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Performance of a monolithic $LaBr_3$:Ce crystal coupled to an array of silicon photomultipliers

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A gamma-ray detector composed of a single $28 \times 28 \times 20\ mm^3$ $LaBr_3$:Ce crystal coupled to a custom built 4×4 array of silicon photomultipliers was tested over an energy range of 30 keV to 9.3 MeV. The silicon photomultipliers were initially calibrated using 20 ns light pulses generated by a light emitting diode. The photodetector responses measured as a function of the number of incident photons were found to be non-linear and consistent with model predictions. Using corrections for the non-linearity of the silicon photomultipliers, the detector showed a linear response to gamma-rays with energies from 100 keV to the maximum available energy of 9.3 MeV. The energy resolution was found to be 4% FWHM at 662 keV. Despite the large thickness of the scintillator (20 mm) and a 5 mm thick optical window, the detector was capable of measuring the positions of the gamma-ray interaction points. The position resolution was measured at 356 keV and was found to be 8 mm FWHM in the detector plane and 11 mm FWHM for the depth of interaction. The detector can be used as a building block of a larger calorimeter system that is capable of measuring gamma-ray energies up to tens of MeV.

1. Introduction

Cerium doped lanthanum bromide ($LaBr_3$:Ce) has some of the best scintillation properties among currently known scintillator materials. Doped with 5% of cerium, lanthanum bromide crystals have a scintillation decay time of 16 ns [1,2] and a very high light yield of more than 60 000 photons/MeV [1,3,4]. A gamma-ray energy resolution of better than 3% at 662 keV has been measured for $LaBr_3$:Ce crystals coupled to photomultiplier tubes (PMTs) [1,3,5,6]. The relatively high atomic number of lanthanum ($Z=57$) makes the scintillator suitable for detection of medium and high-energy gamma-rays.

A silicon photomultiplier (SiPM) is a solid-state light detector that combines the high gain of traditional PMTs with low-voltage operation, robustness, low mass and compact design typical of semiconductor devices and required in many modern applications. A single SiPM consists of a large number of avalanche photodiodes (microcells) connected in parallel, with each photodiode working in Geiger mode. The output signal of an SiPM is essentially defined by the number of microcells fired. SiPM response to light is thus limited by the total number of microcells in the detector and has a non-linear dependence on the number of incident photons. At low light levels when only a small fraction of microcells is fired, the SiPM non-linearity is small and can often be ignored. However, for high light levels this is not the case and SiPM signals require calibration. A detailed review of the SiPM properties can be found in [7].

Many studies have already reported promising results from using SiPMs for readout of $LaBr_3$:Ce crystals. A coincidence resolving time of around 100 ps FWHM has been achieved for 511 keV annihilation photon pairs using two $3 \times 3 \times 5\ mm^3$ $LaBr_3$:Ce crystals with SiPM readout [8]. The energy resolutions measured in several studies, 6.4% FWHM at 511 keV [9], 6.5% at 511 keV [10], 5.7% at 662 keV [11], were significantly worse than the $LaBr_3$:Ce resolution typically obtained with photomultiplier tubes. However, resolutions of 4.5% and 5% at 662 keV have recently been achieved using SiPM arrays from Hamamatsu and SensL [12].

The purpose of this study is to evaluate the suitability of using SiPMs with $LaBr_3$:Ce for detection of gamma-rays with energies of up to tens of MeV. A particular application of such detectors would be calorimeter modules for combined Compton and pair telescopes in

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gamma-ray astronomy [13,14]. To efficiently absorb the energy of gamma-rays, these calorimeters would require the thickness of $LaBr_3$:Ce to be at least several centimetres. In addition to a good energy resolution, a position resolution of better than 1 cm would typically be required for optimal reconstruction of Compton events [15]. Another possible application would be a spaceborne gamma-ray spectrometer for the determination of the elemental composition of planetary surfaces [16].

For the purpose of this study, a 4×4 array of SiPMs was built and initially tested using a light emitting diode (LED). The measured response curves were compared to the simulation results obtained with a simple SiPM model accounting for saturation and cross-talk effects. Then the SiPM array was coupled to a $LaBr_3$:Ce crystal and tested with gamma-rays of different energies.

The 3D position of a gamma-ray interaction point in a single scintillator crystal can be deduced from the distribution of the scintillation light across the multi-pixel photodetector coupled to the crystal. This method is known to work very well for relatively thin scintillators (10 mm or less) [17–19]. In particular, a position resolution of 1.6 mm FWHM at 511 keV was achieved using a 10 mm thick $LaBr_3$:Ce crystal [9]. However, efficient detection of high-energy gamma-rays requires thicker calorimeters. The position resolution of a monolithic scintillator strongly depends on the scintillator thickness and one of the goals of this study is to measure the resolution that can be achieved using a thicker scintillator. While required calorimeter thickness can be achieved using several detector layers, it is important to maximise the thickness of individual layers in order to reduce the mass of passive materials inside the calorimeter, such as crystal housing, photodetectors and front-end electronics.

2. Detector and readout electronics

A detector module was built at University College Dublin using a single $28 \times 28 \times 20\ \text{mm}^3$ $LaBr_3$:Ce crystal supplied by Saint-Gobain Crystals and a 4×4 array of SiPMs. The SiPM array was custom built using sixteen $6 \times 6\ \text{mm}^2$ blue sensitive SiPMs supplied by SensL (MicroFB-60035-SMT). The SiPMs were mounted on a printed circuit board (PCB) with a space of 0.2 mm between adjacent pixels as shown in Fig. 1. In this paper, SiPM pixels, or simply pixels, refer to the 16 individual SiPMs and should not be confused with SiPM microcells. Each SiPM pixel had 18 980 microcells, yielding a total of 303 680 microcells for the 4×4 array. Two 16-pin connectors placed on the underside of the SiPM array supplied the same bias voltage to all SiPMs and allowed the readout of individual SiPM signals. The temperature of the array could be monitored using a PT100 sensor mounted on the underside of the board. The specifications of the SiPMs used in the array are listed in Table 1.

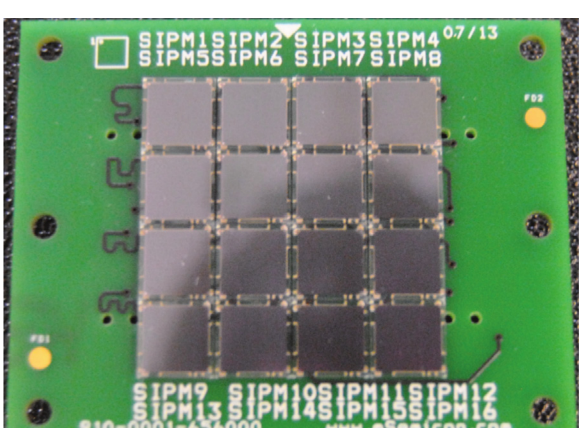

Fig. 1. SiPM array. The individual SiPMs have external package dimensions of 7×7 mm and are mounted on a PCB with a space of 0.2 mm between adjacent pixels, which results in a gap of 1.2 mm between the active areas of the pixels.

The scintillator crystal was surrounded by PTFE reflector and hermetically encapsulated with 0.5 mm of aluminium with a 5 mm thick quartz window. A 3 mm thick opaque perspex housing was used to attach the crystal to the SiPM array as shown in Fig. 2. BC-630 optical grease from Saint-Gobain Crystals was used for coupling the optical window of the crystal package to the SiPMs.

SiPMs typically have a large output capacitance, reaching about 4 nF per pixel for the detectors used in this work, and therefore require a readout with a low input impedance to prevent the SiPM signals from getting excessively slow. This is particularly important for timing applications, but can also affect the pulse height resolution for small signals as longer integration times collect more noise caused by the SiPM dark current. A discussion of possible solutions can be found in [20]. In this work, a custom board was built for individual readout of the 16 SiPM pixels, based on the single-channel preamplifier design recommended by SensL [21]. The board contained 16 fast transimpedance amplifiers with a gain of 200 V/A. In addition, a summing amplifier connected to the outputs of the 16 preamplifiers provided a common detector signal, which could be used as a data acquisition trigger. The board was connected to the back of the SiPM array using two 16-pin connectors and employed SMA connectors for the 17 output signals. The preamplifier stages could be bypassed using on-board jumpers and the individual SiPMs signals could be measured over 22 Ω resistors (in parallel with the 50 Ω input resistance of a signal digitiser). This allowed the SiPMs signals to be measured for high intensities of incident light without saturating the readout electronics.

The amplified SiPM signals were acquired using two 8-channel CAEN V1720 waveform digitisers (12 bit, 250 MS/s). The on-board FPGAs were used to perform digital signal integration. The integration window was set to 400 ns to account for the long fall time of the SiPM signals, which was defined by the microcell recovery time (about 200 ns). A V1718 VME controller was used to transfer the acquired data to a computer over a USB interface. The use of the digital integration system was not essential for optimum operation of the detector and was dictated primarily by the available multichannel equipment. A similar detector performance can be expected with suitable (low impedance) charge-sensitive preamplifiers, combined with pulse shapers and multichannel analysers.

The SiPM bias voltage and the $+5/-5$ V power required for the preamplifiers were supplied by an Aim-TTi QL355T power supply unit. The majority of the measurements was performed using a bias voltage of 28 V, corresponding to a difference between the bias voltage and the breakdown voltage (over-voltage) of about 3.5 V. The SiPM breakdown voltage is known to change as a function of temperature (a change of 18 mV/°C was measured for the SiPMs used in this study as discussed in Section 5). In order to maintain the constant over-voltage (which defines the SiPM gain), a closed loop bias regulating system was used. The system was based on the Acra KAM-500 chassis from Curtis–Wright Avionics and included a KAD/ADC/113 analogue-to-digital converter, which monitored the temperature of the SiPM array using the PT100 sensor, and a KAD/DAC/002 power supply, which was connected in series with the main QL355T power supply and supplied an offset voltage generated as a function of the measured temperature.

3. SiPM response model

The response of an SiPM to light depends on a number of effects, such as the photon detection efficiency (PDE), dark count rate, optical cross-talk, after-pulsing, avalanche multiplication (gain) and microcell