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Timing and Energy Resolution of new near-UV SiPMs coupled to LaBr₃:Ce for TOF-PET

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Abstract

The high light output and fast decay time of LaBr₃:Ce scintillation detectors leads to excellent timing performance. To realize the potential of timing resolution with LaBr₃:Ce we have investigated the performance with SiPMs, which enable 1-to-1 coupling to individual crystals, and which have been optimized for the near-ultraviolet (NUV) scintillation light emission of LaBr₃:Ce. Coincidence timing resolution (CTR) of 100 ps was measured for a 4×4×5 mm³ LaBr₃:30%Ce crystal directly coupled to a large-area 4×4 mm² NUV-SiPM. Results show very little dependence on temperature, in the range of −20° to 20°C, and bias voltage, from 2 V to 5 V over breakdown. Optimal performance was achieved at an over-voltage (OV) range of 3 V – 5 V, at which high gain and high photon detection efficiency are achieved. Though saturation was evident at 511 keV, an energy resolution of 6.8% was measured after correcting for non-linearity. We also measured a CTR of 110 ps for a 4×4×5mm³ LaBr₃:5%Ce crystal and 245 ps for a 4×4×30 mm³ LaBr₃:5%Ce crystal using the NUV-SiPM. The poorer timing measurement for the 30-mm long crystal is due mainly to a systematic shift in the time pick-off as a function of the depth-of-interaction. The excellent temperature stability, fast rise time, high gain, and low noise of the

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NUV-SiPM make it a practical and highly appealing photodetector for the readout of a LaBr₃:Ce TOF-PET detector.

I. Introduction

A new generation of time-of-flight (TOF) PET scanners have demonstrated that improved image quality can be achieved by incorporating an accurate TOF measurement into the reconstruction process [1], renewing interest in detector designs with very good timing resolution [2]. Lanthanum Bromide (LaBr₃) scintillators, which have high light output and fast decay times, resulting in a high radiant flux, have demonstrated annihilation photon coincidence timing resolution of <100 ps [3], [4], as well as an energy resolution at 511 keV of less than 4%, using small crystals coupled directly to high performance timing PMTs. These characteristics make LaBr₃:Ce an ideal scintillator for a TOF-PET detector design, however the ultimate intrinsic performance is greatly affected by the photodetector and configuration with the scintillation crystal array. A TOF-PET detector requires not only very good timing and energy performance, but also good sensitivity and spatial resolution. These latter characteristics are determined by the dimensions of the individual crystals for a detector design based on a pixelated crystal array. For the Lanthanum Bromide (LaBr₃:5%Ce) based scanner at the University of Pennsylvania [5] the crystal array consists of 4×4×30 mm³ pixels. The scanner is composed of 24 detector modules, each with 1620 pixels, coupled through a light-guide to 51-mm diameter PMTs. There are a total of 38,880 pixels and 432 PMTs in the complete system. While a prototype detector array achieved a coincidence timing resolution of 325 ps [6], the system timing resolution of the complete system is 375 ps. The high light output and fast timing of LaBr₃ leads to superior timing resolution compared to commercial TOF scanners, with similar detector designs, which are based on LYSO (Philips Healthcare and GE Healthcare) or LSO scintillators (Siemens Healthcare), and have reported system timing resolutions in the range of 500–600 ps [7]–[9]. It has been demonstrated that there is a clinical benefit from TOF [10]–[14], specifically for whole-body oncology studies with FDG, and it is understood that the relative gain with TOF, and commensurate clinical benefit, would increase with better timing resolution.

There have been many recent investigations with silicon photomultipliers (SiPMs), whose intrinsic characteristics compare favorably with those of fast timing PMTs, and therefore show promise as photodetectors for TOF-PET [15]–[18], and have already been incorporated into a commercial PET scanner design (Philips Vereos) which is expected to have improved performance. SiPMs exhibit high photon detection efficiency (PDE), spatially uniform and temporally stable transit time, fast rise time, and high signal to noise. In addition, these devices enable the flexibility to design detectors with 1:1 coupling to scintillation crystals with small cross-section, which is not practical with PMTs. Therefore, with direct coupling of the crystal to the SiPM device we can expect to achieve the optimal timing resolution, without compromising the spatial resolution. The near ultraviolet (UV) emission of LaBr₃, however, presents a challenge, as most SiPMs have a peak sensitivity in the visible range. To fully realize the timing characteristics of LaBr₃:Ce with this new solid-state technology, Fondazione Bruno Kessler (FBK) has designed and prototyped a SiPM, referred to as the near-UV (NUV) SiPM, using p+/n technology optimized to offer higher

PDE at the peak emission wavelength of LaBr₃:Ce near 380 nm [19]. Results of measurements with LaBr₃:Ce crystals directly coupled to these devices are presented in this paper.

II. Near Ultra-violet Silicon Photomultiplier

The NUV-SiPM technology was developed at FBK for maximizing the detection efficiency of the light generated by scintillators commonly used in PET, such as LYSO:Ce, emitting in the blue region of the spectrum ($\lambda_{\text{max}} = 420$ nm), and LaBr₃:Ce, emitting in the near-UV ($\lambda_{\text{max}} = 380$ nm). To this purpose, the NUV-SiPM technology is based on a $p+/n$ junction, as opposed to the original FBK SiPM technology (referred to as RGB-SiPM) that was based on an $n+/p$ junction resulting in peak sensitivity in the 460–570 nm wavelength range [20]. Excellent timing and energy resolution were reported using the RGB-SiPMs coupled to LYSO [18]. Measurements have also been taken with LaBr₃:Ce (and CeBr₃) scintillators coupled to RGB-SiPMs [18], and while the results were encouraging, timing resolution was superior with fast PMTs, suggesting the mismatch between the PDE of the RGB-SiPMs and the emission spectrum of LaBr₃ degraded the timing measurement. The PDE of the RGB-SiPM at 390 nm is 22% while the PDE of the NUV-SiPM at 390 nm is 32% (both at 4.5 V over breakdown); both devices have exactly the same layout (42% fill factor using a 50 μm cell size) [19]. The NUV-optimized technology, whose peak PDE is from 380–400 nm, a region in which the detection efficiency of the RGB-SiPM rapidly decreases, is fundamental to fully exploit the advantages of LaBr₃:Ce.

Absorption of blue and near-UV photons in silicon is very superficial, implying that the active junction region be close to the surface. With an $n+/p$ junction, near-UV photons will trigger an avalanche primarily with hole carriers. This is not ideal because the triggering probability of holes is lower and increases slowly as the over-voltage is increased, compared to electron carriers. On the contrary, in a $p+/n$ junction the avalanche is started mainly by electrons when exposed to near-UV light, thereby enhancing the detection efficiency because of the higher triggering probability, at any over-voltage, of electron carriers. This also implies that high PDE can be achieved at a lower over-voltage, reducing the dark count rate and correlated noise. Hence, a $p+/n$ junction for UV light provides better performance in terms of both detection efficiency and noise properties.

Temperature stability and breakdown voltage uniformity have also been improved in the NUV-SiPM design, due to careful electric field engineering. The NUV-SiPM technology has a reported breakdown voltage (V_{BD}) uniformity of 160 mV FWHM, across the production wafer, and a breakdown voltage temperature coefficient of 25.8 mV/°C [19]. These characteristics are very important in the system-level design of a PET system.

The NUV-SiPM parameters and measured performance metrics are summarized in Table I. In the measurements described below, we characterize the performance of a large-area NUV-SiPMs, with a 4×4 mm² active area and a cell size of 50×50 μm^2 , coupled to LaBr₃:Ce scintillators.

III. Experimental Setup and Methods

Two different sizes of LaBr₃ crystals were used: 4×4×5 mm³ and 4×4×30 mm³. The crystals were polished on all 6 faces and wrapped in Teflon. See Table II for characteristics of LaBr₃:Ce compared to LYSO. The performance of the crystals were first tested with PMTs, which served to compare both energy and timing performance to the SiPM. To establish a reference for timing resolution we used the Hamamatsu R4998 PMT: rise time = 700 ps, TTS = 160 ps, and QE = 17%. To establish a reference for energy resolution we used the Photonic XP20D0 PMT: rise time = 1500 ps, TTS = 600 ps, and QE = 25%.

Following the PMT measurements the crystals were carefully positioned and directly coupled to the 4×4 mm² SiPM active area, using optical grease (Saint Gobain BC-630). The procedure was carried out in a dry box due to the hygroscopicity of the LaBr₃. The scintillator + SiPM assembly was then encapsulated in a Lucite tube with a silicon compound (GE RTV 615 A/B), which prevents the ambient humidity from damaging the crystal surfaces, and provides a simple, yet effective approach for our experimental measurements, obtaining the final arrangement shown in Fig. 1. All measurements were performed at room temperature unless specifically stated.

The energy response of the LaBr₃ NUV-SiPM was studied using a range of gamma energies from isotopes ⁵⁷Co (122 keV), ¹³³Ba (81 keV, 303 keV, 356 keV), ²²Na (511 keV, 1275 keV), and ¹³⁷Cs (662 keV). Data were acquired from all sources simultaneously by carefully choosing the source to detector distances so that signal pile-up was minimal and each gamma energy peak could be adequately resolved. The energy response was measured using a range of over-voltages (OV): 3V OV – 5V OV. The saturated energy response was estimated using the equation shown below (adapted from [21]), where IC is the measured integrated charge and E is the known gamma energy.

$$IC = a(1 - e^{-bE}) \quad (1)$$

The coefficients, a and b, were determined by a least squares solution. Energy resolution at 511 keV was measured with the ²²Na source, both in a singles and in a coincidence acquisition, using a saturation correction derived from eq [1].

The experimental setup used for the characterization of the timing performance of the LaBr₃ scintillator coupled to a NUV-SiPM is shown in Fig. 2. We used a reference detector, composed of a 4×4 mm² RGB-HD SiPM, with 30×30 μm² cells, coupled to a 3×3×5 mm³ LYSO crystal. The RGB-HD technology is a recent upgrade of the RGB technology, which features a higher fill factor (FF) and a lower cell size [22], providing very good timing performance [23]. The timing resolution of the reference detector was measured in coincidence with an identical detector for each temperature. The coincidence timing resolution (CTR) of the pair of reference detectors ranged from 168 ps to 131 ps from 20°C to -20°C. During the measurements described below, the reference detector was biased at its optimal operating voltage and its known single detector timing resolution was subtracted in quadrature for estimating the CTR of the NUV-SiPM LaBr₃ detector. The detectors were placed in a temperature controlled dark box and the temperature of the air surrounding the

detector is used as the measurement temperature. All the measurements were repeated twice, and with large statistics, to minimize the uncertainty of our reported experimental results.

We used the same front-end circuit, which is described in [25], for both the reference and the NUV-LaBr₃:Ce detector. The circuit is placed as close as possible to the detector, in order to minimize the parasitic capacitance of the connections, which could slow down the rising edge of the pulses. The current signal coming from the SiPM is converted to a voltage and is split into two stages for energy and timing; a current-feedback amplifier, based on the AD8000 from Analog Devices (Norwood, MA), is used for each stage. A Pole-Zero (PZ) filter is used in the timing stage to create a differentiated signal; this has the effect of reducing the duration of dark event pulses, eliminating the need for baseline compensation methods that drastically complicate time pick-off of the signal when a leading edge threshold is used.

The output of the energy stage and of the timing PZ stage are connected to a digitizing oscilloscope, which triggers the signals coming from the two detectors in coincidence and sends the acquired data to a PC, where all of the data processing occurs. The oscilloscope is a DSO9104A model from Agilent, featuring a sampling rate of 10 GS/s and an analog bandwidth of 1 GHz. The energy of each event detected by the LaBr₃ scintillator is calculated by digitally integrating of the output of the first stage, over 200 ns, and only photopeak events are used for timing ($E > 450$ keV). We use a digital constant fraction algorithm for time pick-off (threshold set to ~7% of max pulse height), applying a linear interpolation between consecutive samples for better accuracy. The time pick-off threshold is systematically varied to repeatedly calculate the CTR for many values of the triggering threshold, in a suitable range, and the data set that provides the best CTR, for all the events, is considered the CTR of the measurement.

IV. Results

A. Energy resolution

Fig. 3 shows the energy spectrum generated using a ²²Na source. With the very high light output of LaBr₃, direct coupling of the crystal, and 6400 cells in the NUV-SiPM device, energy saturation in the ²²Na spectrum is clearly visible. This measurement was taken using the LaBr₃:30%Ce crystal; saturation effects are expected to be more pronounced when using LaBr₃ with lower Ce concentrations, due to their higher light output. Measurements of gamma energies up to 1.275 MeV were acquired using several isotopes and the resulting integrated charge of the gamma photopeak as a function of gamma energy is plotted in Fig 4. The saturation response was modeled using eq. [1] and generally provides a good fit to the data. Using this relationship, between the integrated charge and known gamma energy, the energy spectrum was recalculated, correcting for the nonlinear behavior of the energy response. A saturation corrected energy histogram from the ²²Na source is shown in Fig. 5. After saturation correction the 1.275 MeV photopeak is no longer distinguishable because of the heavily saturated response of the detector past 662 keV. The 511 keV peak, however, is still very well resolved, and separated from Compton backscatter events, allowing for good identification of photoelectric interactions. The ²²Na source was then used in a coincidence acquisition to quantify the energy resolution, defined as the FWHM/peak after correcting for

saturation, of the LaBr_3 -NUV detector. Energy resolution was quantified at several over-voltages, each having a specific saturation correction, and the calculated energy resolutions at 511 keV are shown in Fig. 6. The detector is less saturated at lower over-voltages, as seen by the smaller degradation from the uncorrected FWHM/peak to the energy resolution after the saturation correction is applied. In the range of useful operating over-voltages (3V OV to 5V OV), the energy resolution is better than 7%.

B. Timing resolution

Coincidence timing resolution values for the LaBr_3 :30%Ce crystal as a function of NUV-SiPM over-voltage can be seen in Fig. 7. Timing resolution was measured as the FWHM of the coincidence time difference spectrum for photopeak events, with the contribution of the reference detector subtracted in quadrature. Thus, the CTR values correspond to two identical detectors in coincidence ($\text{CTR} = 2 \times \text{single detector timing resolution}$). The results for CTR are stable over a wide range of temperatures (-20°C to $+20^\circ\text{C}$), reflecting the low dark noise behavior of the NUV device and the benefit of our pole-zero shaped timing signal. The results also show that the CTR is stable over a range of over-voltages. Though the PDE is increased when operating the detector with a high over-voltage, so too is the detector noise. As seen from the data shown in Fig. 7, these effects seem to balance out, as the CTR does not significantly change from 3V OV to 5V OV. This favors the operation of the NUV detector somewhere less than the maximum over-voltage so that saturation is less and energy resolution at 511 keV is slightly improved. Measurements were also taken with a LaBr_3 :5%Ce crystal, which has slightly higher light output, but slower rise time than LaBr_3 :30%Ce, which lead to slightly worse CTR for a similarly sized crystal. These findings are consistent with earlier measurements reported in [3]. The timing resolution values with the NUV-SiPM, measured at an over-voltage of 4.5 V at 20°C for each LaBr_3 crystal, are summarized in Table III. Also shown are results for the 30-mm long crystal. We know that depth-of-interaction (DOI) effects in a long crystal degrade the timing resolution; the charge response decreases with DOI, and the time pickoff varies with DOI [26]—if DOI is not known, timing resolution will degrade due to both effects. We choose the 30-mm long crystal since this is the crystal dimension used in the *La-PET* scanner to achieve acceptable sensitivity for the PET system. The energy and timing resolution results from the LaBr_3 crystals readout using several PMTs are shown in Table IV for comparison with the NUV-SiPM results.

V. Discussion

The timing and energy results generated with the new near-UV SiPMs coupled to LaBr_3 :Ce represent a large improvement over current TOF detector designs. Our timing resolution measurements, summarized in Tables III and IV, demonstrate that the intrinsic performance of the NUV-SiPM device is as good as the R4998 PMT, considered our best timing PMT, and significantly better than the XP20D0 PMT, a high performance, cost-effective PMT for TOF-PET. Although the timing characteristics of the Hamamatsu R4998 are excellent, this PMT is a very expensive and custom-made device, not scalable to a full PET scanner that requires hundreds to thousands of PMTs. For the *La-PET* prototype scanner, we chose the Photonic XP20D0 PMT. This PMT is larger (51-mm vs. 25-mm of the R4998), much less

expensive, and has excellent pulse height resolution, leading to very good energy and spatial resolution for the Anger-logic detector incorporated in *La-PET*. However, this PMT does not have comparable timing resolution to the R4998 or NUV-SiPM device, as illustrated in Tables III- IV. It is also important to note that we cannot build a cost-effective PMT-based detector with 1:1 coupling (with good spatial resolution) leading to PMT detector designs based on Anger-logic through light sharing. SiPMs are compact, allowing for 1:1 coupling designs, and therefore it may be fair to compare the 245 ps timing resolution with the 30-mm long $\text{LaBr}_3:5\%\text{Ce}$ crystal directly coupled to the NUV-SiPM and encapsulated—the results of which translate directly to a manufactured detector based on 1:1 coupling—to the 325 ps timing resolution with the same size crystals incorporated into an Anger-logic detector [6].

The outcomes shown here may be compared with those reported in [3] and [27]. The CTR for the 5-mm long crystals are similar (for both 5% and 30%Ce), but the results for the 30-mm long crystal are worse; in [3] we reported 212 ps for $\text{LaBr}_3:5\%\text{Ce}$ with the R4998 PMT and 276 ps with the XP20D0. The similar timing performance measured with both the fast timing PMT and NUV-SiPM, of the 5-mm and 30-mm long $\text{LaBr}_3:5\%\text{Ce}$ crystals, leads us to believe that the worse timing resolution of the 30-mm long crystal is not caused by the photodetectors but was inherent to the crystal. We believe the surface polishing of the 30-mm crystal used in the previous work was better, demonstrating the fragility of light extraction with long, hygroscopic crystals, as variations in light transport along the length of the crystal degrade timing and controlling the crystal surface properties is challenging. We expect the CTR of 30-mm long LaBr_3 crystals and NUV-SiPMs will improve with better polishing of the crystal surfaces. It is also important to consider methods to measure the DOI and account for the variations in light collection and time pickoff that lead to degradation of timing resolution. There are a variety of techniques that have been proposed to measure DOI, but one method that takes advantage of the difference in rise time between $\text{LaBr}_3:5\%\text{Ce}$ and $\text{LaBr}_3:30\%\text{Ce}$ has been proposed in [27]. With measurement of DOI, we can expect to improve the timing resolution, as well as reduce the parallax error in a PET system.

The good energy resolution of the NUV-SiPM will be a benefit when considering DOI detector designs and will improve scanner performance. The NUV- LaBr_3 result for energy resolution, accounting for saturation ($\sim 7\%$), is actually very good for PET, which typically is 11–12% for LSO or LYSO detectors using PMTs. However, the SiPM saturation ultimately limits the energy performance and does not reflect the best energy resolution that can be achieved with LaBr_3 , which can be 3–4% at 511 keV. Better energy resolution in PET is important since it leads to a reduction in the number of accepted scattered events, by enabling the use of a high energy threshold, which improves the noise-equivalent count-rate, and generally results in more accurate data correction and quantitation [28].

It is important to note the large area of the NUV-SiPM used in this work ($4\times 4\text{ mm}^2$)—its area is almost a factor of two greater than other commonly used $3\times 3\text{ mm}^2$ SiPM designs [4]. Our presented results using the NUV-SiPM device with $4\times 4\text{ mm}^2$ area allows for a greater flexibility to predict performance depending on the specific scintillator array design and detector coupling used. We would expect an improvement in timing resolution if the NUV-

SiPM design was reduced to $3 \times 3 \text{ mm}^2$ to match a reduced scintillator cross section in 1:1 coupling, or if designing a light sharing detector, we would expect a large savings in electronic channel count, with modest degradation in performance, if the NUV-SiPM design was enlarged to $5 \times 5 \text{ mm}^2$ in area.

Lastly, we note that while the PDE at 380 nm has been improved in the NUV-SiPM design, the PDE at 380 nm may not be as high as other solid-state technologies, however timing resolution results with LaBr₃ are similar for the NUV-SiPM and other SiPM devices [4]. This is encouraging for the NUV-SiPM because there is potential that the PDE can be further improved by following the same strategy adopted for the RGB SiPM from FBK: the high-density (HD) technology [22]. This leads to higher fill factor to improve the PDE at a given excess noise factor, while simultaneously extending the dynamic range. We hope to test new NUV-HD devices soon, and eventually move towards practical, pixelated detector designs with arrays of NUV-SiPMs to preserve both spatial and timing performance of LaBr₃ scintillators.

VI. Conclusion

In summary, we have demonstrated the excellent performance of the NUV-SiPM devices when combined with LaBr₃ scintillation crystals. The NUV technology, optimized for the detection of near-UV light, is fundamental for capturing the fast timing properties of LaBr₃. The readout of LaBr₃ with NUV-SiPMs produces some of the best CTRs our lab has measured and demonstrates a large improvement over previous measurements with LaBr₃ and RGB-SiPMs. This combination would lead to $< 250 \text{ ps}$ TOF using 30-mm long crystals, or even better TOF resolution with shorter crystals or with detectors designed to measure depth-of-interaction. Compared to current commercial TOF-PET, such an improvement in TOF resolution would be expected to bring improved detectability, an important clinical task, as well as improved quantitative accuracy, an important estimation task for both clinical and research investigations.

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Figure 1. $4 \times 4 \times 5 \text{ mm}^3$ and $4 \times 4 \times 30 \text{ mm}^3$ LaBr_3 scintillators coupled to a $4 \times 4 \text{ mm}^2$ NUV-SiPM and encapsulated using a silicon compound to insulate from the ambient humidity and enable realistic measurements outside of a dry box.

Figure 2.

Top, block diagram of data acquisition. The signals were split into two branches for energy determination (copy) and timing (P/Z). The pole-zero differentiated (P/Z) circuit was optimized to minimize the effect of dark counts on timing performance [24]. Below, digitized signal shapes (acquired at 2 GS/sec) of the energy and timing signals; the rise time of the shaped timing signal is ~2ns.

Figure 3.

Energy spectrum of the LaBr₃:30%Ce scintillator coupled to the NUV-SiPM device acquired with ²²Na source shows both the 511 keV and 1.2 MeV photopeaks. The data was acquired at 20° C using an OV 5V.

Figure 4.

Measured photopeak charge, from the $\text{LaBr}_3:30\%\text{Ce}$ scintillator coupled to the NUV-SiPM device, as a function of gamma energy. The saturation response was fit using equation 1.

Figure 5.

Energy spectrum of the $\text{LaBr}_3:30\%\text{Ce}$ scintillator coupled to the NUV-SiPM device acquired with ^{22}Na source corrected for the nonlinear SiPM saturation. The data was acquired at 20°C using an OV 5V.

Figure 6.

Energy resolution of the LaBr₃ scintillator coupled to the NUV-SiPM device as a function of photon energy, and corrected for saturation. All results are from measurements taken at 20° C.

Figure 7.

Coincidence time resolution for $4 \times 4 \times 5 \text{ mm}^3$ $\text{LaBr}_3:30\%\text{Ce}$ scintillator coupled to NUV-SiPM for a temperature range of -20° to $+20^\circ\text{C}$.

Table I

Design and performance characteristics of the NUV-SiPM. This p+/n technology achieves peak wavelength detection at 390nm, while maintaining sensitivity at longer wavelengths.

Characteristic	NUV-SiPM
Technology	p+/n
Area	4×4mm ²
Cell Size	50μm×50μm
Total Number of Cells	6400
Fill Factor	42%
Peak PDE Wavelength	390nm
PDE (390nm) @ 4.5 V over breakdown	32%
Breakdown Voltage at 20 °C	25.5V
Maximum Over-voltage	5V
V (breakdown)/T	26mV/°C
Primary Dark Rate @20°C @ 4.5V OV	200KHz/mm ²

Table II

Performance characteristics of LaBr₃ and LYSO scintillators. The Absolute light output values correspond to measurements for crystals used in this paper, but normalized to LaBr₃:5%Ce as reported by Saint-Gobain.

	LaBr₃ 5% Ce	LaBr₃ 30% Ce	LYSO
Light output (ph/keV)	63	51	30
Rise time (ns)	0.93	0.2	0.1
Decay constant (ns)	16	18	40
Peak emission (nm)	380	380	420
Stopping power (cm)	2.1	2.1	1.2

Table III

Results for LaBr_3 scintillators coupled to NUV-SiPM biased at 4.5 OV and measured at room temperature (20°C).

LaBr_3 Size (mm)	% Cerium	Energy Resolution	CTR (ps)
4×4×5	30	6.8%	100
4×4×5	5	6.6%	110
4×4×30	5	7%	245

Table IV
Results for LaBr₃ scintillators coupled to Hamamatsu R4998 PMT and Photonis XP20D0 PMT.

LaBr ₃ Size (mm)	% Cerium	Energy Resolution R4998	CTR (ps) R4998	Energy Resolution XP20D0	CTR (ps) XP20D0
4×4×5	30		98	4.2%	
4×4×5	5	5.3%	130	3.7%	185
4×4×30	5	5.8%	239	4.5%	285