of characterisation tests performed on the S12571-050C and S12572-050C MPPCs, coupled to a paper/Al-foil wrapped, $13 \times 13 \times 50$-mm$^3$ BC-416 plastic scintillator, in order to assess the photosensor requirements of this project.\footnote{The electronics of an existing $1 \times 1$-mm$^2$ unit (SiPM #1853) produces a noise signal of $\sim 5.5$ mV (width $\sim 50$ ns) at $V_{ob} = 1.5$ V, while that of the $3 \times 3$-mm$^2$ SiPM (#269) is $\sim 8$ mV at $V_{ob} = 0.0$ V, with a duration of $\sim 150$ ns.} As shown in Figure 2.3.2, units of both SiPM series did not have any accompanying electronics, and so readout circuits were constructed “in-house” in the DDL at the University of Regina, with those given in Figure 3.2.1 being found to provide SiPM output pulse shapes of sufficient amplitude and duration.\footnote{The electronics of an existing $1 \times 1$-mm$^2$ unit (SiPM #1853) produces a noise signal of $\sim 5.5$ mV (width $\sim 50$ ns) at $V_{ob} = 1.5$ V, while that of the $3 \times 3$-mm$^2$ SiPM (#269) is $\sim 8$ mV at $V_{ob} = 0.0$ V, with a duration of $\sim 150$ ns.}
<table>
<thead>
<tr>
<th>Series</th>
<th>Serial Number</th>
<th>Operating voltage (V)</th>
<th>Gain $G$ ($10^5$)</th>
<th>Dark count $(k/(0.5 \text{ thr}))$</th>
<th>Refractive index</th>
<th>Spectral response (nm)</th>
<th>Peak response (nm)</th>
<th>PDE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S12571-050C</td>
<td>184</td>
<td>66.85</td>
<td>12.6</td>
<td>91.7</td>
<td>1.41</td>
<td>320-900</td>
<td>450</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>188</td>
<td>66.91</td>
<td>12.5</td>
<td>88.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S12572-050C</td>
<td>266</td>
<td>66.91</td>
<td>12.5</td>
<td>1000</td>
<td>1.59</td>
<td>320-900</td>
<td>450</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>267</td>
<td>66.91</td>
<td>12.4</td>
<td>1100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>269</td>
<td>66.84</td>
<td>12.5</td>
<td>950</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: Properties of the individual Hamamatsu S12571-050C ($1 \times 1 \text{ mm}^2$) and S12572-050C ($3 \times 3 \text{ mm}^2$) MPPC units used in the EIC/SPARRO collaboration. The "Serial number" of each device is of the form 3L000XXX, in which XXX refers to the three-digit number shown. "Dark" refers to the dark-count measurement. In both series, units have the stated operating voltages, recommended to be 2.6 V above breakdown ($V_{br} = 65 \pm 10 \text{ V}$) by the Hamamatsu data sheets. The PDE values are at peak wavelengths, and do not include crosstalk and afterpulsing. All properties are stated for a temperature of 25°C. The series data shown is from the corresponding Hamamatsu data sheets (see text), while that of the individual units is from their accompanying packaging.
Figure 3.2.1: Readout electronics constructed in the DDL at the University of Regina for the $1 \times 1\text{-mm}^2$ and $3 \times 3\text{-mm}^2$ series of SiPMs (both series have no accompanying electronics). The $RC$ circuit was used to change the shape of the output pulse.
familiarity and experience with older (2010) Hamamatsu units, devices such as the S12045X SiPM array ($3 \times 3 \text{ mm}^2$) were employed as “control” units with which to evaluate the newer units. While external-trigger tests (using a PMT) showed that $1 \times 1\text{ mm}^2$ units could successfully reproduce the characteristic ADC spectra of $^{241}\text{Am}$ and $^{90}\text{Sr}$, it was found that they could not produce a signal sufficient enough for use in a self-triggering configuration (the preferred set-up). Self-triggering tests on the $3 \times 3\text{ mm}^2$ SiPMs successfully reproduced the characteristic energy spectra of $^{90}\text{Sr}$ ($\beta$-spectrum) and $^{60}\text{Co}$ ($\gamma$-spectrum), respectively, over a range of overbias voltages. The results of the report suggested that for the $3 \times 3\text{ mm}^2$ units, a clear distinction between signal and background could be obtained, tentatively identifying the St2572-050C series – with the simple readout circuit shown in Figure 3.2.1b – as the preferred choice of photosensor for use in this project.

### 3.3 Experimental Method

While the cost and space requirements of the PRD would naturally favour a singles mode of operation, there remains the possibility that a design involving two $3 \times 3\text{ mm}^2$ units – operating in coincidence – would be the part of the preferred set-up. Therefore, tests for both singles and coincidence configurations – with schematics shown in Figures 3.3.2 and 3.3.3, respectively – were considered for SiPM units (discussed in Section 3.2), coupled to a light-producing medium, for several wrapping materials chosen for their high reflectivity.

Recall that in addition to a contribution from the source, the SiPM output signal necessarily includes a background component which, in turn, contains an inherent contribution

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12External trigger tests on the $3 \times 3\text{ mm}^2$ units were not performed, since in having the capacity of nine times the light collection of their smaller counterparts, they would also be expected to reproduce the $^{90}\text{Sr}$ spectrum comfortably for EIC’s requirements.
due to noise. The background originates mainly from cosmic rays, as well as natural and artificial sources in the surrounding environment, while the noise contribution arises from that associated with the SiPM (see Section 2.3.3) and, to a lesser extent, the accompanying electronics [129]. In the tests reported here, the size of the source signal relative to that of the background and noise components was obtained by measuring the count rates of the noise (measured in the absence of the scintillator and source), background (measured in the presence of the scintillator, but no source), and “total” (i.e., combined source, background and noise) signals over a range of discriminator threshold voltages.

In coincidence measurements, each SiPM unit was positioned opposite to each other in physical contact at either end of the wrapped scintillator. When required, the source was placed in contact with the wrapping approximately half-way along the scintillator. Each SiPM had a bias voltage, $V$, at the operating voltage listed in Table 3.1, supplied to it by a separate Keithley 6487 Picoammeter, with the resulting SiPM output signal being processed by readout electronics. Two discriminator models were employed during this project: a Phillips Scientific Model 705 Octal Discriminator and a CAEN N840 8 Channel Leading Edge Discriminator, while a Joerger Model VS Dual-channel 100 MHz Visual Scaler recorded the number of counts over an arbitrary time interval. While this arrangement allowed the coincidence measurement to be performed by a Phillips Scientific Model 755 Quad Four-fold Logic

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3For horizontal detectors, the experimentally accepted value for the vertical flux of cosmic-ray muons of energy $E_{\mu} > 1$ GeV is $\sim 1/cm^2/min$ at sea level [171].
4Keithley Instruments, Inc., 28775 Aurora Road, Cleveland, OH 44139, United States (http://www.keithley.com/).
5Phillips Scientific, 31 Industrial Avenue, Suite 1, Mahwah, NJ 07430, United States (http://www.phillipsscientific.com/).
6CAEN Technologies, Inc., 1140 Bay Street, Suite 2C, Staten Island, NY 10305, United States (http://www.caentechologies.com/).
7Joerger Enterprises Inc., 51 Idle Day Drive, Centerport, NY 11721, United States (http://www.joegerinc.com/).
Unit, singles measurements for each SiPM could be conveniently performed by subsequently re-routing the corresponding input to the logic unit directly to the output of the discriminator. A similar arrangement was used in obtaining the background and noise measurements.

For a given threshold voltage, the count rate was determined by measuring the total number of counts (read from the Joerger Scaler) recorded over a given time interval, the latter measured using a stopwatch. The length of time used in each trial was decided on an *ad hoc* basis: for example, at lower thresholds (in which a larger number of counts could be expected), time intervals typically yielding greater than 100 counts were used. For moderate-to-high thresholds, if the resulting count rate was low enough that the 100-count minimum was impractical, longer time intervals were often chosen to ensure sufficient statistics were obtained to more fairly represent the count rate.

Preliminary tests showed that in some instances, the measured noise signal was larger than the corresponding background and $^{90}$Sr source signals.$^{18}$ To help minimise the noise contribution, the detectors and accompanying readout electronics were moved to a grounded, $\sim 35 \times 23 \times 12$ cm$^3$ copper box, constructed at the University of Regina, which it was hoped would provide the components with electromagnetic shielding from external radiofrequencies. Further tests showed that by shielding the detectors and power cables in such a manner, an appreciable reduction in noise (in some cases a factor of $\sim 5$ at $\sim 50$ mV threshold) could be achieved. This shielding configuration was retained throughout the experimental trials.

As always, care was taken to ensure that the SiPM and scintillator operated in an environment in which external sources of light (in particular, the ambient light of the laboratory) were kept to a minimum. All photosensitive devices were housed and operated in a dark

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$^{18}$This phenomenon was also observed when replacing the BC-416 plastic scintillator with the linear alkylbenzene (LAB) scintillator.
Figure 3.3.2: The experimental set-up used in singles measurements of the activity of a source (shown for a SiPM coupled to a wrapped BC-416 plastic scintillator). The dashed-outlined boxes are included for clarity: the upper box encloses the power supplies, while the lower indicates the electronics and measuring devices. Although the CAEN discriminator is shown, the Phillips model was also used in some instances (see text).
Figure 3.3.3: The experimental set-up used in coincidence measurements of the activity of a source, for two SiPMs (shown for two S12572-050C units coupled to a BC-416 plastic scintillator). The dashed-outlined boxes are included for clarity: the upper box encloses the power supplies, while the lower indicates the electronics and measuring devices. Although the Phillips discriminator is shown, the CAEN model was also used in some instances (see text).
enclosure: initially in a 4.5-m long, dark box, housed in the DDL, which was later replaced by the grounded copper box placed within the dark box. The various components forming the detector were connected to power supplies, current, voltage and signal-processing devices on the outside by carefully controlled openings in the walls of both enclosures. Additional precautions were employed to minimise extraneous light, such as draping a thick black cloth over the box, and switching off the laboratory lights.

3.4 Light-Producing Media: Evaluation of the BC-416 Scintillator with Various Wrappings

Attention is now paid to tests on the $13 \times 13 \times 50$-mm$^3$ block of BC-416 plastic scintillator, wrapped with various reflective materials, which – when coupled to the preferred choice of SiPM – maximises the number of photons originating from within the scintillator which are subsequently detected by the photosensor, producing a SiPM output signal with an appreciable signal-to-noise ratio. Recalling the $50 \times 90 \times 15$-mm$^3$ dimensions of the CT007 unit, the challenge is to limit the detection apparatus to a volume of $\sim 60 \times 13 \times 13$ mm$^3$, with the remaining space reserved for EIC’s electronic circuitry and Bluetooth™ technology.

Benchmark tests on commercial PRDs are often performed using $^{60}$Co (emitting $\gamma$-rays of energy $\sim 1.3$ MeV), with some industry standards also requiring the capability to detect gammas of energies as low as $\sim 60$ keV (provided, for example, by $^{241}$Am). In the current report, radiation levels at the lower limit of those typically found in potentially hazardous environments were replicated experimentally using the commercially available laboratory sources listed in Table 3.2.
It is well known that scintillators emit photons over a broad range of wavelengths [172], with many such materials having a peak emission in the general range 375 nm-480 nm [115, 172-177] (see, for example, Tables 2.1 and 2.2), providing a favourable optical coupling to commercially available SiPMs including, for example, those used in the current tests (see Table 3.1). To maximise the amount of light incident upon a SiPM, it is common practice to wrap a scintillator in a highly reflective material (providing a high reflection coefficient at the scintillator’s emission wavelength), in order to minimise the photon flux generated within the scintillator from being refracted through its surface. Additional techniques that are often employed to improve light collection include finely polishing the scintillator surface, or introducing a light guide to focus the scintillation light onto the photosensitive surface of the SiPM. A “dry” scintillator-detector coupling necessarily includes a thin air-gap between the two media, resulting in some light being lost due to reflection from the scintillator-air and air-SiPM boundaries. Application of an intermediate layer of a substance – such as optical epoxy (referred to above), optical grease or a silicon “cookie” – can noticeably increase light collection: such materials have refractive indices similar to those of the scintillator and SiPM surface, providing an optically favourable path for the transport of light to the detector.

3.4.1 Paper/Al-Foil Wrapping

Common white printer paper and aluminium foil were initially chosen as reflective materials to wrap the BC-416 plastic scintillator. The former has a typical reflectivity of ~ 0.90 (for undyed paper at a wavelength of 450 nm) [179], while Janecek and Moses [180] have reported a reflection coefficient of ~ 0.78 (at 440 nm) for commercially available aluminium foil of 0.025 mm thickness. Paper and aluminium-foil sheaths were constructed such that a layer of
### Table 3.2: Summary of the radioisotopes used in the PRD tests.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Cat. No.</th>
<th>$T_{1/2}$</th>
<th>Source</th>
<th>$E$ (MeV)</th>
<th>$A_0$ (10$^3$ Bq)</th>
<th>$A$ (10$^3$ Bq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{241}$Am</td>
<td>ST162</td>
<td>432.2 y</td>
<td>$\alpha$</td>
<td>5.485, 5.443, 5.388, 5.546, 5.512</td>
<td>3.70 (01/03/04)</td>
<td>3.65</td>
</tr>
<tr>
<td>$^{133}$Ba</td>
<td>SS258</td>
<td>10.51 y</td>
<td>$\beta$</td>
<td>0.080, 0.133</td>
<td>0.395 (01/05/90)</td>
<td>0.091</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>SS098</td>
<td>5.271 y</td>
<td>$\beta$</td>
<td>0.318</td>
<td>0.375 (01/11/89)</td>
<td>0.019</td>
</tr>
<tr>
<td>$^{90}$Sr</td>
<td>SS389</td>
<td>28.79 y</td>
<td>$\beta$</td>
<td>0.546</td>
<td>36.9 (15/11/08)</td>
<td>33.8</td>
</tr>
<tr>
<td>$^{90}$Y</td>
<td>SS389</td>
<td>64.00 h</td>
<td>$\beta$</td>
<td>2.2801, 0.5194, 0.0938</td>
<td>1.7607</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\gamma$</td>
<td>2.1862</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.2: Summary of the radioisotopes used in the PRD tests. “Cat. No.” is the catalogue number in the Radioactive Materials Inventory at the University of Regina. $A_0$ is the approximate original activity of the sample, calculated using the date of purchase (included in parentheses, in dd/mm/yy format) and the approximate activity, $A$ (listed in the inventory and assumed to have been measured on the date of its publication, July 10, 2012). $T_{1/2}$ is the half-life of the isotope (“y” and “h” indicating years and hours, respectively), while “Source” and $E$ refer to, respectively, the radiation type ($\alpha$, $\beta^-$ and $\gamma$-decay) and corresponding (approximate) energy, emitted by the isotope and/or its decay product(s). In some instances, only a selection of energies are listed. Note that $^{90}$Sr $\beta^-$-decays via $^{90}$Sr $\to^{90}$Y $\to^{90}$Zr (with the $^{90}$Zr being stable); the 1.7607 MeV and 2.1862 MeV $\gamma$s – and various ~ 1.8 – 18 keV X-rays (not shown) – emitted by $^{90}$Y have such low frequencies that $^{90}$Sr/$^{90}$Y is almost a pure $\beta^-$ emitter (with the 2.2801 MeV electron dominant). Data was obtained from reference [178].
aluminium-foil tape, manufactured by Venture Tape,\textsuperscript{19} was glued to one side of the white paper, with the foil attached to the inside surface of the sheath. This arrangement was carefully folded to enclose the four $13 \times 50\text{-mm}^2$ and one $13 \times 13\text{-mm}^2$ surfaces of the scintillator, with the remaining end-face being in contact with the SiPM.

In the following figures, comparisons are made between the frequency obtained in the presence of a source and those measured for the background and noise (using either the Phillips Scientific Model or CAEN discriminators). Note that while each of the graphs includes the frequency-threshold behaviour of the “source”, it is recalled that the overall SiPM signal due to scintillating photons originating from the source necessarily includes that of the background which, in turn, contains a noise component. Therefore, it is by observing the frequency curve of the overall signal \textit{relative} to that of the background which provides an indication of how the frequency of the \textit{actual} source varies with threshold, and hence the quality of the light-producing medium in distinguishing the source component of the SiPM signal at a given threshold.

Characteristic frequency-threshold plots were expected for both singles and coincidence measurements. At low thresholds, even thermal electrons in the Si substrate can trigger a sufficiently large output voltage signal in the SiPM to contribute to the total count. Consequently, the noise component contributes appreciably at the lowest thresholds, before decreasing by typically 2-4 orders of magnitude over a small range of threshold voltages as the threshold is increased above the voltage generated by most of the low-level SiPM and electronic noise.

Figure 3.4.4 shows plots using the Phillips Scientific Model discriminator with the out-

\textsuperscript{19} Venture Tape Corporation, 30 Commerce Road, Rockland, MA 02370-1053, United States (http://www.venturetape.com).
put signal amplified $\times 10$, the latter explaining the considerably higher frequencies measured over a larger threshold range with respect to those tests employing the CAEN device. The singles curves for units #266 and #267 (Figures 3.4.4a and 3.4.4b, respectively) are more-or-less identical, with the “total” frequency decreasing steadily from $\sim 6$ kHz to $\sim 3$ kHz over the $40 - 100$ mV threshold range. Meanwhile, the frequency due to the $^{90}$Sr source increases quite substantially with respect to the background/noise over the same range, with the former comprising almost all of the measured frequency ($\sim 1$ kHz) for $\gtrsim 80 - 100$ mV compared to the latter ($\lesssim 10$ Hz).

With respect to the coincidence plot (Figure 3.4.4c), there is an appreciable count rate due to the source even at lower thresholds, while the background and noise fall-off considerably (the former levelling-off somewhat to lie between $0.4 - 1.0$ Hz). Beyond $\sim 25$ mV, almost all of the frequency over the measured range is due to the source.

It is evident in Figures 3.4.4a-3.4.4c that the background decreases significantly with increasing discriminator threshold as the output signal resulting from scintillation photons due to secondary radiation sources in the surrounding environment of the DDL falls below threshold. The fact that all three $^{90}$Sr signal curves are significantly larger than their respective backgrounds over mid-to-high thresholds suggests that the background is not due to cosmic rays, which would be expected to deposit a similar energy ($\sim 2$ MeV/(g/cm$^2$)) in the 13-mm thick scintillator as the $^{90}$Sr $\beta^-$-particles (2.2801 MeV), resulting in similar frequency magnitude thresholds.\(^{20}\)

\(^{20}\)In calculating the energy deposition per unit distance travelled, $-dE/dx$, of particles in a material using the Bethe formula [181], it is found that at low incident momenta, the energy loss $-dE/dx$ decreases to a minimum, before increasing steadily with increasing momentum. Particles with momenta corresponding to this minimum – such as cosmic-ray muons – are known as minimum ionising particles (MIPs), and the loss $-dE/dx$ within a material is relatively constant, with the stated value of 2 MeV/(g/cm$^2$) being the commonly accepted result [171].
(a) Singles (SiPM #266): $^{90}\text{Sr}$, BC-416 scintillator, Al-foil wrapping.

(b) Singles (SiPM #267): $^{90}\text{Sr}$, BC-416 scintillator, Al-foil wrapping.

(c) Coincidence (SiPMs #266 and #267): $^{90}\text{Sr}$, BC-416 scintillator, Al-foil wrapping.

Figure 3.4.4: Frequency-threshold graphs, in the presence of the $^{90}\text{Sr}$ source, for SiPMs #266 and #267, dry coupled individually (in singles mode) and collectively (in coincidence mode) to a paper/Al-foil-wrapped, BC-416 plastic scintillator. Note that it is the behaviour of the “source” (i.e., dark blue) curve relative to the background (red) curve which provides an indication of how the frequency of the $^{90}\text{Sr}$ signal varies with threshold (see text). Measurements were performed with the SiPM signal being amplified (×10) prior to entering the Phillips Scientific Model discriminator.
In Figure 3.4.4, as with all frequency-threshold graphs in this chapter, the error, \( \sigma_f \), in frequency \( f = N/\Delta t \), in which \( N \) is the total number of counts (with error \( \sigma_N = \sqrt{N} \)), is given via

\[
\sigma_f = \sqrt{ \left( \frac{\partial f}{\partial N} \right)^2 \sigma_N^2 + \left( \frac{\partial f}{\partial \Delta t} \right)^2 \sigma_{\Delta t}^2 } \tag{3.4.1}
\]
as

\[
\sigma_f = \sqrt{ \frac{N}{(\Delta t)^2} \left[ 1 + N\sigma_{\Delta t}^2 \right] } , \tag{3.4.2}
\]
in which \( \sigma_{\Delta t} \) is the error in the run-time \( \Delta t \).

Figure 3.4.5 involves the \( ^{60}\text{Co} \) source with the CAEN discriminator and an unamplified signal. Over the much smaller range of thresholds, the graphs exhibit the characteristic behaviour discussed above. For example, in the singles curves, for thresholds \( \lesssim 4 \text{ mV} \), the background/noise frequency dominates the overall signal (even comprising approximately one-third of it at 4 mV), before the noise falls off by a factor of \( 10^4 \) over the range 4 – 8 mV. The background does not decrease as dramatically, being reduced to \( \sim 0.1 – 1 \text{ Hz} \) over the range 6 – 25 mV. While the overall signal approaches that of the background at higher thresholds, in the threshold “window” of 5 – 15 mV the signal due to the \( ^{60}\text{Co} \) is dominant: for example, at 10 mV the source frequency measured by SiPM #266 is a factor of \( \sim 50 \) larger than the background. That is, the PRD operating in this configuration within this threshold window would easily detect \( ^{60}\text{Co} \).

As in Figure 3.4.4c, the frequency contribution from the source dominates the coincidence curve (Figure 3.4.5c) at low threshold, being 3 – 4 times larger than background/noise.
(a) Singles (SiPM #266): $^{60}$Co, BC-416 scintillator, Al-foil & BC-620 wrappings.

(b) Singles (SiPM #267): $^{60}$Co, BC-416 scintillator, Al-foil & BC-620 wrappings.

(c) Coincidence (SiPMs #266 and #267): $^{60}$Co, BC-416 scintillator, Al-foil & BC-620 wrappings.

Figure 3.4.5: Frequency-threshold graphs similar to those in Figure 3.4.4, except for the $^{60}$Co source, coupled to a BC-416 plastic scintillator wrapped alternately in Al foil and BC-620 reflective paint. Measurements were performed with the CAEN model discriminator and no amplification.
even at the lowest recorded measurement. The noise is reduced by a factor of $\sim 1000$ over a range of 2 mV, providing a negligible contribution at thresholds beyond 3 mV. A similar threshold window of $2 - 13$ mV exists over which the vast majority of the counts arise from the source rather than background.

### 3.4.2 BC-620 Reflective Paint Wrapping

Bicron BC-620, a diffuse, reflective paint manufactured by Saint-Gobain Crystals,\(^2\) was tested as a scintillator wrapping. This is a highly efficient reflector (with a reflectivity of $\sim 0.96$ over a wavelength range of $\sim 440 - 550$ nm\(^2\)) employing a special grade of titanium dioxide in a water-soluble binder. Each $13 \times 50$-mm$^2$ side received three coats of paint.

Singles and coincidence measurements for the $^{60}$Co source are presented alongside those for the paper/Al-foil wrapping in Figure 3.4.5. In comparison with the corresponding measurements of the latter, it is evident that above the smaller thresholds, replacing the paper/Al-foil with reflective paint leads to a steady increase in light production over the mid-range ($\sim 6 - 17$ mV) of thresholds, before the two signal curves reach a maximum difference, and approach each other at the higher threshold voltages. In both singles measurements, the frequency curve for the reflective paint is approximately four-times greater than that of the paper/Al-foil by $\sim 15$ mV, and almost an order of magnitude larger by $\sim 17$ mV. Meanwhile, in coincidence mode, the frequency curves of the background are of similar shape and magnitude as those observed in the paper/Al-foil measurements, while the total curve for the paint is a factor of $\sim 10$ times larger than the corresponding paper-foil result in the range $15 - 17$ mV.

\(^{21}\)Saint-Gobain Crystals, 17900 Great Lakes Pkwy, Hiram, OH 44234, United States (http://www.crystals.saint-gobain.com/).

The performance of both wrappings over the mid-range of thresholds suggests that, given the relative inexpense of both materials, the BC-620 reflective paint would be more suitable for the needs of the current project.

### 3.4.3 Polytetrafluoroethylene (PTFE) Thread Seal Tape Wrapping

Due to its very high reflectivity ($\sim 0.99$ at 440 nm \cite{172, 182-184}), common, store-bought Polytetrafluoroethylene (PTFE) thread seal tape was considered as a wrapping.\footnote{PTFE is a synthetic fluoropolymer of tetrafluoroethylene, often known as “Teflon”, the brand name originally due to the DuPont Company (E. I. du Pont de Nemours and Company), who discovered the compound.} Figures 3.4.6 and 3.4.8a show frequency-threshold data for $^{241}$Am, $^{133}$Ba and $^{60}$Co sources. It is clear from the singles measurements in Figure 3.4.6 that in the case of $^{60}$Co, beyond the initial sharp decline below 5 mV, the total frequency remains in the range $\sim 1$ – 40 Hz over a wide threshold window, only falling below 1 Hz at approximately 23 mV. While the background curves are generally in agreement with those found using the previous wrappings ($\sim 0.1$ Hz beyond the initial decrease at low thresholds) – suggesting that any systematic errors in the measurements are at a minimum – it is evident that the signal due solely to the $^{60}$Co is significantly larger than the background, comprising $\gtrsim 95\%$ of the total count rate over the 10 – 20-mV window.

In Figure 3.4.7, the frequency ratios of the BC-620 to paper/Al-foil, and PTFE to paper/Al-foil signals, as a function of the threshold, are presented for the source data given in Figure 3.4.6. For example, at a threshold of 17 mV, the PTFE frequency is $\sim 2$ times greater than that of the BC-620 for the singles measurements, with this factor increasing to $\sim 3$ for the coincidence results. At 20 mV, a direct comparison between the corresponding data shows that the PTFE frequency is larger than that of the BC-620 by factors of $\sim 3.5$, $\sim 4.3$ and $\sim 7.1$, for the #266, #267 and coincidence measurements, respectively. The superior response of
the PTFE wrapping over such a wide threshold window (e.g., 15-20 mV), with respect to the other candidates, suggests a preference for it as the wrapping of choice when coupled to the BC-416 scintillator.

Motivated by the superior performance of the PTFE wrapping, a further test looked at the possibility of enhancing the light collection of the SiPM by optically coupling its surface to the bare end-face of the wrapped scintillator with optical epoxy. Recall that in dry contact, since an air-gap necessarily exists between the two surfaces, there is the possibility of light exiting the scintillator being reflected off the epoxy surface of the SiPM, and hence not be collected. However, the optical glue has a refractive index similar to that of the plastic scintillator, enabling the photons to travel from the scintillator to the SiPM without reflection, thus improving light collection by the SiPM.

Figure 3.4.8a shows the resulting singles data for three sources and background. Comparing the background and $^{60}$Co curves with those in Figure 3.4.6b, the effect of the glue can be seen to increase the frequencies by factors of $\sim 3 - 10$ over the range $5 - 20$ mV. However, the $^{241}$Am source performs poorly, with most of the $\alpha$-particles being stopped by the PTFE wrapping: the few scintillation photons detected by the SiPM are not recorded at moderate-to-high thresholds, and so the resulting frequency curve is essentially that of the background. Although producing a slightly higher frequency than $^{60}$Co between $3 - 7$ mV, the $^{133}$Ba curve does not maintain this count rate, the lower-energy $\gamma$-rays being unable to generate large enough SiPM voltage signals at higher thresholds, the frequency quickly decreasing to background level at $\sim 16$ mV.

The effect of polishing the scintillator before wrapping can be understood by comparing the above measurements with those of a polished scintillator. Figure 3.4.9 shows the results
Figure 3.4.6: Frequency-threshold graphs for the PTFE-wrapped, unpolished BC-416 plastic scintillator using the $^{60}$Co source. The data has been overlaid on that of Figure 3.4.5, to allow for comparison with both the paper/Al-foil and BC-620 results. Measurements were performed with the CAEN model discriminator, no amplification, and a dry SiPM/scintillator contact.
(a) Singles (SiPM #266): $^{60}$Co, BC-416 scintillator; BC-620:Al-foil & PTFE:Al-foil ratios.

(b) Singles (SiPM #267): $^{60}$Co, BC-416 scintillator; BC-620:Al-foil & PTFE:Al-foil ratios.

(c) Coincidence (SiPMs #266 & #267): $^{60}$Co, BC-416 scintillator; BC-620:Al-foil & PTFE:Al-foil ratios.

*Figure 3.4.7*: BC-620:Al-foil and PTFE:Al-foil frequency ratios for the BC-416 plastic scintillator using the $^{60}$Co source, based upon the corresponding data in Figure 3.4.6, to allow for a comparison between the BC-620 and PTFE results.
(a) Singles (SiPM #266): $^{241}$Am, $^{133}$Ba & $^{60}$Co, BC-416 scintillator, PTFE wrapping.

(b) Singles (SiPM #269): $^{90}$Sr, LAB scintillator, paper/Al-foil wrapping.

Figure 3.4.8: Frequency-threshold graphs for PTFE-wrapped scintillators. (a) The $^{241}$Am, $^{133}$Ba & $^{60}$Co sources, using SiPM #267 in glued contact (singles mode) with a PTFE-wrapped BC-416 plastic scintillator. Measurements were performed with the CAEN discriminator. (b) The $^{90}$Sr source, using SiPM #269 in in greased contact (singles mode) with a paper/Al-foil-wrapped vial of LAB (liquid) scintillator. The background was recorded using the Phillips Scientific discriminator while the frequencies due to the source and noise were measured using a Tektronix TDS2022 Oscilloscope.
(a) Singles (SiPM #266): $^{60}$Co, BC-416 scintillator, Al-foil, BC-620 & PTFE wrappings.

(b) Singles (SiPM #267): $^{60}$Co, BC-416 scintillator, Al-foil, BC-620 & PTFE wrappings.

(c) Coincidence (SiPMs #266 & #267): $^{60}$Co, BC-416 scintillator, Al-foil, BC-620 & PTFE wrappings.

Figure 3.4.9: Frequency-threshold graphs for the PTFE-wrapped, polished (†) BC-416 plastic scintillator for the $^{60}$Co source. The corresponding data in Figure 3.4.6 – for paper/Al-foil-, BC-620- and PTFE-wrapped unpolished (§) BC-416 scintillator – has been overlaid for comparison with the paper/Al-foil and BC-620 results. Measurements were performed with the CAEN discriminator and no amplification.
of Figure 3.4.6 with the background and $^{60}$Co curves for the corresponding polished scintillator overlaid. Both the source and background curves for the polished scintillator fail to maintain the frequency level of their unpolished counterpart over a wide threshold range. In singles and coincidence modes, while the unpolished scintillator yields significantly larger source frequencies at 5 mV compared to the polished results (a factor of $\sim 50$ in all three instances), there is a marked decrease in the source curves of the unpolished scintillator with increasing threshold. For example, at 20 mV the polished and unpolished signal curves are of similar size for the singles measurements, while in coincidence mode the unpolished signal frequency is $\sim 2 - 3$ times smaller than the corresponding polished result.

3.5 Light-Producing Media: Evaluation of the LAB Scintillator

Liquid organic scintillators such as linear alkylbenzene (LAB)\footnote{LAB (C$_{6}$H$_{5}$C$_{n}$H$_{2n+1}$, in which $n = 10$–13) is a solvent mixture of several monoalkyl-derivatives of benzene [185]. Physical properties of typical LAB-based liquid scintillators are listed in Table 2.2.} are of importance in several fields (see, for example, references [186–189]), particularly in low-energy neutrino detection [185, 190, 191].\footnote{LAB is the preferred scintillator of the DEAP-3600 (Dark Matter Experiment using Argon Pulse-shape discrimination) experiment based at the SNOLAB facility (the Sudbury Neutrino Observatory, Ontario, Canada), the SNO+ neutrino detector (also housed at SNOLAB) [192], and in other neutrino detectors such as the RENO experiment (South Korea), LENA (Finland) and Daya Bay Reactor Neutrino Experiment (China).} Such materials hold several advantages over plastic and crystalline scintillators: for example, they are of low cost, possess a transparency to self-radiation [185] ($\sim 20$ m in the case of LAB), and often produce a higher light yield.

Although a full immersion of a SiPM in the LAB would maximise the light-collection solid angle of the detector, an uncertainty over its behaviour in chemical contact with the detector.
tector led to the submersion plan not being pursued. While LAB is of low toxicity, compatible chemically with acrylic polymers [185], and possesses a relatively high flash temperature (130°C [193]), no data was available to assess any potential chemical corrosion on the SiPM components (for example, epoxy surface and mount) over time. Consequently, a 3 × 3-mm² SiPM (#269) was attached (with a greased contact) to the surface of a cylindrical vial containing LAB, with the whole ensemble wrapped in aluminium foil followed by white paper (Figure 3.6.10a). Measurements were performed with the Phillips Scientific discriminator (background) and Tektronix TDS2000C Digital Storage Oscilloscope26 (90Sr source and noise).

Singles measurements are shown in Figure 3.4.8b for a 90Sr source. Compared to the singles measurements in Figure 3.4.4a or 3.4.4b, which used the paper/Al-foil-wrapped plastic scintillator, it can be seen that the frequency curve for the total signal is at least an order of magnitude smaller over the range of thresholds considered (taking into account the ×10 amplification of the previous test). The total frequency shows an appreciable decrease over the threshold range, more so than the corresponding decrease in, for example, Figure 3.4.4a. This behaviour, together with concerns over its chemical reactivity, led to the paper/Al-foil-wrapped liquid scintillator being eliminated as a candidate light-producing medium.

3.6 Light-Producing Media: The Lead Mini-calorimeter

As an alternative to the wrapped plastic and liquid scintillators discussed above, a miniature lead calorimeter (Figure 3.6.10c) was tested as a light-producing medium. This was a 26 × 13 × 13-mm³ block, machined out of an excess piece of lead/scintillating-fibre matrix

26Tektronix Inc., 14350 SW Karl Braun Drive, P.O. Box 500, Beaverton, OR 97077, United States (http://www.tek.com/).
(Figure 3.6.10b) obtained during the construction of fifty-two, \( \sim 228 \text{ cm}^2 \times 390 \text{ cm} \) GlueX electromagnetic calorimeter modules at the University of Regina in 2011. Forty-eight such modules were used in the barrel calorimeter (BCAL) of the GlueX experiment, housed in Hall D at the Thomas Jefferson National Accelerator Facility (Jefferson Lab\textsuperscript{27}) \[194–196]\textsuperscript{28}

In high-energy physics experiments, calorimeters measure the energies and spatial locations of both charged and neutral particles incident upon the detector. The output signal from a calorimeter is proportional to the total energy deposited (with the proportionality factor determined through calibration of the detector). For an incident particle depositing its energy in the absorbing material, characteristic energy-dependent interactions initiate particle showers/cascades which are subsequently detected. In an electromagnetic calorimeter, incident electrons and photons initiate electromagnetic showers of secondary photons, electrons and positrons. As the shower proceeds through the depth of the calorimeter, the overall number of secondary particles in the medium increases exponentially, with each successive generation having a decreased average energy. Secondary electrons can dissipate their energy through ionisation,\textsuperscript{29} whereas the dominant interactions for secondary photons in lead at low energies are photoelectric absorption \((E_{\text{photon}} \lesssim 0.5 \text{ MeV} \textsuperscript{197})\) and Compton scattering \((E_{\text{photon}} \approx 0.5 - 5 \text{ MeV} \textsuperscript{197})\). These particles produced in the electromagnetic showers can impact the embedded scintillating fibres throughout the depth of the calorimeter, generating scintillation photons which travel the length of the fibre, via total internal reflection, to the

\textsuperscript{27}Thomas Jefferson National Accelerator Facility, 12000 Jefferson Ave, Newport News, VA 23606, United States (https://www.jlab.org/).

\textsuperscript{28}The scintillating fibres were Kuraray SCSF-78MJ, double-clad, blue-green fibres, manufactured by Kuraray (Kuraray America Inc., Headquarters 2625 Bay Area Boulevard, Suite 600 Houston, TX 77058, United States (http://www.kuraray.us.com/)).

\textsuperscript{29}For electron energies greater than the critical energy \(E_c\), radiative loss through bremsstrahlung and Čerenkov radiation dominates the energy loss from ionisation.
Photograph of the \(\sim 48\)-mm-high, \(\sim 14\)-mm-diameter PTFE-wrapped vial.

Schematic of the lead-scintillating-fibre (Pb-SciFi) matrix.

Photograph of the \(26 \times 13 \times 13\) mm\(^3\) lead mini-calorimeter.

Figure 3.6.10: Photographs and/or schematic of the lead mini-calorimeter and LAB scintillator. (a) Photograph of the vial containing the scintillator, with the \(3 \times 3\)-mm\(^2\) SiPM #269 attached to the outer, curved surface of the vial (its two pins being clearly visible). The vial was wrapped in PTFE tape (see Section 3.7). (b) The schematic of the Pb-SciFi matrix shows the placement of the 1-mm fibres (from Leverington [196]). (c) Photograph of the lead mini-calorimeter. This lead/scintillating-fibre matrix was machined out of an excess piece obtained during construction of the GlueX electromagnetic barrel calorimeter modules at the University of Regina (see text).
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photodetector.

Empirically, it is found that the probabilities of Compton scattering and photoelectric absorption vary as \( Z/E_{\text{photon}} \) and \( Z^{4.5}/E_{\text{photon}} \), respectively, for an atomic number \( Z \) of the absorbing medium.\(^{39}\) In lead (\( Z = 82, E_c = 7.42 \text{ MeV} \) [197]), it is found [197] that at the photon energies listed in Table 3.2, Rayleigh scattering, Compton scattering and photoelectric absorption are the important processes attenuating the shower particles.

Placing a Hamamatsu S10943-0258(X) series SiPM (3×3 mm\(^2\)) in dry contact with an end-face of the miniature lead calorimeter-scintillating fibre block, the \(^{60}\)Co source was placed on one side. Various electronics set-ups were used in the tests in order to identify the best configuration. For example, the SiPM was self-triggered, discriminating on the split-output signal (using the Phillips Scientific Model device at 60 mV threshold) after having amplified the signal (using the \( \times 10 \) LeCroy amplifier). A PMT was employed as an external trigger (using a light-guide between the mini-calorimeter and PMT), with a discriminator threshold of \( \sim 17 \) mV.

However, it was found that the mini-calorimeter yielded a count rate of \( \sim 3 \)-times lower than in the case of the BC-416 block, indicating a considerably lower efficiency of light detection in comparison with the plastic scintillator. This can be attributed to the significant absorption of incident radiation by the lead. For \( E_{\text{photon}} = 1.333 \text{ MeV} \) photons in lead, the total mass attenuation coefficient is \( \mu_m = 0.0564 \text{ cm}^2/\text{g} \), with the dominant contribution from Compton scattering \( (\mu_m^{\text{Compton}} = 0.0433 \text{ cm}^2/\text{g}) \), followed by photoelectric absorption \( (\mu_m^{\text{photo.abs.}} \sim 0.0104 \text{ cm}^2/\text{g}) \), with that due to (nuclear field) pair production being \( \mu_m^{\text{pp}} = 0.0007 \text{ cm}^2/\text{g} \) [198]. Calculations show that the incident photon intensity is atten-

\(^{39}\)At higher energies \( (E_{\text{photon}} \gtrsim 5 \text{ MeV} \) for photons in lead [197]), pair-production is the dominant photon process in matter, with a cross section \( \sim Z^2 \log_e (2E_{\text{photon}}) \).
uated by $\sim 47.3\%$ after travelling 1 cm in lead, with a $\sim 27.7\%$ energy absorption. For $\beta$-radiation, since $E_{\text{electron}} = 0.318 \text{ MeV} \ll E_c$, the energy loss will be largely due to collisions/ionisation in the lead: it is found that electrons and positrons have a mass stopping power of $1.238 \text{ MeV cm}^2/\text{g}$ \cite{[199]}. These values suggest that the relatively low efficiency of the mini-calorimeter can be attributed to a significant absorption of the incident radiation from $^{60}\text{Co}$ by the lead: only a few incident particles manage to deposit their energy in the scintillating fibres.

3.7 Application of EIC Electronics

Various frequency-threshold measurements were repeated with the nuclear electronics in the DDL replaced by those associated with a Tri-Met TM372A sample counter provided by EIC (Figure 3.7.11). Designed as a completely self-contained, gross $\alpha$-counter, the TM372A (model #4) originally contained a sample tray, with a ZnS scintillator coupled to a PMT. The electronics consisted of a discriminator and $\times 10$ amplifier, implemented using the “Gain” switch (Figure 3.7.11a); a “Pre-set Time” can be used to establish a user-defined time range over which a scaler counts the number of detected events in real time, output via an LED display.

3.7.1 Light-Producing Media: BC-416 Plastic Scintillator

Recall that using the DDL electronics, it was established that of the candidate light-producing media, a $3 \times 3$-mm$^2$ SiPM glued to the PTFE-wrapped BC-416 plastic scintillator provided
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Figure 3.7.11: Photograph of the TM372A unit, provided by EIC. (a) Front view of the device, showing the various controls referred to in the text. (b) View of the circuit.
the more favourable light-collection combination. An almost identical configuration was adopted for measurements with the TM372A device, with black electrician’s tape wound around the SiPM-scintillator in order to reduce light leakage from, and extraneous light to, the detector (a layer of white paper was introduced between the PTFE and black tape).

Using the readout electronics shown in Figure 3.2.1b, the $3 \times 3$-mm$^2$ SiPM was connected to the preamplifying circuit of the TM372A device. Preamplifiers typically employ an $RC$ circuit in order to shape the SiPM pulse – increasing its amplitude and decay time – prior to it being processed by subsequent electronics. The amplitude of the output signal determines the charge deposited in the SiPM (which is proportional to the energy), whereas a long decay time ($\sim 100 \mu$s) ensures complete charge collection from the SiPM (the rise time is controlled by the characteristics of the detector itself). In TM372A’s existing preamplifying circuit, the pulse shape is dominated by a $1 \, \text{M} \Omega$ resistor: the effect of this original $RC$ circuit – as well as two slight modifications – on the frequency of the resulting SiPM output signal were investigated. An accompanying $100 \, \text{k} \Omega$ resistor, placed in parallel with the $1 \, \text{M} \Omega$ component (to increase the amplitude of the pulse), and an additional $1 \, \mu \text{F}$ capacitor (to increase the decay time, through the time constant $RC$) were both attached, in turn, to the TM372A board.

Frequency-threshold behaviour for source, background and noise measurements was analysed for the above configurations, with the discriminator threshold adjusted using the rotary button shown in Figure 3.7.11a, and the number of counts recorded in the pre-set time establishing the frequency.\footnote{Note that the scale on the discriminator of the TM372A could not be established relative to that of the CAEN and Phillips devices.} The TM372A also supplied the bias to the detector (adjustable via a potentiometer), with a small connection added to the electronics board (Figure 3.7.11b) to allow monitoring of the bias using a multimeter. As in the trials using the DDL electronics, the
ambient RF signal was minimised by housing the SiPM/scintillator in the sealed, grounded copper box.

For the purposes of discussing the results, let the 1 MΩ circuit be referred to as “circuit A”, that incorporating both the parallel 1 MΩ and 100 kΩ resistors be “circuit B”, and that involving the 1 μF capacitor alongside the 1 MΩ and 100 kΩ resistors be “circuit C”. Figure 3.7.12 shows results for 241Am, 133Ba and 60Co, along with their corresponding noise and background spectra, for circuits A, B and C.

Over the range of thresholds, it can be seen that circuits B and C result in the larger noise frequencies: for example, in the case of circuit B the noise is a factor of ~ 40 bigger than that of circuit A at a ~ 0.5-unit threshold, rising to ~1700 times larger than that of circuit A at a 1.3 unit threshold. Meanwhile, the noise curve for circuit C (i.e., the addition of the 1 μF capacitor) does not offer any appreciable increase with respect to circuit B. That is, it is the addition of the 100 kΩ resistor to the RC circuit which results in a higher noise frequency. Whereas the noise of circuit A falls away quite rapidly with increasing threshold, those of circuits B and C provide significant contributions to the background and “total” signal over a large range of thresholds.

For 241Am (Figure 3.7.12a), over a narrow threshold window of ~ 0.5 – 0.9 units the source signal due to circuit A is slightly larger than its corresponding background, while the same appears to be the case for circuits B and C over the range ~ 1.0 – 1.5 units. However, in all three cases, the signals quickly approach the background, becoming more-or-less indistinguishable at high thresholds.

In contrast, for 133Ba (Figure 3.7.12b), while the backgrounds remain at ~ 1 – 2 Hz beyond 1.2 threshold units, the total frequencies are clearly distinguishable over the same range.
A similar pattern is true in the case of $^{60}$Co (Figure 3.7.12c): once the noise falls below approximately 1 Hz, the total signals in all three circuits are about 50 times larger than their respective backgrounds. Therefore, a comparison of the source signals suggests that while the current set-up struggles to identify the $^{241}$Am source, it is quite capable of detecting both $^{133}$Ba and $^{60}$Co.

Although previous work had suggested a preference for the $3 \times 3$-mm$^2$ SiPM units, it was nevertheless decided to perform a series of trials incorporating the $1 \times 1$-mm$^2$ units using EIC's electronics. Since Figure 3.7.12 established that the preamp circuit with only the additional 100 kΩ consistently led to higher frequencies, the frequency-threshold behaviour of $^{133}$Ba and $^{60}$Co using one of the $1 \times 1$-mm$^2$ SiPMs was investigated. The noise, background and total frequencies (shown in Figure 3.7.13a) appear to be of approximately one order of magnitude less than their $3 \times 3$-mm$^2$ counterparts.\[3\]

### 3.7.2 Light-Producing Media: LAB Scintillator

Frequency-threshold measurements were performed with the set-up shown in Figure 3.6.10a – that is, with a $3 \times 3$-mm$^2$ SiPM (unit #269) in a greased coupling to the curved surface of a cylindrical vial containing LAB scintillator, the ensemble wrapped in PTFE tape – was tested with the EIC electronics (with unit #266 used, for convenience, to measure the noise). Each source of interest was placed, in turn, against the PTFE wrapping, diametrically opposite the SiPM. Since the corresponding BC-416 measurements discussed above demonstrated that the $RC$ circuit with the additional 100 kΩ resistor consistently led to the highest frequencies, this

\[3\] As shown in Figure 3.7.12, units #184 and #188 were both used in measurements (see Table 3.1). Whereas unit #188 was glued to the PTFE-wrapped scintillator for background and source measurements, it was convenient to use unit #184 to measure the noise.
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(a) $^{241}$Am: BC-416 scintillator & PTFE wrapping.

(b) $^{133}$Ba: BC-416 scintillator & PTFE wrapping.

(c) $^{60}$Co: BC-416 scintillator & PTFE wrapping.

Figure 3.7.12: Frequency-threshold graphs for the PTFE-wrapped BC-416 plastic scintillator. (a) The $^{241}$Am source. (b) The $^{133}$Ba source. (c) The $^{60}$Co source. In each case, the noise measurements were obtained using SiPM #266, while the background and source used SiPM #267. The specific $RC$ circuits are indicated as follows; $A$: 1 MΩ resistor, $B$: 1 MΩ and 100 kΩ resistors in parallel, and $C$: 1 μF capacitor alongside the parallel 1 MΩ and 100 kΩ resistors.
configuration was implemented.

Measurements of the background, and in the presence of $^{133}$Ba and $^{60}$Co sources, for two “degrees” of wrapping were performed. Initially, a straightforward (“normal”) PTFE wrapping of the curved and bottom surfaces of the vial was considered. However, since potential loss of light through the screw-cap end of the vial was of concern, an additional, more “complete” PTFE wrapping over the vial screw thread and opening was performed (before replacing the black screw cap).

Figure 3.7.13b shows the results of the various trials. It is seen that the “complete” PTFE wrapping does indeed give rise to slightly higher frequencies, relative to the “normal” wrapping, in all three cases (background and sources). Apart from the case of the “complete” wrapping within the very narrow window of 1-2 threshold units, the results show that for $^{133}$Ba the signal is not sufficiently above background over the threshold range to suggest that $\gamma$-rays from $^{133}$Ba could be detected with confidence using this set-up. In contrast, above $\sim 1$ threshold unit, the total signal involving $^{60}$Co consistently remains more than one order of magnitude above the background.

3.7.3 Light-Producing Media: PEN Scintillator

Polyethylene Naphthalate (PEN) is a thermoplastic polyester synthesised by the polycondensation of dimethyl-2,6-naphthalenedicarboxylate and ethylene glycol [122]. Of great importance in the textile industry, PEN is readily available due to the significant worldwide commercial market surrounding its use in, for example, common household objects such as din-

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Note that as in Figure 3.7.13a, the measurements shown in Figure 3.7.13b used two MPPC units as a matter of convenience, with #267 being in greased contact with the scintillator (for source and background measurements), and #266 used for noise.
ner sets and plastic containers. Using a spectrometer, Nakamura et al. [122] have measured a light yield of $\sim 10500$ photons/MeV and peak emission wavelength of 425 nm, suggesting that PEN possesses scintillation properties comparable to well-known commercial organic scintillators such as BC-408, while being superior to BC-416 (Table 2.2).

A $210 \times 290 \times 1$ mm$^3$ sheet of PEN, obtained from Teijin Chemicals, was cut into thirteen $13 \times 1 \times 50$ mm$^3$ strips. Gluing the $13 \times 50$ mm$^2$ sides together (using epoxy glue) formed a $13 \times 13 \times 50$ mm$^3$ prism of similar dimensions as the BC-416 scintillator block discussed previously. A $3 \times 3$ mm$^2$ SIPM (#267) was glued to one of the $13 \times 13$ mm$^2$ end-faces, and the resulting combination wrapped completely in successive layers of PTFE tape, white paper and black tape. This scintillator-detector arrangement was placed in the copper dark box, as previously, with the 100 kΩ resistor still employed as part of the RC circuit.

From Figure 3.7.13, it is apparent that the $^{90}$Sr, $^{60}$Co and background curves obtained using PEN are of relatively low frequency. For example, comparing the $^{60}$Co curve with that obtained with the BC-416 plastic scintillator (Figure 3.7.12c), it is quite clear that after its initial sharp decrease at very low threshold values, the frequencies obtained using PEN are at least two orders of magnitude smaller over a wide range of thresholds. Given the light-yield of PEN reported by Nakamura and co-workers, it is difficult to understand the rather large deviation between PEN and BC-416 in the present results. A possible source of discrepancy may involve

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9The optical adhesive employed was BC-600 Optical Cement, a clear epoxy resin formulated specifically for creating optical joints with plastic scintillators such as BC-416. The epoxy consists of a two-part mixture of resin and hardener (manufactured by Saint-Gobain Crystals) – in the ratio of 100:28 – producing a low-viscosity adhesive which cures at room temperature. See, for example, the data sheet at http://www.crystals.saint-gobain.com/uploadedFiles/SG-Crystals/Documents/SGC%20BC600%20Data%20Sheet.pdf.

37As in Figure 3.7.13b, it was convenient to use MPPC unit #266 to measure the noise.
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Figure 3.7.13: Frequency-threshold graphs of singles data, measurements performed with EIC electronics. No amplification was applied. (a) The $^{133}$Ba and $^{60}$Co sources, using SiPMs #184 and #188, glued to PTFE-wrapped, BC-416 plastic scintillator. (b) The $^{133}$Ba and $^{60}$Co sources, using SiPMs #266 and #269 with a greased coupling to a vial of LAB liquid scintillator: † indicates a "normal" amount of PTFE wrapping, ‡ indicates a "complete" amount PTFE wrapping (see text). (c) The $^{60}$Co and $^{90}$Sr sources, using SiPMs #266 and #267 glued to a PTFE/paper/black-tape-wrapped PEN scintillator. Note that in each figure, the use of different units from the same MPPC series was purely for convenience (see text).
the PEN scintillator used in the current tests being an amalgamation of strips of PEN, rather than as a single block.

3.8 Neutron Detection with SiPMs

Traditionally, $^3$He has been amongst the most effective isotopes used in neutron detection. In a $^3$He-filled detector, thermal neutrons ($\sim 0.025$ eV) are absorbed by $^3$He, the process $^3$He $+ \alpha \rightarrow ^1$H $+ ^1$H $+ 0.764$ MeV having a relatively large absorption cross section ($3330$ b [107]). The charged products are subsequently detected by a gas proportional counter (see, for example, Crane and Baker [200]). Helium-3 is obtained as a by-product of the $\beta$-decay ($^3$H $\rightarrow ^2$He $^+ + e^- + \bar{\nu}_e$) of the tritium extracted from nuclear-weapons production. However, due to the reduction in nuclear-weapon stockpiles by the United States and Russia, and increased use by U.S. Homeland Security, the past several years have seen a world-wide shortage of $^3$He [201]. This has prompted alternative methods of thermal neutron detection [201, 202] to be sought.

One approach has been to use neutron conversion in neutron-active materials such as $^6$Li or $^{10}$B together with a ZnS scintillator (Table 2.1) in a colourless, epoxy binder (for example, LiF-ZnS(Ag), with the silver acting as an activator). These neutron-active materials allow for an enhanced neutron-detection capability, offering a more localised and more rapid neutron-detection capability than is possible using the more traditional gas detectors [200].

In a $^3$He-filled detector, thermal neutrons ($\sim 0.025$ eV) are absorbed by $^3$He, the process $^3$He $+ \alpha \rightarrow ^1$H $+ ^1$H $+ 0.764$ MeV having a relatively large absorption cross section ($3330$ b [107]). The charged products are subsequently detected by a gas proportional counter (see, for example, Crane and Baker [200]). Helium-3 is obtained as a by-product of the $\beta$-decay ($^3$H $\rightarrow ^2$He $^+ + e^- + \bar{\nu}_e$) of the tritium extracted from nuclear-weapons production. However, due to the reduction in nuclear-weapon stockpiles by the United States and Russia, and increased use by U.S. Homeland Security, the past several years have seen a world-wide shortage of $^3$He [201]. This has prompted alternative methods of thermal neutron detection [201, 202] to be sought.

One approach has been to use neutron conversion in neutron-active materials such as $^6$Li or $^{10}$B together with a ZnS scintillator (Table 2.1) in a colourless, epoxy binder (for example, LiF-ZnS(Ag), with the silver acting as an activator). Thermal neutrons incident upon the $^6$Li initiate the process $^6$Li($\alpha$,n,$^4$He)$^7$H (with an absorption cross section $\sim 910$ b and detection efficiency of $\sim 55\%$ [203]), the resulting heavy $\alpha$-particles exciting the ZnS(Ag) scintillator. The $\sim 160000$ scintillation photons produced per initial neutron [204, 205] (efficiency $\sim 9.2\%$ at 450 nm) [204] are detected using wavelength-shifting (WLS) fibres [202, 206] cou-
pled to an appropriate photosensor. In PRDs, where space is limited, scintillator-based detectors are known [107] to provide a larger neutron detection efficiency per unit volume than, for example, $^3$H-tubes. Although several authors have utilised large-area single- or multi-anode PMTs [207–211], these photodetectors are not feasible in PRDs due to cost and volume considerations. Osovizky, Ginzburg and co-workers have recently employed a PMT in the development of a prototype device, offering a 100-cm$^2$ detection area, capable of the simultaneous detection of $\alpha$- and $\beta$-particles [212]. Low-cost, small-sized devices such as the SiPM seem to be ideally suited for implementation in such systems. However, as outlined elsewhere, the intrinsic dark rate of SiPMs operated at room temperature is significantly higher than that of the PMT: direct replacement of PMTs by SiPMs requires a substantial reduction of the dark rate of the latter, which can only be achieved through an appreciable cooling [140, 213] (lending additional cost and space-requirements to the PRD). Recently, Stoykov and co-workers [214, 215] have reported the development of a ($1 \times 1$ mm$^2$) SiPM-based $^6$LiF-ZnS($^6$LiF) neutron detector of dimensions $2.4 \times 2.8 \times 50$ mm$^3$ to be operated at room temperature.

Boron-10 has a large thermal neutron absorption cross section ($\sim 3838$ b [193]), based upon the well-known neutron-capture reactions $^{10}$B($^3$n,$^7$He)$^7$Li, namely

$$^{10}\text{n} + ^{10}\text{B} \rightarrow \begin{cases} \, ^7\text{Li} \left( 1.015 \text{ MeV} \right) + ^4\text{He} \left( 1.777 \text{ MeV} \right) \quad (6\%) \\ \, ^7\text{Li}^* \left( 1.47 \text{ MeV} \right) + ^4\text{He} \left( 1.47 \text{ MeV} \right) + \gamma \left( 0.478 \text{ MeV} \right) \quad (94\%) \end{cases}. \quad (3.8.3)$$

As a result, many $^{10}$B-enriched materials are better suited to neutron detection than, for exam-
ple, $^6$Li. For instance, semiconducting boron carbide (B$_4$C)\textsuperscript{39} has been used for several years in thin-film diodes for solid-state neutron detection (see, for example, references \cite{217–220}).

After neutron capture, the $^7$Li and $\alpha$-particles have short ranges, depositing their energies into the scintillator. However, as the main-branch reaction in (3.8.3) suggests, a considerable number of photons are emitted, which can be subsequently detected in a similar approach as above – for example, via a WLS fibre coupled to a photosensor.

A prototype thermal neutron detector was constructed using a simple, but novel, approach involving B$_4$C for neutron conversion (according to (3.8.3)), and ZnS(Ag) to convert the resulting $\alpha$-particles into scintillating photons (which could be subsequently collected by a WLS fibre coupled to a SiPM). Figure 3.8.14 provides a schematic of the detector: a single $\sim$ 20-cm long piece of WLS fibre was cut and polished, and coated with a single layer of ZnS(Ag) powder using a clear, non-yellowing and commercially available spray adhesive.\textsuperscript{40} The coated fibre was housed in a B$_4$C micropowder\textsuperscript{41} “sheath”, with Scotch-tape enclosing the ensemble. Fixing this set-up to a support, one end of the WLS fibre was placed in dry contact flush against the surface of a Hamamatsu S12571-050C 1 x 1-mm$^2$ SiPM.\textsuperscript{42}

The detector was placed in close proximity to the $^{241}$Am-Be neutron “howitzer” located inside the radiosources storage room in the Department of Physics at the University of Regina. Positioned such that a steady stream of thermal neutrons was incident upon it, a series of tests

\textsuperscript{39}It is well known (see, for example, Domnich et al. \cite{216}) that the stoichiometry of boron carbide is not exactly 4 : 1. In practice, the material is always very slightly carbon deficient, and X-ray crystallography reveals a complex structure of C-B-C chains mixed with B$_{12}$ icosohedra.

\textsuperscript{40}Krylon All-Purpose Spray Adhesive, manufactured by the Krylon Products Group, 101 W. Prospect Ave., Cleveland, OH 44115, United States (http://www.krylon.ca/).

\textsuperscript{41}The B$_4$C micropowder was obtained from Delta Scientific Laboratory Products Ltd., 346 Watline Avenue, Mississauga, ON L4Z 1X2, Canada (http://www.delta-sci.com/).

\textsuperscript{42}The properties of the S12571-050C SiPM and its accompanying readout module (C11205-150) were already well-known to researchers in the SPARRO group. For example, in spite of its large amplifier, the unit was known to have very little noise.
(a) ZnS(Ag)- and $B_4C$-coated WLS fibres.  
(b) Neutron-detection schematic.

![Photograph/schematic of the neutron-detection set-up and ADC spectra.](image)

Figure 3.8.14: Photograph/schematic of the neutron-detection set-up and ADC spectra. (a) The upper WLS fibre is coated with ZnS(Ag) (white), while the lower fibre shows a ZnS(Ag)-coated fibre with an outer layer of $B_4C$ micro-powder, enclosed in a common tape sheath. (b) Schematic of the experimental set-up. Neutrons incident on the outer $B_4C$ layer ultimately result in scintillation photons entering the WLS fibre (see text). (c) & (d) Normalised ADC spectra (signal, background and noise) from thermal neutron detection at 34 mV threshold.
were performed to assess the quality of the detector. Figures 3.8.14c and 3.8.14d show signal, background and noise spectra at a discriminator threshold of 34 mV. While the background was measured several metres away from the neutron source, the noise component was obtained by measuring the signal due solely to a (separate) ZnS(Ag)-coated fibre.

The pedestal peak at low energy is clearly visible in the ADC spectra, with the background and noise signals having largely disappeared by channels 350 and 750, respectively. It is possible to conclude that since the source signal forms an appreciable and clearly identifiable portion of the overall ADC spectrum, these preliminary tests show that neutrons are indeed being detected, and that further development of the prototype is of interest.
Chapter 4

Application: Nuclear Imaging

Scintigraphic methods in nuclear medicine have their origins in the pioneering work of Seidlin et al. [221] in 1946, and in the development of the first rectilinear scanner [222] and Anger (scintillation) camera [223] in the 1950s. Significant advances in subsequent decades have firmly established medical imaging as an important field in modern clinical medicine and medical research. Modern imaging devices are potentially capable of resolving structures at a cellular level, and such technology is proving to be an essential tool in the molecular imaging of biological processes in both humans (for example, in oncology [224] and neurology [225–227]) and small animals (in drug development [228]).

Radioisotope use in plant physiology pre-dates medical imaging [70], with $^{14}$CO$_2$ first utilised as a tracer in photosynthesis studies in 1939 [229, 230]. However, specialised systems and techniques developed for imaging and image processing in nuclear medicine and biomedical research will continue to be of critical importance in, for example, plant phenomics [231],

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1Plant phenomics is the study of the structural, biochemical, physiological and performance-related characteristics/traits of plants in response to, for example, genetic mutation and environmental factors [231].
in the twenty-first century [232]. For instance, fears of the effects of rapid population growth and global climate change on the supply of food [233] have led to interest in the production of crops that are resistant to stresses resulting from factors such as droughts and temperature extremes, as well as attacks from microbial, viral and bacterial sources [233]. Although the genetic modification of crops is commonplace, their yield is determined by both the genotype of the plant and its growth environment [233].

Reviews of non-invasive imaging and image processing have been given by Dhondt et al. [231] and Fiorani et al. [234]. Imaging modalities used to study plants have included visible techniques [235], as well as CT [236] (in imaging the root-soil interface) and MRI [235]. Carbon-11, and other isotopes used in the radiolabelling of molecules of biological importance (such as $^{13}$N, $^{15}$O and $^{18}$F), are all positron emitters, making positron emission tomography (PET) a valuable imaging technique for plant studies. There have been numerous studies reported in the literature which have developed and/or applied PET devices to the plant and soil sciences. For example, several groups have studied processes in subsurface soils – such as the geochemical transport (by imaging and modelling soil hydrology [237–240]), as well as monitoring in situ bacterial activity [241]. At the Brookhaven National Laboratory, Pritchard and co-workers [242] used a modified clinical PET scanner to study the distribution of metabolites in plant roots, while Budassi et al. [243] and Wang et al. [233] have developed prototype PET-based plant imagers. Other groups have also reported modified clinical and pre-clinical PET devices: in Japan, the “PETIS” system (“Positron Emitting Tracer Imaging System”) [244–250] has been used to study barley [244] and rice [245, 246]. The “Plant Tomographic Imaging System” (“PlanTIS”) [251–254], developed at the PhytoSphere Institute in Jülich, Germany, has been used to study phloem transport in the leaves of a species of oak
tree [255]. There is also a report of a hybrid device: Garbout et al. [256] have used a hybrid clinical PET/CT scanner to track the uptake of $^{14}$CO$_2$ through the plant and root structure of a radish plant.

Of relevance to the current study is the “PhytoPET” system due to Weisenberger and co-workers [67, 69, 71, 257–259].\(^2\) Housed in the Phytotron in Department of Biology at Duke University, PhytoPET is a collaboration between Duke, Jefferson Lab and the University of Maryland,\(^3\) that utilises the accelerator facilities of the Triangle Universities Nuclear Laboratory (TUNL) to produce $^{14}$C. Through funding by the Sylvia Fedoruk Centre, there is a plan to introduce a similar system at the University of Regina: initially, an exact replica of the Duke device (employing position-sensitive PMTs as the photosensor) will be installed and tested, and subsequently upgraded to include SiPMs.

PET systems utilising PMTs are typically bulky, expensive devices with a limited quantum efficiency. Even replacing the PMT by APDs (the latter offering, for example, a higher QE and more compact structure) presents difficulties with timing properties and a degraded signal-to-noise ratio [260]. Recently, there has been considerable interest in combining arrays of SiPMs into large-area, multi-channel detector modules [72, 261–276]. Such devices often include readout electronics and are available commercially as turnkey systems optimised for use in PET detectors (see, for example, references [272, 275]). Depending upon the arrangement of electronic readout channels, two distinct detector designs have emerged [277], resulting in so-called position-sensitive SiPMs [263, 268, 278–280] and array-pixel SiPMs [62, 281–283].\(^4\) In the former, each pixel in the detector is connected in a simple readout tech-

\(^2\)The same group have also developed “PhytoBeta” [68, 70], a compact $\beta^+/-\beta^-$-particle imager for $^{14}$CO$_2$-leaf imaging.

\(^3\)West Virginia University was also part of the institutional collaboration until 2012.

\(^4\)Here, we consider a SiPM array as a square configuration of $n^2$ pixels ($n = 1, 2, 3, \cdots$). Each pixel is
nique (for example, by a built-in resistor-grid method), with only five readout channels re-
quired (four for positioning and one for timing [263, 268, 278, 279]). While this approach has
enjoyed some success, the spatial and temporal resolution of these devices is currently limited
by their large capacitance and high dark-count rate [277, 284].

The array-pixel design is based upon numerous separate SiPM pixels located on the same
silicon substrate. Although each pixel provides excellent timing [275, 285, 286], and 1:1 cou-
pling is possible (thus minimising detector decoding errors) [277], such a design results in a
relatively large number of output channels if each pixel is readout individually. Under such
circumstances, a complicated channel multiplexing architecture is typically implemented to
reduce the number of output channels leaving each module [287–294].

This project utilises two such array-pixel SiPM devices, with the reported results intended
to provide a preliminary step towards a complete characterisation of both detector modules,
in preparation for their proposed use in the PhytoPET system. As such, Section 4.1 provides
a brief discussion of the physics underlying standard PET scanners, while in Section 4.2 an
overview of the structure and operation of the selected SiPM array detector is presented. A
basic synopsis of the multiplexing architecture used in the SiPM array is discussed in Section
4.3 in order to facilitate an understanding of the results presented in Section 4.4.

Given the necessity for fast, high-light-yield scintillators in modern PET systems, previ-
ously reported works involving the MatrixSM-9 system [277, 295] have focused exclusively
on coupling with LYSO and/or LSO scintillators. Furthermore, in their user MatrixSM-9
manual, SensL provide a list of “recommended settings” for various system parameters, op-
considered to be a collection of $\sim 10^3 - 10^4$ microcells.

While multiplexing decreases the number of output channels, lowering the cost and decreasing the com-
plexity of the subsequent DAQ electronics [294], it can also lead to a degradation in detector performance [277].
timised using LYSO, as well as a $^{22}\text{Na}$ energy spectrum. While it will be necessary for similar scintillators to be eventually incorporated into the Saskatchewan PhytoPET system, the current work presents results of important module-characterisation tests using a BC-416 plastic scintillator as part of the initial “proof-of-principle” phase of the project, while offering experience to the group in thoroughly understanding the basic operational characteristics of the units before using them for image reconstruction.

### 4.1 A Brief Introduction to PET Physics

Following the evaluation of each SiPM array detector, subsequent trials are planned which will operate the two detectors in coincidence mode. Interest in coincidence measurements is motivated by the physical mechanism underlying positron emission tomography. In conventional PET systems, a radionuclide $^A_Z\text{X}$ inserted into a sample (e.g., patient) undergoes positron ($\beta^+$)-decay via $^A_Z\text{X} \rightarrow ^A_{Z-1}\text{Y} + \beta^+ + \nu_e$ (in which $\nu_e$ is an electron neutrino). After travelling several millimetres, the positron annihilates with an electron ($e^-$) through the process $e^- + \beta^+ \rightarrow \gamma\gamma$ (Figure 4.1.1a). The two 511 keV photons, emitted essentially back-to-back, are detected in coincidence by two scintillator/photosensor arrangements (typically a pixellated crystal array coupled to a PMT) placed on diametrically opposite sides of the sample. The detection of such events establishes a so-called line of response (LOR), that is, a volume of the sample in which the annihilation could have occurred. Dedicated image-reconstruction

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$^6$Note that the range of positrons is material- and $\beta^+$-energy-dependent, decreasing with the increasing material density, as well as being proportional to the $\beta^+$ energy. For example, consider the maximum/average ranges of $\beta^+$ (of maximum energy $E^\text{max}_{\text{positron}}$) in water for the following radionuclides: $^6\text{C}$ ($E^\text{max}_{\text{positron}} = 0.97$ MeV): 3.8 mm/0.85 mm, $^{11}\text{N}$ ($E^\text{max}_{\text{positron}} = 1.20$ MeV): 5.0 mm/1.15 mm, $^{18}\text{O}$ ($E^\text{max}_{\text{positron}} = 1.74$ MeV): 8.0 mm/1.80 mm, and $^{18}\text{F}$ ($E^\text{max}_{\text{positron}} = 0.64$ MeV): 2.2 mm/0.46 mm. See, for example, Saha [46].

$^7$Shibuya et al. [296] have measured the non-collinearity of the two 511 keV photons from the human body to deviate from 180° by a Gaussian distribution with FWHM (0.54 ± 0.02)°.
algorithms are used to process all such LORs from a circular ring of detectors (Figure 4.1.1b), yielding a spatial map of the radionuclide activity in the sample. For example, cluster information recorded in “Region of Interest” mode from MatrixSM-9 blocks operating in coincidence can be used in positional algorithms such as the centre-of-gravity algorithm due to Anger [297].

4.2 The SensL MatrixSM-9 System

As part of SensL Photonics’ series of large-area SiPM array detectors, the Matrix system\(^8\) (Figure 4.2.2) was the first modular, turnkey readout system designed specifically for imaging applications in nuclear medicine (see, for example, the MatrixSM-9 user manual\(^9\)). Such a device provides a fully solid-state, four-side scalable photodetector optimised for coupling to fast scintillator arrays of LYSO or BGO (Table 2.1). The high degree of modularity, relative pixel uniformity, digitised output signal, good timing resolution and reasonable energy resolution \([295]\), coupled with the advantages of the SiPM, make the system a suitable alternative to PMT-based detectors in applications which require high-resolution imaging, such as in positron emission tomography (pre-clinical PET, positron emission mammography and small-animal PET), SPECT and the gamma camera [295].

There have been at least two studies characterising the energy and time properties of the Matrix 9 system in assessing its suitability for PET. Sanjani et al. [295] coupled two detectors

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\(^8\) SensL’s nomenclature identifies the particular series of SiPMs used in the Matrix 9 modules. For example, use of the “L” (2010) and “M” (2012) series of SiPMs are reflected in the names of the MatrixSM-9 and MatrixSL-9 models, respectively. The past three years have seen the release of the “B” (2013) and “C” (2014) series, with the “J” series imminent.

Figure 4.1.1: Overview of the operation of a conventional positron emission tomography (PET) scanner. (a) Cartoon showing the physical mechanism underlying PET: the positron ($\beta^+$) from a $\beta^+$-emitting radionuclide annihilates with a nearby electron ($e^-$), producing two back-to-back 511 keV photons. (b) Example of the circular scintillator/photodetector arrangement used in conventional PET systems. The photograph shows the multi-anode PMT configuration used in the PhytoPET system at Duke University (courtesy of the Jefferson Laboratory).
Figure 4.2.2: Overview of SensL's MatrixSM-9 system, showing the modular nature of the detector. (a) Basic components of the system. Note that the front-end electronics board shown on the right is housed permanently within the MatrixSM-9 Readout Module shown on the left. The $3 \times 3$ SiPM array is clearly visible on the Sensor Head of the MatrixSM-9 Readout module (see text). The MatrixSM-9X1 or MatrixB-9X1 Sensor Head were not used in this study, and so their details may be omitted. From the SensL “Matrix System User Manual” (http://www.sensl.com/downloads/ds/UM-MatrixSM9.pdf). (b) Cartoon of the connections between three Readout Modules, each with a serial connection to the EVB communications/coincidence board by an 80-way flexible IDC connector (green). Power to the board and modules is provided by $+5\,\text{V}$ and $+35\,\text{V}$ inputs, respectively. The board itself may be connected to a PC via a high-speed USB cable. From Sanjani et al. [295]. See also Figure 4.2.2. (c) The EVB communications board, showing the three primary connections (USB2, IDC and power inputs). From the Matrix System User Manual.
to a $13.1 \times 13.1 \times 20 \text{ mm}^3$ pixelated $(4 \times 4)$ LYSO crystal and, using a $^{22}\text{Na}$ source, evaluated the energy resolution and gain uniformity of both detectors, and measured their coincidence time resolution. Meanwhile, motivated by the success of a small-animal PET scanner based upon the PMT [298], Du et al. [277] coupled an $8 \times 8 \times 6 \text{ mm}^3$ LSO array to an L-series Matrix 9 module (and using a $^{68}\text{Ge}$ source) to evaluate the detector as a candidate to replace the PMT.

Figure 4.2.2 provides an overview of the modular design of the system. There are two principal hardware subsystems: one or more Readout Modules (of dimensions $\sim 46 \times 48 \times 133 \text{ mm}^3$) – each housing a Sensor Head and integrated front-end readout board – and a Matrix-EVB communication/coincidence board. Power to the system was supplied by a W-IE-NE-R$^{10}$ multi-channel high- and low-voltage modules housed in an MPOD mini crate,$^{11}$ with main power provided by an LV module ($4 \text{ V} - 5.5 \text{ V, } 1 \text{ A to the Matrix-EVB board} \text{ and } 0.5 \text{ A per Readout Module}$) and bias ($35 \text{ V} - 40 \text{ V, } 5 \text{ mA per Readout Module}$) supplied by the HV module.

The Sensor Head (Figure 4.2.2) is a large-area $3 \times 3$ array of 144 SiPM pixels, based upon SensL’s SiPM technology (MatrixSM-9-30035-OEM), with each array comprised of 16 SiPMs arranged in a $4 \times 4$ configuration, the surface covered by $\sim 0.5\text{-mm}$ thick thermoset clear epoxy glass (of refractive index 1.54 at 589 nm). Properties of the SensL M-series are provided in Table 4.1. Upon detection of an event by the Sensor Head, the resulting signal is processed by the front-end electronics: a specific multiplexing architecture (Section 4.3) channels an array and pixel signal through a preamplifier and then a comparator, providing the spatial


$^{11}$For documentation, see the W-IE-NE-R MPOD manual (revision 2.7.1) at http://file.wiener-d.com/documentation/MPOD/WIENER_MPOD_Manual_2.7.1.pdf.
location of the event. The signal is time-stamped, shaped (yielding the energy of the signal), and flagged (through programmable array/pixel effective threshold discriminators). A 12-bit serial ADC digitises the signal, which is subsequently read out to the EVB communications board through a fast serial interface, while timing information is acquired via a 16-bit TDC with a timing resolution of 0.5 ns. Additional details of the signal processing by the ADC and TDC devices can be found in the MatrixSM-9 user manual.

The Matrix-EVB board is capable of supporting up to sixteen individual Readout Modules operating in singles or coincidence modes. It provides a common 50 MHz clock, and upon receiving and buffering event data from the Readout Module(s) (Figure 4.2.2) at a rate of 50 Mbps, transfers spatial, temporal and energy data to the PC via a two-way high-speed USB interface (Figure 4.2.3b). In coincidence mode, additional temporal-coincidence analysis on candidate events is performed by SensL firmware installed on the board itself, reducing the data transfer rate to the PC.

A series of software and firmware tools freely available from the SensL website provides a user-friendly interface with the Readout Module and EVB board, both in the processing, analysing and displaying of channel event data received from the EVB board, and in the programming of various operational parameters via the Main-Dialogue screen of the GUI (Figure 4.2.4a). Of particular interest are the following settings:

• **Array Threshold & Pixel Threshold**: sets the effective discriminator threshold voltages for the nine array and sixteen pixel signal channels by amounts above corresponding

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### Table 4.1: Properties of the SensL MatrixSM-9-30035 SiPM model, of size $3 \times 3$ mm². Each unit contains 4774 microcells, with a microcell size of $35 \times 35 \mu$m. All measurements are made at $V_{ob} = +2$ V (that is, $V_{br} + 2$ V) and 21°C. Values obtained from the SensL M-series data sheet, available from http://sensl.com/downloads/ds/DS-MicroMseries.pdf.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
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<tr>
<td>Breakdown voltage, $V_{br}$</td>
<td>27.0 V - 28.0 V</td>
<td>Defined as the reverse bias at which a 100 nA current flows in dark conditions</td>
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<td>Overvoltage</td>
<td>1.0 V - 5.0 V</td>
<td></td>
</tr>
<tr>
<td>Spectral range</td>
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</tr>
<tr>
<td>Peak wavelength, $\lambda_{max}$</td>
<td>500 nm</td>
<td></td>
</tr>
<tr>
<td>PDE (at $\lambda_{max}$)</td>
<td>20%</td>
<td>“True” sensor PDE, excluding crosstalk and afterpulsing</td>
</tr>
<tr>
<td>Gain, $G_e$</td>
<td>$2.3 \times 10^6$</td>
<td>Anode-to-cathode readout</td>
</tr>
<tr>
<td>Dark current</td>
<td>3.8 $\mu$A (typical)</td>
<td>8.0 $\mu$A (max.)</td>
</tr>
<tr>
<td>Dark current rate</td>
<td>10 MHz (typical)</td>
<td>Derived from dark-current measurement as $N_{dark} = \frac{I_{SiPM}}{G_e/q} (Hz)$</td>
</tr>
<tr>
<td></td>
<td>22 MHz (max.)</td>
<td></td>
</tr>
<tr>
<td>Rise time</td>
<td>0.8 ns</td>
<td>Measured as 10%-90% of peak amplitude</td>
</tr>
<tr>
<td>Signal pulse width</td>
<td>2 ns</td>
<td>Fast output (FWHM)</td>
</tr>
<tr>
<td>Microcell recovery time</td>
<td>130 ns</td>
<td>Time for microcell to recharge (90%-10% of pulse peak amplitude)</td>
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<td>Capacitance (anode cathode)</td>
<td>870 pF</td>
<td>Internal capacitance of sensor</td>
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<td>Capacitance (fast terminal to cathode)</td>
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<td>Temperature dependence of $V_{br}$</td>
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<td>Change in $V_{br}$ from pulsed laser gain measurements</td>
</tr>
<tr>
<td>Cross talk</td>
<td>21%</td>
<td></td>
</tr>
</tbody>
</table>
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(a) Dimensions of the MatrixSM-9 Sensor Head, showing the $12 \times 12$ pixel array.

(b) Data transfer between the Sensor Head, readout and communications boards.

Figure 4.2.3: Schematics of the MatrixSM-9 Sensor Head and readout/communications boards: (a) The schematic of the Sensor Head, showing the 144 SiPM pixels arranged in a $12 \times 12$ configuration. The overall dimensions are $46.31 \times 47.80$ mm$^2$, with each pixel measuring $3.17 \times 3.17$ mm$^2$. The intra-array dead space is $\sim 0.2$ mm, while the inter-array dead space is $2.22$ mm and $2.75$ mm in the horizontal and vertical directions, respectively. The pixel sensitive area is $8.12$ mm$^2$, and $dE/E$ (FWHM) for LYSO at 511 keV is $< 17 \%$. The optical response uniformity over all pixels - defined as the ratio of the pixel response to the median pixel response - is $< \pm 10 \%$. Figure from Du et al. [277] (b) Data transfer between two Sensor-Head/Readout-Electronics modules (top part of the figure) and the coincidence/communication board (bottom part). Figure from SensL's "MatrixSM Family Product Brief", revision 1.1, November 2013 (retrieved from http://www.sensl.com/downloads/ds/PB-Matrix9SM.pdf).
array/pixel offset values.

- **SPM Bias**: allows the bias voltage provided to all 144 SiPM pixels to be set collectively: set to 32.5 V.

- **Mode**: enables the user to choose between:
  - *Plot pixels*: event count-rate data is displayed on the GUI map in real time.
  - *Stream to file*: FIFO event data is streamed continuously to an output file (for post-processing).

- **Format**: determines the mode of operation, based upon information recorded for a fired pixel:
  - *Single energy mode*: displays the time stamp, pixel/array location and energy value of the fired pixel.
  - *Region of interest*: displays additional energy information of the cluster – that is, the energies of the eight surrounding pixels.
  - *All Energies*: displays additional energy information of all sixteen pixel energies in the corresponding array.

Although adjustable via the GUI interface, the remaining parameters shown in Figure 4.2.4 were fixed at values suggested in the SensL MatrixSM-9 manual (optimised for 511 keV gamma rays and LSO/LYSO scintillator). After running the detector block over a user-defined time interval at a particular array and pixel threshold, the resulting data is save to file and analysed.
(a) MatrixSM-9 GUI: Main-Dialogue screen.

(b) MatrixSM-9 GUI: Energy/timing-plot screen.

Figure 4.2.4: Screenshots of the MatrixSM-9 GUI software, showing the main and energy/timing screens. Values of typical settings are shown in both cases (see text).
4.3 Multiplexing: The Scrambled Crosswire Readout

Several multiplexing schemes have been reported in the literature. For instance, a simple row-column summing method combines the output signals originating from the same row/column, producing four outputs which are used to obtain the position and energy of an incident scintillation photon. Initially developed for multi-anode PMTs [299], this has been applied to SiPMs by Wang et al. [270]. A different strategy, also originally applied to PMTs [300] and subsequently to SiPMs, is the so-called Discretised Proportional Counter (DPC) approach [288, 291, 294, 301–303]. This technique feeds the SiPM signals into a charge division resistor network to produce four outputs, again allowing spatial and energy information of the initial photon to be calculated.

Figure 4.3.5a shows the multiplexing architecture used in the SensL MatrixSM-9 readout module to reduce the complexity of the readout electronics. The Scrambled Crosswire Readout (SCR) technique enables the 144 pixels to be readout by only twenty-five data channels. In each array, a total SiPM array signal is formed by summing the sixteen cathode pixel signals. Meanwhile, the anode signals from the same pixel in each of the nine arrays are summed together to form a SiPM pixel signal. Therefore, the hypothetical 144 output channels are reduced to 9 array and 16 pixel channels.

To enable very precise time stamps to be recorded (of particular importance when operating in coincidence mode), the SCR design requires the availability of a fast trigger signal. When a particular SiPM pixel fires, the resulting pixel signal triggers the DAQ to digitise the 16 pixel signals while the array pulse identifies the corresponding array. In this way the array/pixel location of the fired pixel can, in theory, be found. However, as pointed out by Du et al. [277], since it is the first array signal arriving at the DAQ which is analysed, the array
location of a fired pixel can be determined incorrectly. If the effective array threshold is sufficiently low that the array is triggered by noise, the array in which the “true” event originated will be erroneously determined. It is only at high array thresholds – above that of the noise, but still less than the true array signal – that the correct event location will be recorded.

4.4 Measurements Using the SensL MatrixSM-9 Modules

In the present work, the EVB communications board is identified by its ID number 15B181E9, and the two detector blocks, with ID numbers 2CCF2 and 2CFFA4, are referred to as the “OLD” and “NEW” modules, respectively. A series of noise and source singles measurements were performed initially with two MatrixSM-9 detector blocks, with the goal of characterising each block in preparation for a set of coincidence measurements (characterisation involved finding the optimal operating conditions with respect to array/pixel discriminator thresholds, minimal noise contribution, and appreciable count rate over an acceptable run time). As in Chapter 3, noise measurements were performed by operating the detector blocks in the absence of a source or scintillator. Source measurements were recorded using the same 13 × 13 × 50 mm³ PTFE-wrapped BC-416 plastic scintillator used in Chapter 3, which was placed up against the Sensor Head (in a dry or wet connection – the latter using grease or a Si-cookie), with a source placed approximately half-way along the scintillator. Measurements were performed with the entire ensemble – Readout Modules, scintillator and source – placed in a dark box, with a thick black cloth draped over the box to minimise light-leakage into the box. The ambient temperature inside black box was not controlled, but monitored using a common thermometer placed ~1-2 cm from the Sensor Head, with the temperature

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This labelling scheme is purely chronological, referring to their acquirement by the University of Regina.
(a) The Scrambled Crosswire Readout multiplexing technique. From Du et al. [277].

(b) The MatrixSM-9 array-labelling scheme.

(c) The MatrixSM-9 pixel-labelling scheme.

Figure 4.3.5: Schematic of the multiplexing and labelling schemes used in the MatrixSM-9 system. (a) The Scrambled Crosswire Readout (SCR) multiplexing technique used in the Matrix9-SM module. From Du et al. [277]. (b) The array- and pixel-labelling scheme used by the MatrixSM-9 software. Note that whether or not these labels correspond to those on the physical Sensor Head depends upon the orientation of the detector block (see text). From the MatrixSM-9 user manual.
of the Sensor Head itself monitored via an integrated digital temperature sensor located under the detector head (granularity 0.125°C), with output on the Main Dialogue screen.

To identify a pixel on a Sensor Head, the MatrixSM-9 software uses the representation shown in Figures 4.3.5b and 4.3.5c, which correspond to the map on the Main-Dialogue screen. However, there is some potential for confusion in using this labelling scheme in conjunction with the physical Sensor Head. Although the rectangular sides differ by 1.49 mm (Figure 4.2.3a), with respect to the eye the Sensor Head arguably appears square. In all subsequent measurements, the Readout Module was oriented such that the 80-way IDC connector on its end-face is positioned horizontally, with the SensL logo upright. This introduces a rotation of the array/pixel labels, whereby the location of, for example, array “0”, on the Sensor Head is rotated +90° relative to array “0” on the GUI map.

Figure 4.4.6 shows several configurations of scintillator-SiPM array couplings investigated as part of this work. Typical PET systems can incorporate numerous pixelated scintillators, with the end-face dimensions of each matched precisely to the active area of a SiPM array, and a careful alignment of each pixel to a corresponding SiPM. However, the current set-up utilised a single block of the plastic scintillator, with the $13 \times 13$-mm$^2$ end-face being of slightly smaller area than the $13.48 \times 13.48$-mm$^2$ area of each array in the Sensor Head. Although pixelated scintillators would not normally be positioned astride neighbouring arrays in PET systems – as in positions “A” and “B” in Figure 4.4.6a – the response of the MatrixSM-9 to such configurations was investigated nevertheless.

Figures 4.4.8 and 4.4.7 show a series of frequency histograms at a pixel threshold voltage of 0.07 V for the “OLD” and “NEW” modules, with the PTFE-wrapped BC-416 scintillator (together with the $^{90}$Sr source) in dry contact astride positions “A” and “B”, respectively. It is
Figure 4.4.6: Schematic showing the approximate positions of the 13 × 13-mm² end-face of the BC-416 plastic scintillator (not drawn to scale), relative to the Sensor Head. (a) The end-face positioned astride multiple arrays: position “A” (astride arrays 6 and 7) and position “B” (astride arrays 4, 5, 7 and 8). (b) The end-face positioned over array 4: in position “C” the end-face is offset from the 4 × 4 SiPM configuration by ~ 2.72 mm, while in position “D” the end-face lies over the 4 × 4 SiPM configuration.
evident that in comparing results of both modules at the same array threshold, quite different frequency histograms can result, in spite of both devices being of the same series. In both figures, for each module, at the lowest array threshold (0.08 V) the frequency histograms show quite an appreciable noise contribution distributed throughout the 144 pixels (especially in the case of the “OLD” module), while at an array threshold of 0.13 V, the noise is sufficiently reduced, revealing those arrays indeed covered by the scintillator. These results are consistent with the observation of Du et al. [277] discussed above; that is, the undesirable triggering by noise at low array thresholds leads to an erroneous determination of the location of the fired pixels, resulting in a “smearing out” of the scintillator’s “image” across the whole array-pixel structure. It is only when the array threshold is set above the noise that the correct locations of the fired pixels are recorded.

However, it is notable that in both Figures 4.4.8 and 4.4.7, the source-induced scintillator “image” is not limited to those pixels in actual contact with the scintillator face (that is, those pixels indicated as being fully or partially covered in Figure 4.4.6a). Rather, any of the pixels in the corresponding arrays appear capable of being fired. As well as due to some effect arising from the SCR architecture, a possible explanation for this phenomenon could be the dry scintillator/Sensor-Head contact, leading to unwanted reflections between the various boundaries. An interesting test would be to repeat these experiments with a greased contact, in order to minimise any such reflections.

An additional feature of these low-array-threshold results (see, for example, Figures 4.4.7a and 4.4.8a) is that although triggered by (random) noise, a remarkably regular pattern emerges between frequency histograms of individual arrays in the same module. One possible reason for this effect is that in the case of a particularly “hot” (i.e., high-frequency) pixel, for example,
Figure 4.4.7: Frequency (i.e., count-rate) histograms (with the vertical scale in Hz) resulting from a $^{90}$Sr source, placed on a PTFE-wrapped BC-416 plastic scintillator placed astride two contiguous arrays (numbers 6 and 7 in Figure 4.3.5b) – that is, position “A” in Figure 4.4.6a. Results are presented at a pixel threshold (PT) of 0.07 V over a range of array thresholds (AT): (a) AT: 0.08 V (“OLD” module). (b) AT: 0.11 V (“OLD” module). (c) AT: 0.13 V (“OLD” module). (d) AT: 0.08 V (“NEW” module). (e) AT: 0.11 V (“NEW” module). (f) AT: 0.13 V (“NEW” module). In all six cases, the FIFO run time was 60 s, and the temperature of the Sensor Head at the beginning of the run is included. The white areas correspond to frequencies of less than $1/60$ Hz.
Figure 4.4.8: Frequency histograms similar to those shown in Figure 4.4.7, except with the scintillator placed astride four contiguous arrays (numbers 4, 5, 7 and 8 in Figure 4.3.5b) - that is, position "B" in Figure 4.4.6a. Results are presented at a pixel threshold (PT) of 0.07 V over a range of array thresholds (AT): (a) AT: 0.08 V ("OLD" module). (b) AT: 0.11 V ("OLD" module). (c) AT: 0.13 V ("OLD" module). (d) AT: 0.08 V ("NEW" module). (e) AT: 0.11 V ("NEW" module). (f) AT: 0.13 V ("NEW" module). In all six cases, the FIFO run time was 60 s, and temperature of the Sensor Head at the beginning of the run is included. The white areas correspond to frequencies of less than $1/60$ Hz.
there is a high probability that noise will trigger the same pixel position in all the other arrays, resulting in the same pixel having a relatively high frequency in each of the other arrays. That is, the high number of counts in the original hot pixel will be smeared out amongst pixels of the same location in the other arrays.

Du et al. [277] have quantified the mispositioning of events on the central array (and hence the reduction in the “true” frequency of array 4), due to the undesirable noise-induced triggering mechanism discussed above, by introducing the *array-trigger error*, $\xi$, given by

$$
\xi = 100 \left\{ 1 - \frac{n_k}{\sum_{i=0}^{8} n_i} \right\}, \quad (i = 0, 1, \cdots, 8) ,
$$

as the percentage of total recorded events *not* detected by array 4. Here, $n_i$ is the number of events detected by array $i$. Using a $^{68}$Ge source together with a LSO scintillator, optically coupled to the MatrixSM-9 surface with optical grease, these authors have reported array-trigger-error curves for a fixed pixel threshold (0.3 V) over a wide range (0 V - 0.75 V) of array thresholds and at different temperatures ($5 - 25 \, ^\circ\text{C}$, in $5 \, ^\circ\text{C}$ steps). In Figure 4.4.9, this idea has been generalised to produce an array-trigger-error surface, in which $\xi$ has been calculated for a range of array- and pixel-threshold voltages. Here, measurements have been performed with the BC-416 scintillator in position C (Figure 4.4.6b), in greased contact with the module surface, over the temperature range $\sim 23.5 - 29 \, ^\circ\text{C}$. Note that although the array-trigger-error curves of Du et al. extend out to an array threshold of 0.75 V, in Figures 4.4.9a and 4.4.9b the maximum array threshold value is 0.2 V. It was found that at such values, obtaining sufficient statistics required increasingly longer run times. This disparity between the two experiments can be attributed to the superior light-producing capacity of LSO as compared to BC-416 (see, for example, Tables 2.1 and 2.2).
Figure 4.4.9: Array-trigger-error (defined in the text) surfaces for the "OLD" and "NEW" modules. The BC-416 plastic scintillator (with $^{90}$Sr source placed on top) was coupled to the central array (array 4) of each module in turn, in position C (see Figure 4.4.6b). The measurements contributing to both surfaces were taken over an approximate range $23.5 - 29$ °C of Sensor-Head temperatures.
With respect to Figures 4.4.9a and 4.4.9b, it is evident that the array-trigger error can vary appreciably with array threshold, as seen by the large change in $\xi$ over a $\sim 0.02$-V range. In contrast, apart from the feature at low pixel threshold and high array threshold in the case of the “OLD” module, $\xi$ does not change significantly with a change in pixel threshold. This suggests that the array-trigger error is mainly dependent upon the array threshold, while being largely independent of the pixel threshold. This is consistent with the implication of Section 4.3: due to the SCR architecture, although the pixel signal triggers a particular pixel/SiPM it is both the pixel and array signals which verify this event.

Furthermore, the surfaces show that although both modules are of the same model, they show distinctly different characteristics. In particular, while both figures show the same general shape, the “OLD” module maintains a larger array-trigger error over a wider range of array thresholds, with the sharp decrease in $\xi$ occurring at $\sim 0.12$ V, compared to $\sim 0.08$ V for the “NEW” module. This effect can be seen in Figures 4.4.7 and 4.4.8: for example, in the latter, the “OLD” module still shows a significant amount of noise at array thresholds of 0.08 V and 0.11 V (that is, at positions high on the array-trigger-error “plateau”). Meanwhile, the corresponding plots for the “NEW” module show a much lower amount of noise; the AT=0.08 V, PT=0.07 V result is in the region of the surface dominated by the steep decrease, and the AT=0.11 V, PT=0.07 V is on the low-trigger-error plateau (i.e., in which $\xi \sim 0\%$).

In these measurements, scintillator-array alignments were performed by eye, and so were susceptible to slight differences when, for example, switching between the two modules or re-assembling configurations in order to repeat earlier measurements. To investigate the resulting systematic errors that could result from such misalignments, the scintillator was placed in positions C and D (Figure 4.4.6b) – with the former offset from the latter by $\sim 2.5$ mm –
with an upper portion of the scintillator face lying in the dead space between arrays 1 and 4. Under such circumstances, it is reasonable to expect a slightly reduced amount of light hitting array 4 in position C as compared to D. In position C, care was taken to ensure that the scintillator was not astride arrays 1 and 4: preliminary measurements at high array thresholds demonstrated that, consistent with the above results, no pixels in array 1 fired.

Figure 4.4.10 shows the histograms of the (absolute) difference in frequencies between the two configurations for the scintillator in greased contact with both modules in turn. The array and pixel thresholds were chosen somewhat arbitrarily: with the exception of Figure 4.4.10a, in order to minimise the potential effect of array-trigger errors, the selected array thresholds all correspond to $\xi \sim 0\%$. These figures show that apart from, for example, pixel 2 of array 4 – which has a frequency difference of $\sim 30 - 40$ Hz – that of the vast majority of pixels seems to differ by $\lesssim 10$ Hz. Even in Figure 4.4.10a, in which Figure 4.4.9 suggests an appreciable array-trigger error, the absolute difference in frequency between the two positions is $\lesssim 2 - 3$ Hz. Therefore, in general, a slight misalignment of the scintillator in the manner shown in Figure 4.4.6b leads to a relatively small difference in frequency, as expected.
(a) OLD: AT: 0.12 V, PT: 0.13 V, 
$T = 28.375\, ^\circ C$.

(b) OLD: AT: 0.17 V, PT: 0.12 V, 
$T = 26.875\, ^\circ C$.

(c) OLD: AT: 0.18 V, PT: 0.14 V, 
$T = 27.5\, ^\circ C$.

(d) NEW: AT: 0.12 V, PT: 0.13 V, 
$T = 23.375\, ^\circ C$.

(e) NEW: AT: 0.17 V, PT: 0.12 V, 
$T = 24.5\, ^\circ C$.

(f) NEW: AT: 0.18 V, PT: 0.14 V, 
$T = 24.625\, ^\circ C$.

Figure 4.4.10: Frequency-difference histograms mimicking a misalignment of the PTFE-wrapped BC-416 plastic scintillator coupled to array 4 (using a $^{90}$Sr source). The scintillator was placed, in turn, at positions C and D of Figure 4.4.6b. The histograms show the (absolute) frequency difference between resulting measurements. With the exception of (b) and (e) – in which the FIFO run time was 60 s – the run times were 600 s. The temperatures of the Sensor Head at the beginning of the run are included. The white areas correspond to frequencies of less than $1/60$ Hz.
Chapter 5

Conclusion

Silicon photomultipliers have emerged as a rival device to traditional photosensors such as the photomultiplier tube (PMT) in numerous fields, providing many of the properties of the PMT while offering several additional advantages. Two applications of SiPMs were considered in this work: in developing a prototype personal radiation detector, and in the imaging of a radioactive source using arrays of SiPMs.

Fears over the potential use of illicit fissile material by terrorist organisations, as well as the biological threat posed by decades of use of radioactive material in, for example, military armament and nuclear-waste management, have made the need for increasingly more efficient radiation scanners/detectors crucially important. In partnership with EIC, the first part of this study focused on implementing SiPMs to develop a prototype gross-gamma counter for use by first responders and emergency workers entering potentially hazardous environments. EIC’s interest in producing a commercial product placed size and cost limitations on the prototype: the goal was to maximise the light-collection capacity of the detector while minimis-
CHAPTER 5. CONCLUSION

ing its cost. Initial measurements established individual units of the Hamamatsu S12572-050C series (with a photosensitive area of $3 \times 3$ mm$^2$) as the preferred choice of SiPM. Although nine-times larger than units of the $1 \times 1$-mm$^2$ S12571-050C series, initial self-triggering tests (the preferred configuration from the point of view of size) had established that the $3 \times 3$ units offered a superior light-collection, without being prohibitively more expensive. Subsequent trials with various combinations of light-producing media, coupled to the $3 \times 3$-mm$^2$ SiPMs, and operating in singles mode, were tested using both Regina’s and EIC’s nuclear electronics. It was established that a $13 \times 13 \times 50$-mm$^3$ BC-416 plastic scintillator, wrapped in common, highly reflective PTFE thread-seal tape, provided the largest signal-to-background measurements for gammas from $^{60}$Co and $^{133}$Ba over a moderate range of discriminator thresholds, while satisfying the spatial requirements of EIC’s existing device.

It is well known that, under identical conditions, a scintillator with a greater light yield offers a larger light-collection capacity. Although not limited to those listed in Tables 2.1 and 2.2, there are a number of materials capable of providing a significant improvement in light production than the BC-416 scintillator, and thus considered to be a more-desirable light-production medium for use in the above project. In the current PRD project, incorporating a scintillator such as LYSO or LSO in a commercially available device would not be cost-effective. While the low-cost and high light yield of NaI(Tl) would suggest it to be the ideal scintillator, its strong hygroscopicity and long decay time make it unsuitable for this work. BC-416 is marketed as a general, all-purpose scintillator, and as such is considerably less expensive than an equivalent volume of, for example, LYSO or LSO. However, a future PRD project at the DDL will seek to explore the use of GAGG scintillators as the preferred light-producing medium. Of moderate expense, such materials offer $\sim 7$ times the light yield of
Preliminary results of the neutron-detection project suggest that thermal neutrons can be detected above the background using a Hamamatsu SiPM, coupled to a WLS fibre coated with successive layers of ZnS(Ag) and B$_4$C. Further work is ongoing, with plans to develop a detector utilising a bundle of ZnS(Ag)/B$_4$C-coated WLS fibres. In a possible future collaboration with EIC, this work has the potential to lead to a marketable neutron-detection device.

As outlined in Chapter 4, while details and results of existing plant-imaging systems have been discussed in the literature, such devices have not as yet incorporated SiPMs as the photosensor. The nuclear-imaging project sought to gain a familiarity with two SensL MatrixSM-9 SiPM arrays, in preparation for their ultimate use in the “PhytoPET” plant-imaging system to be installed at the University of Regina. Initial trials imaged a $^{90}$Sr source, placed on top of the PTFE-wrapped $13 \times 13 \times 50$-mm$^3$ BC-416 plastic-scintillator block, coupled to both SiPM array modules in turn. Frequency “maps” with the scintillator in contact with the Sensor-Head surface, but sitting astride multiple SiPM arrays, showed that at sufficiently high array thresholds, a multitude of pixels in the corresponding arrays fired, even those pixels not directly covered by the scintillator. Important features of the Scrambled Crosswire Readout multiplexing architecture were observed, consistent with the observations of Du et al. [277]: in particular, the importance of the array-signal threshold voltage in providing an accurate array location of a fired pixel. The effect of a slight misaligning the scintillator block on the Sensor-Head surface was investigated, with the resulting difference in frequency typically being of a few Hertz in magnitude, as expected. Each module was characterised by producing its array-trigger-error surface, providing a quantitative basis from which effective array and
pixel discriminator thresholds can be chosen.

For the purposes of PET imaging, the light-yield of plastic scintillators is unacceptably low, while the superior performance of materials such as LYSO/LSO have resulted in their widespread use in such systems. Indeed, with respect to the MatrixSM-9 system, several of the recommended operational settings used in the current measurements – involving BC-416 – were optimised by SensL using a LYSO scintillator. Hence, although frequency measurements presented in the second part of this report provide a preliminary step in characterising the modules, they are necessarily at the lower end of what would be expected from a scintillator with superior light-yield. Work on evaluating both modules is ongoing, with further trials being performed using BC-416 with the modules operating in singles and coincidence modes. There are plans to replace BC-416 with LYSO and GAGG scintillators, as well as to introduce active and passive collimators into the experimental set-up. The culmination of the initial phase of the project will include imaging a so-called “phantom”, in order to test and, if necessary, “fine-tune” the performance of the experimental set-up. While such work will enable the SPARRO Group to develop a better understanding of the operational aspect of the project, a major part of the future work will involve the development of dedicated image-reconstruction algorithms. In this endeavour, the expertise of members of the Department of Computer Science at the University of Regina will prove invaluable.
References


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