Improved LabPET Detectors Using $\text{Lu}_{1.8}\text{Gd}_{0.2}\text{SiO}_5 : \text{Ce}$ (LGSO) Scintillator Blocks

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Abstract—The scintillator is one of the key building blocks that critically determine the physical performance of PET detectors. The quest for scintillation crystals with improved characteristics has been crucial in designing scanners with superior imaging performance. Recently, it was shown that the decay time constant of high lutetium content $\text{Lu}_{1.8}\text{Gd}_{0.2}\text{SiO}_5 : \text{Ce}$ (LGSO) scintillators can be adjusted by varying the cerium concentration from 0.025 mol% to 0.75 mol%, thus providing interesting characteristics for *phoswich* detectors. The high light output (90%–120% NaI) and the improved spectral match of these scintillators with avalanche photodiode (APD) readout promise superior energy and timing resolutions. Moreover, their improved mechanical properties, as compared to conventional LGSO ($\text{Lu}_{0.4}\text{Gd}_{1.6}\text{SiO}_5 : \text{Ce}$), make block array manufacturing readily feasible. To verify these assumptions, new *phoswich* block arrays made of LGSO-90%Lu with low and high mol% Ce concentrations were fabricated and assembled into modules dedicated to the LabPET scanner. Typical crystal decay time constants were 31 ns and 47 ns, respectively. *Phoswich* crystal identification performed using a digital pulse shape discrimination algorithm yielded an average 8% error. At 511 keV, an energy resolution of 17–21% was obtained, while coincidence timing resolution between 4.6 ns and 5.2 ns was achieved. The characteristics of this new LGSO-based *phoswich* detector module are expected to improve the LabPET scanner performance. The higher stopping power would increase the detection efficiency. The better timing resolution would also allow the use of a narrower coincidence window, thus minimizing the random event rate. Altogether, these two improvements will significantly enhance the noise equivalent count rate performance of an all LGSO-based LabPET scanner.

Index Terms—Avalanche photodiodes, energy resolution, LabPET, LGSO, positron emission tomography, scintillators, small-animal PET scanner, timing resolution.

Manuscript received September 15, 2014; revised November 21, 2014; accepted December 28, 2014. This work was supported by Grants from the Natural Science and Engineering Research Council of Canada (NSERC), the Canadian Institutes of Health Research (CIHR), and *Fonds de recherche du Québec - Nature et technologies (FRQNT)*. The Sherbrooke Molecular Imaging Center is a member of the FRSQ-funded *Centre de Recherche du Centre hospitalier universitaire de Sherbrooke (CHUS)*.

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I. INTRODUCTION

SCINTILLATORS largely determine the basic performance of PET scanners. Expectedly, major efforts have been committed to discover new scintillation materials, and also to improve characteristics of existing ones, such as stopping power, light output and emission decay time [1]–[4]. For instance, time-of-flight PET, which inherently needs an outstanding timing resolution, prompted the search for new scintillators with higher light yield combined with faster decay time [5], [6]. In addition, better timing and energy resolution for PET support the development of applications using lower energy radiation such as SPECT (140 keV) and CT (~ 60 keV).

New high lutetium content $\text{Lu}_{1.8}\text{Gd}_{0.2}\text{SiO}_5 : \text{Ce}$ (LGSO-90%Lu) scintillators with high light output (90–120% NaI) and tunable fast decay times were recently introduced [7], [8]. The range of decay times from 31 to 47 ns, which can be adjusted by varying the Ce concentration from 0.025 to 0.75 mol%, makes them especially advantageous for creating *phoswich* arrangements, where the scintillating crystal can easily be identified with a simple pulse shape discrimination technique without sacrificing the timing resolution [9]–[12]. Moreover, the similar emission and absorption properties of these new scintillators simplify the selection of the photodetector spectral response and avoid photon absorption in the other crystal of a *phoswich* assembly, since the two crystals are transparent to their own light.

Direct replacement of the current LGSO-20%Lu ($\text{Lu}_{0.4}\text{Gd}_{1.6}\text{SiO}_5 : \text{Ce}$) and LYSO ($\text{Lu}_{1.9}\text{Y}_{0.1}\text{SiO}_5 : \text{Ce}$) scintillators in the LabPET detector module would enhance the scanner performance [13]. Table I compares the previously reported crystal characteristics for LGSO-90%Lu along with the two LabPET scintillators: LGSO_{LabPET} and LYSO_{LabPET}. Some physical characteristics of LGSO-90%Lu and LYSO_{LabPET}, such as density and effective Z, are very similar, but the higher light yield of LGSO-90%Lu when coupled to an avalanche photodiode (APD) readout makes it particularly attractive. Compared to the LGSO_{LabPET}, the LGSO-90%Lu features a higher stopping power, a better light output and a faster decay time. Because of its higher lutetium content, the natural radioactivity of LGSO-90%Lu is however higher than LGSO_{LabPET}, but still comparable to LYSO_{LabPET}, whose lutetium proportion is 95%.

Digital Object Identifier 10.1109/TNS.2015.2388757

TABLE I
LGSO AND LYSO PHYSICAL CHARACTERISTICS

	LGSO-90%Lu	LGSO _{LabPET}	LYSO _{LabPET}
Lutetium content (%)	90	20	95
Density (g/cc)	7.3	6.5	7.19
μ at 511 keV (cm ⁻¹)	0.801	0.662	0.787
Effective Z	63	58	63
Photoelectric probability $P(\tau)$ (%)	34	28	33
Detection efficiency ϵ 10 mm (%)	55	48	55
Decay time (ns)	31–47	65–75	40
Light output with APD (% NaI)	93–122	55	85
Peak emission (nm)	420–430	415–425	420
References	[7], [8]	[14]	[14]

II. MATERIALS AND METHODS

A. Experimental Setup

Fast and slow LGSO-90% Lu samples, having nominal Ce concentrations of 0.025 mol% and 0.75 mol% respectively, were selected to allow the largest separation between decay times (31 ns and 47 ns) facilitating the crystal identification. LGSO_{31ns} and LGSO_{47ns} were then assembled in a *phoswich* arrangement as in LabPET modules [13]. In the current module, the [LGSO/LYSO]_{LabPET} *phoswich* pairs are assembled and individually wrapped in unbounded silver foil before being placed four at a time into a hermetic Kovar package. In the new proposed configuration, the crystals are processed by Agile Technologies (Knoxville, TN, USA) starting from a larger piece of scintillator provided by Hitachi Chemical (Ibaraki, Japan), cut and mechanically polished to the required size, then bonded with 3M ESR reflector and assembled into a solid pixelated block with four adjacent *phoswich* pairs. Fig. 1(a) shows a schematic of the *phoswich* block design for one module along with its dimensions. The crystals are slightly smaller in the new module compared to the LabPET module, since the pitch was kept the same and the reflector thickness was changed ($\sim 75 \mu\text{m}$ with 3M ESR compared to $\sim 25 \mu\text{m}$ with silver foil).

In the current LabPET module, the LGSO_{LabPET} was chosen as the longer crystal to compensate for its lower stopping power compared to the LYSO_{LabPET}. Since the stopping power is the same for LGSO_{31ns} and LGSO_{47ns}, it was decided to evaluate the two possible assemblies (Type I and Type II, Fig. 1(b)). For each configuration, the *phoswich* block was mounted with 4 reach-through APDs [15] of the same type as in the standard LabPET modules having a $1.1 \times 3.6 \text{ mm}^2$ active area (Excelitas Technologies, Vaudreuil, QC, Canada), one for each *phoswich* pixel, and the assembly was hermetically enclosed in a standard LabPET package. To provide some assessment of the assembly procedure on detector performance, 20 such prototype modules (10 Type I and 10 Type II) were assembled.

Energy and timing resolution measurements were performed at a stable temperature ($27.0 \pm 0.5^\circ\text{C}$) with a ^{68}Ge (511 keV) radioactive source. This temperature is typical of the detector temperature in a LabPET scanner in normal operation. The APD bias was chosen to optimize timing resolution. Detection efficiency was assessed for the new Type I and Type II modules and compared to standard LabPET ones. For that measurement, a ^{137}Cs (662 keV) source was positioned 40 cm away from the detectors to insure that the incident radiation flux is the same for

Fig. 1. Schematic of the new LGSO *phoswich* block assembly with the optical coupling and 3M ESR reflector specifications (a) along with the two investigated module configurations: Type I and Type II (b).

all the detectors. The ^{137}Cs source was intentionally chosen instead of a positron emitter because its activity was high enough to limit the acquisition time and, thus, minimize temperature fluctuations during measurements in an open environment. The number of single counts above four energy thresholds (194, 324, 453 and 583 keV) were obtained using a 10-minute measurement and compared to the number of counts obtained with current [LGSO/LYSO]_{LabPET} modules in an identical setup. These four thresholds can be translated into a relation between the detection efficiency ratio and the lower energy threshold.

To evaluate the rate of natural radioactivity, a 2-h measurement was performed using the same setup, but without external radioactivity, and single counts were recorded. All measurements were performed with standard LabPET digital data acquisition electronics [16].

B. Gamma Spectroscopy Measurements

To assess the intrinsic performance of the crystals, measurements were performed on individual pixels from the modules. Whereas results from these needle-like crystals with an unfavorable form factor ($2 \times 2 \times 11.9/13.3 \text{ mm}^3$ with a 55° slant plane) will be degraded relative to small cubic crystals ($3 \times 3 \times 3 \text{ mm}^3$) commonly used in spectroscopic studies [17], these

TABLE II
SPECTROSCOPIC MEASUREMENTS ON INDIVIDUAL CRYSTALS

	LGSO _{47ns}	LGSO _{31ns}	LGSO _{LabPET}	LYSO _{LabPET}
Decay time (ns)	47.1 ± 0.2	30.7 ± 0.1	83 ± 3 (78%) 22 ± 1 (22%)	43 ± 1
Photoelectron yield (phe ⁻ /MeV)	28000±2000	18000±2000	19600±300	30700±400
Initial emission rate at 511 keV (phe ⁻ /(MeV ns))	620±40	590±80	302±5	770±10
Timing resolution (ns)	1.5 ± 0.1	1.7 ± 0.1	3.0 ± 0.2	1.8 ± 0.1
Energy resolution (%)	11.0±0.5	11.6±0.3	8.3±0.2	10.6±0.3
Peak emission wavelength (nm)	432	420	426	422
Window fraction $f_{250-650}$	0.62	0.65	0.57	0.63
Form factor	0.084	0.075	0.075	0.084

measurements allow direct comparison with similar crystals in the *phoswich* modules.

Several physical characteristics were inspected, namely the decay time, the photoelectron yield, the energy and timing resolutions, the peak emission wavelength and the crystal form factor (defined as the ratio of the detection surface area to the crystal volume). The decay time was measured by collecting 10 000 signals from the scintillators coupled to a fast PMT (RCA 4802-1) using a digital oscilloscope at 2 GSa/s (DSO6034 A, Agilent Technologies). The signals were averaged and the decay part of the curve was fitted using a single or double exponential regression. To evaluate the peak emission, UV-excited luminescence spectra were obtained using a spectrofluorometer (Hitachi F2000).

Four different scintillator types were investigated: LGSO_{LabPET} and LYSO_{LabPET} from the current LabPET module and LGSO_{31ns} and LGSO_{47ns} from the Type I module. Four samples of each scintillator were measured. All experiments were performed with the crystals coated with Bicon BC-620 white paint, with the exception of the photoelectron yield measurements that have been performed with scintillators wrapped in > 6 layers of PTFE tape. All crystals were optically coupled to a $4 \times 4 \text{ mm}^2$ UV-enhanced c7532 APD (Excelitas) operated at a gain of 120. The APD was connected to a custom low-noise charge-sensitive preamplifier (RCA 3.0) followed by an ORTEC 452 spectroscopy amplifier employed for all light yield and energy resolution measurements with a shaping time of 0.25 μs . The APD gain was calibrated by direct irradiation of the APD with 9 keV X-rays from a ^{67}Ga radiation source with the APD operated at low gain. The absolute light yield was then estimated by comparing to a reference pulse injected by a precision pulser at the input of the preamplifier through a calibrated 1 pF test capacitor. The intrinsic timing performance of the crystals coupled to an APD was assessed by coincidence against a fast PMT (RCA 4802-1) and plastic scintillator (NE102-A1-15c6 V) detector using a zero-cross time circuit connected to a time-amplitude converter (Ortec 467). For timing measurements, the signal from the APD-crystal detector was shaped with a fast filter amplifier (Ortec 474) having a 20 ns time constant and used to trigger a constant fraction discriminator with a 40% fraction and 4 ns (LGSO_{31ns}), 8 ns (LYSO_{LabPET} and LGSO_{47ns}) or 20 ns (LGSO_{LabPET}) delay. All data were acquired at ambient temperature ($\sim 21.0 \pm 0.5^\circ\text{C}$) in a temperature controlled room.

III. RESULTS

A. Gamma Spectroscopy Measurements

Spectroscopic measurements for the individual crystals are reported in Table II and are in fair agreement with the scintillators physical characteristics (Table I). The results indicate excellent decay time uniformity between the four LGSO-90%Lu samples of each type. However, the tested LGSO_{31ns} samples did not possess a higher photoelectron yield than the LGSO_{LabPET} and LYSO_{LabPET}, as reported earlier [7], indicating that the crystal production may not be stable and that better results could be expected later on. The LGSO_{47ns} also presented a slightly lower photoelectron yield than the LYSO_{LabPET}. The lower light yield of the LGSO_{31ns} and LGSO_{47ns} could also be due to self-absorption, but the UV emission and excitation spectra did not show significant overlap. Comparison with current LabPET crystals suggests that modules made of LGSO-90%Lu will have a slightly degraded energy resolution. The LGSO_{LabPET} achieves a better energy resolution despite its lower light yield because there is likely less competition between Ce1 and Ce2 luminescence centers in this scintillator [18]. The LGSO_{31ns} and LGSO_{47ns} timing resolution is equivalent to LYSO_{LabPET} resolution (~ 1.7 ns) and significantly better than LGSO_{LabPET} resolution (~ 3.0 ns). Emission wavelengths are very similar for all the scintillators. To enable the comparison of detection efficiency with a 250–650 keV energy window, the window fraction $f_{250-650}$ defined in Eq. (1) is also reported

$$f_{250-650} = \frac{\text{counts} \in \text{photoelectric window}(400 - 600\text{keV})}{\text{counts} \in 250 - 650\text{keV window.}} \quad (1)$$

B. Module Measurements

To characterize the new LGSO_{47ns}/LGSO_{31ns} LabPET modules as a replacement for the current LabPET module, *phoswich* crystal identification is a prerequisite. At first glance, the discrimination with the new *phoswich* combination, having a 16 ns decay time difference, appears more challenging than with the current module having a 25 ns difference. Decay time discrimination was performed using the same procedure as in the LabPET data processing chain [16].

TABLE III
MODULES PERFORMANCE

	Type I		Type II		LabPET	
	LGSO _{31ns}	LGSO _{47ns}	LGSO _{31ns}	LGSO _{47ns}	LGSO _{LabPET}	LYSO _{LabPET}
Energy resolution (%)	21 ± 2	17 ± 2	18 ± 3	17 ± 2	18 ± 1	20 ± 2
Timing res. (250 keV) (ns)	5.2 ± 0.5	4.6 ± 0.3	5 ± 1	4.6 ± 0.3	10 ± 3*	6 ± 2*
Light output ratio (slow/fast)	1.4 ± 0.1		1.2 ± 0.1		0.8 ± 0.1	
Discrimination error (%)	7 ± 1		8 ± 3		5 ± 2	

* obtained with a LabPET8 scanner

Fig. 2. Detection efficiency ratio. The measurement was performed using a 662 keV source, 40 cm away from the detectors.

Fig. 3. Intrinsic ¹⁷⁶Lu spectra for current LabPET and Type I modules.

Table III reports the module performance as a comparison between the Type I, Type II and [LGSO/LYSO]_{LabPET} modules. Contrary to what was observed in the spectroscopic measurements on individual crystals, the energy resolution is similar in all configurations, with a slight advantage with the Type II assembly. This could be explained by the different reflectors used in the two modules; the reflectivity of the silver foil used in the current LabPET module is 85%, while the reflectivity of the 3M ESR used in the Type I and II modules is about 98% above 400 nm. LGSO_{47ns} clearly shows better results than LGSO_{31ns}, regardless of the configuration, mostly due to its higher light yield. The expected relative light yield between the two scintillators (LGSO_{47ns}/LGSO_{31ns}) is 1.6 ± 0.2 , obtained from Type I spectroscopic measurements. The relative light output

estimated from the photopeak positions in the module measurements yields 1.4 ± 0.1 for the Type I configuration and 1.2 ± 0.1 for the Type II configuration. The Type II configuration is slightly more balanced than Type I as it is closer to one and the two crystals should exhibit similar performance.

The average time resolution in coincidence was 4.6 ± 0.3 ns for LGSO_{47ns} in both configurations and 5.2 ± 0.5 ns for LGSO_{31ns} in Type I and 5 ± 1 ns in Type II. The time resolution of both assemblies is similar to the results obtained in a LabPET8 scanner for LYSO_{LabPET} (6 ± 2 ns) and better than results obtained for LGSO_{LabPET} (10 ± 3) [19]. The LGSO_{47ns} scintillator yields the best timing performance in both configurations as its higher light yield compensates for its slower decay time.

The ratio of the new module detection efficiency ϵ_{new} to the LabPET module detection efficiency ϵ_{LabPET} was defined as

$$\frac{\epsilon_{\text{new}}}{\epsilon_{\text{LabPET}}} = \frac{\text{singles}_{\text{LGSO}_{31\text{ns}}} + \text{singles}_{\text{LGSO}_{47\text{ns}}}}{\text{singles}_{\text{LGSO}_{\text{LabPET}}} + \text{singles}_{\text{LYSO}_{\text{LabPET}}}} \quad (2)$$

where the singles rates from a 662 keV source are measured above an energy threshold. The ratios are found to be identical for Type I and Type II modules (the crystal composition is the same), ranging from 1.15 ± 0.05 to 1.21 ± 0.07 with increasing the energy threshold from 200 to 600 keV (see Fig. 2), which corresponds to a ratio of 1.3–1.5 in coincidence.

Fig. 3 shows the spectra obtained without an external radioactive source to evaluate the intrinsic radioactivity of the lutetium. The ¹⁷⁶Lu isotope (2.6% abundance, 3.78×10^{10} years half-life) decays by β^- emission, followed by the emission of γ -ray(s) of 307 keV (94%), 202 keV (78%), and 88 keV (15%) [20]. Since the identification algorithm is less efficient at lower energy, the interaction crystal is poorly discriminated and it is preferable to compare the results at the *phoswich* level rather than the crystal level. Therefore, the two signals were added. From Fig. 3, the background count rate due to natural radioactivity is found to be almost twice higher with the LGSO_{31ns}/LGSO_{47ns} module than with the standard LabPET module, due to the higher Lu content. This could be a problem for SPECT imaging using PET detectors [21], since this unwanted signal must be subtracted.

C. Sensitivity Improvement

A calculation was performed to compare the sensitivity of a PET system based on the new LGSO to the standard LabPET module. To estimate the sensitivity ratio, the first step was to evaluate the photoelectric detection efficiency ϵ of both modules using

$$\epsilon = 1 - e^{-\mu \cdot P(\tau) \cdot L} \quad (3)$$

TABLE IV
PREDICTED IMPACT ON LABPET8 SCANNER PERFORMANCE (250–650 keV)

	Current module	New module
ϵ_w short crystal	43%	43%
ϵ_w long crystal	38%	49%
Relative solid angle*	1	0.96
Sensitivity improvement (%)		+33%
Coincidence time window	20 ns	10 ns
NEC improvement (mouse)		1.4×
NEC improvement (rat)		1.5×

* 3M ESR reflector ($\sim 75 \mu\text{m}$) thicker than silver foil ($\sim 25 \mu\text{m}$)

where μ is the linear attenuation coefficient at 511 keV, $P(\tau)$ is the photoelectric probability and L the crystal length (measured in the middle of the tapered crystals, respectively 11.9 and 13.3 mm for the shorter and longer components of the *phoswich* [see Fig. 1(b)]. The sensitivity comparison is based on a 250–650 keV energy window. This window was chosen to be compliant with LabPET standard acquisition mode and to overcome any possible light crosstalk mostly due to the cut-off frequency around 400 nm of the 3M ESR reflector [22]. Because this energy window was chosen rather than the photopeak only, a window fraction specific to each crystal, $f_{250-650}$, must be added in Eq. (3) to adequately compare the sensitivity. The windowed detection efficiency ϵ_w is defined as

$$\epsilon_w = (1 - e^{-\mu \cdot P(\tau) \cdot L}) / f_{250-650}. \quad (4)$$

The ratio $f_{250-650}$ was assessed using the spectroscopic samples and the results were reported in Table II, which completes the data needed to compare the modules sensitivities. Overall, the LGSO-90%Lu scintillators have more stopping power than $\text{LGSO}_{\text{LabPET}}$ and $\text{LYSO}_{\text{LabPET}}$. Moreover, the photoelectric probability is higher, especially compared to the $\text{LGSO}_{\text{LabPET}}$. The calculated windowed detection efficiencies, ϵ_w , are displayed in Table IV. To evaluate the sensitivity ratio S_r between the two modules, we used

$$S_r = \frac{(\epsilon_w \text{LGSO}31\text{ns} + \epsilon_w \text{LGSO}47\text{ns})^2}{(\epsilon_w \text{LGSOLabPET} + \epsilon_w \text{LGSOLabPET})^2}. \quad (5)$$

The theoretical sensitivity ratio S_r is 1.29, using values from Table I and the window fraction $f_{250-650}$ obtained from spectroscopic measurements (Table II). Even with the slightly smaller packing fraction resulting from the slightly thicker reflector (by a 0.96 factor), the sensitivity would still be improved. Using the theoretical S_r , it is possible to compare with the experimental ratio (Fig. 2). Since the ratio of detection efficiencies was 1.16 ± 0.05 for a 250 keV lower energy limit, the experimental sensitivity improvement will be 1.36 ± 0.06 for a 250–650 keV window. The two values (1.29 and 1.36) are slightly different, mostly because of the imprecision coming from the $f_{250-650}$ ratio in the theoretical evaluation. The mean values of the two different estimations are 1.15 ± 0.05 for the singles ratio and 1.33 ± 0.06 for the coincidence rates ratio.

D. Noise Equivalent Count Rate Improvement

A standard width for the coincidence time window is about $2 \times$ the FWHM time resolution to ensure the recovery of 98% of the coincidence events, assuming a Gaussian coincidence time distribution. Since the time resolution of both crystals in the new module is about half of the $\text{LGSO}_{\text{LabPET}}$ resolution, the coincidence time window can be reduced by up to a factor of 2 with the new detectors, leading to a reduction by a factor of 2 in the random rates. Considering that the LabPET peak noise equivalent count rate (NEC) occurs at a specific total count rates, the peak NEC activity for the new module would be slightly lower than for the current module, corresponding to the ratio of the detection efficiencies (~ 1.15). The NEC improvement can be calculated using

$$\text{NEC improvement} = \frac{\text{NEC}_{\text{LGSO-90\%Lu}} @ [\text{peak activity} / 1.15]}{\text{NEC}_{\text{LabPET}} @ [\text{peak activity}]}, \quad (6)$$

where

$$\text{NEC}_{\text{LGSO-90\%Lu}} @ [\text{peak activity} / 1.15] = \frac{1.33 \times R_T^2}{R_T + R_S + 0.5 R_R} \quad (7)$$

and where R_T is the true rate, R_S is the scatter rate and R_R is the random rate of the LabPET modules. The improved detection efficiency, along with the random rates reduction, would result in an estimated NEC amelioration of $1.4 \times$ for a mouse phantom and $1.5 \times$ for a rat phantom. This was calculated using the LabPET8 scanner data [13].

IV. DISCUSSION

In the present work, the same electronic settings and firmware as for $\text{LGSO}_{\text{LabPET}}$ and $\text{LYSO}_{\text{LabPET}}$ were employed without any modifications. Signal processing could be adapted to the specific characteristics of the LGSO-90%Lu signal shapes.

As confirmed by all the measurements, the use of LGSO-90%Lu in the LabPET modules would be beneficial in many respects. Table IV summarizes the predicted impact on scanner performance using a 250–650 keV energy window, notably a $33 \pm 6\%$ increase in sensitivity and a NEC improvement of a $\sim 1.4 \times$ factor for mouse imaging and $\sim 1.5 \times$ for rat imaging. The results obtained in this work confirm that the proposed all LGSO-based detector module can be manufactured with highly reproducible performance characteristics, as demonstrated by the small standard deviation in all measured data, and hence can be readily implemented in LabPET scanners. Whereas these scintillators performed well in a side-by-side *phoswich* like LabPET detector, they can be expected to perform even better in dual-layer assemblies for DOI detectors. The data reported in Table I suggest that the light yield could be improved if the crystal production was stabilized. If this was the case, this application would benefit from the good light yield of $\text{LGSO}_{47\text{ns}}$, given the unavoidable light loss at the *phoswich* crystal interface. This higher light yield would also open the way to better detection of lower energy signals in applications such as intercrystal recovery in high resolution PET [23], SPECT imaging using PET detectors [24] and counting CT imaging [25].

V. CONCLUSION

The new high lutetium LGSO scintillators with tunable decay time based on cerium concentration offer a great potential for simplifying detector assembly and improving PET imaging performance, by a simple replacement of the LabPET detector modules. These new crystals provide excellent timing resolution while still supporting *phoswich* discrimination. They are expected to improve the LabPET scanner sensitivity and count rate performance, while significantly reducing random rates.

ACKNOWLEDGMENT

The authors would like to thank M. Toshinori Takeyama of Marubeni Specialty Chemicals Inc. (White Plains, NY) and Dr. H. Ishibashi of Hitachi Chemical Co., Ltd. (Ibaraki, Japan) for supplying the LGSO crystal samples.

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Improved LabPET Detectors Using $\text{Lu}_{1.8}\text{Gd}_{0.2}\text{SiO}_5 : \text{Ce}$ (LGSO) Scintillator Blocks

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Abstract—The scintillator is one of the key building blocks that critically determine the physical performance of PET detectors. The quest for scintillation crystals with improved characteristics has been crucial in designing scanners with superior imaging performance. Recently, it was shown that the decay time constant of high lutetium content $\text{Lu}_{1.8}\text{Gd}_{0.2}\text{SiO}_5 : \text{Ce}$ (LGSO) scintillators can be adjusted by varying the cerium concentration from 0.025 mol% to 0.75 mol%, thus providing interesting characteristics for *phoswich* detectors. The high light output (90%–120% NaI) and the improved spectral match of these scintillators with avalanche photodiode (APD) readout promise superior energy and timing resolutions. Moreover, their improved mechanical properties, as compared to conventional LGSO ($\text{Lu}_{0.4}\text{Gd}_{1.6}\text{SiO}_5 : \text{Ce}$), make block array manufacturing readily feasible. To verify these assumptions, new *phoswich* block arrays made of LGSO-90%Lu with low and high mol% Ce concentrations were fabricated and assembled into modules dedicated to the LabPET scanner. Typical crystal decay time constants were 31 ns and 47 ns, respectively. *Phoswich* crystal identification performed using a digital pulse shape discrimination algorithm yielded an average 8% error. At 511 keV, an energy resolution of 17–21% was obtained, while coincidence timing resolution between 4.6 ns and 5.2 ns was achieved. The characteristics of this new LGSO-based *phoswich* detector module are expected to improve the LabPET scanner performance. The higher stopping power would increase the detection efficiency. The better timing resolution would also allow the use of a narrower coincidence window, thus minimizing the random event rate. Altogether, these two improvements will significantly enhance the noise equivalent count rate performance of an all LGSO-based LabPET scanner.

Index Terms—Avalanche photodiodes, energy resolution, LabPET, LGSO, positron emission tomography, scintillators, small-animal PET scanner, timing resolution.

Manuscript received September 15, 2014; revised November 21, 2014; accepted December 28, 2014. This work was supported by Grants from the Natural Science and Engineering Research Council of Canada (NSERC), the Canadian Institutes of Health Research (CIHR), and *Fonds de recherche du Québec - Nature et technologies (FRQNT)*. The Sherbrooke Molecular Imaging Center is a member of the FRSQ-funded *Centre de Recherche du Centre hospitalier universitaire de Sherbrooke (CHUS)*.

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I. INTRODUCTION

SCINTILLATORS largely determine the basic performance of PET scanners. Expectedly, major efforts have been committed to discover new scintillation materials, and also to improve characteristics of existing ones, such as stopping power, light output and emission decay time [1]–[4]. For instance, time-of-flight PET, which inherently needs an outstanding timing resolution, prompted the search for new scintillators with higher light yield combined with faster decay time [5], [6]. In addition, better timing and energy resolution for PET support the development of applications using lower energy radiation such as SPECT (140 keV) and CT (~ 60 keV).

New high lutetium content $\text{Lu}_{1.8}\text{Gd}_{0.2}\text{SiO}_5 : \text{Ce}$ (LGSO-90%Lu) scintillators with high light output (90–120% NaI) and tunable fast decay times were recently introduced [7], [8]. The range of decay times from 31 to 47 ns, which can be adjusted by varying the Ce concentration from 0.025 to 0.75 mol%, makes them especially advantageous for creating *phoswich* arrangements, where the scintillating crystal can easily be identified with a simple pulse shape discrimination technique without sacrificing the timing resolution [9]–[12]. Moreover, the similar emission and absorption properties of these new scintillators simplify the selection of the photodetector spectral response and avoid photon absorption in the other crystal of a *phoswich* assembly, since the two crystals are transparent to their own light.

Direct replacement of the current LGSO-20%Lu ($\text{Lu}_{0.4}\text{Gd}_{1.6}\text{SiO}_5 : \text{Ce}$) and LYSO ($\text{Lu}_{1.9}\text{Y}_{0.1}\text{SiO}_5 : \text{Ce}$) scintillators in the LabPET detector module would enhance the scanner performance [13]. Table I compares the previously reported crystal characteristics for LGSO-90%Lu along with the two LabPET scintillators: LGSO_{LabPET} and LYSO_{LabPET}. Some physical characteristics of LGSO-90%Lu and LYSO_{LabPET}, such as density and effective Z, are very similar, but the higher light yield of LGSO-90%Lu when coupled to an avalanche photodiode (APD) readout makes it particularly attractive. Compared to the LGSO_{LabPET}, the LGSO-90%Lu features a higher stopping power, a better light output and a faster decay time. Because of its higher lutetium content, the natural radioactivity of LGSO-90%Lu is however higher than LGSO_{LabPET}, but still comparable to LYSO_{LabPET}, whose lutetium proportion is 95%.

Digital Object Identifier 10.1109/TNS.2015.2388757

TABLE I
LGSO AND LYSO PHYSICAL CHARACTERISTICS

	LGSO-90%Lu	LGSO _{LabPET}	LYSO _{LabPET}
Lutetium content (%)	90	20	95
Density (g/cc)	7.3	6.5	7.19
μ at 511 keV (cm ⁻¹)	0.801	0.662	0.787
Effective Z	63	58	63
Photoelectric probability $P(\tau)$ (%)	34	28	33
Detection efficiency ϵ 10 mm (%)	55	48	55
Decay time (ns)	31–47	65–75	40
Light output with APD (% NaI)	93–122	55	85
Peak emission (nm)	420–430	415–425	420
References	[7], [8]	[14]	[14]

II. MATERIALS AND METHODS

A. Experimental Setup

Fast and slow LGSO-90% Lu samples, having nominal Ce concentrations of 0.025 mol% and 0.75 mol% respectively, were selected to allow the largest separation between decay times (31 ns and 47 ns) facilitating the crystal identification. LGSO_{31ns} and LGSO_{47ns} were then assembled in a *phoswich* arrangement as in LabPET modules [13]. In the current module, the [LGSO/LYSO]_{LabPET} *phoswich* pairs are assembled and individually wrapped in unbounded silver foil before being placed four at a time into a hermetic Kovar package. In the new proposed configuration, the crystals are processed by Agile Technologies (Knoxville, TN, USA) starting from a larger piece of scintillator provided by Hitachi Chemical (Ibaraki, Japan), cut and mechanically polished to the required size, then bonded with 3M ESR reflector and assembled into a solid pixelated block with four adjacent *phoswich* pairs. Fig. 1(a) shows a schematic of the *phoswich* block design for one module along with its dimensions. The crystals are slightly smaller in the new module compared to the LabPET module, since the pitch was kept the same and the reflector thickness was changed ($\sim 75 \mu\text{m}$ with 3M ESR compared to $\sim 25 \mu\text{m}$ with silver foil).

In the current LabPET module, the LGSO_{LabPET} was chosen as the longer crystal to compensate for its lower stopping power compared to the LYSO_{LabPET}. Since the stopping power is the same for LGSO_{31ns} and LGSO_{47ns}, it was decided to evaluate the two possible assemblies (Type I and Type II, Fig. 1(b)). For each configuration, the *phoswich* block was mounted with 4 reach-through APDs [15] of the same type as in the standard LabPET modules having a $1.1 \times 3.6 \text{ mm}^2$ active area (Excelitas Technologies, Vaudreuil, QC, Canada), one for each *phoswich* pixel, and the assembly was hermetically enclosed in a standard LabPET package. To provide some assessment of the assembly procedure on detector performance, 20 such prototype modules (10 Type I and 10 Type II) were assembled.

Energy and timing resolution measurements were performed at a stable temperature ($27.0 \pm 0.5^\circ\text{C}$) with a ^{68}Ge (511 keV) radioactive source. This temperature is typical of the detector temperature in a LabPET scanner in normal operation. The APD bias was chosen to optimize timing resolution. Detection efficiency was assessed for the new Type I and Type II modules and compared to standard LabPET ones. For that measurement, a ^{137}Cs (662 keV) source was positioned 40 cm away from the detectors to insure that the incident radiation flux is the same for

Fig. 1. Schematic of the new LGSO *phoswich* block assembly with the optical coupling and 3M ESR reflector specifications (a) along with the two investigated module configurations: Type I and Type II (b).

all the detectors. The ^{137}Cs source was intentionally chosen instead of a positron emitter because its activity was high enough to limit the acquisition time and, thus, minimize temperature fluctuations during measurements in an open environment. The number of single counts above four energy thresholds (194, 324, 453 and 583 keV) were obtained using a 10-minute measurement and compared to the number of counts obtained with current [LGSO/LYSO]_{LabPET} modules in an identical setup. These four thresholds can be translated into a relation between the detection efficiency ratio and the lower energy threshold.

To evaluate the rate of natural radioactivity, a 2-h measurement was performed using the same setup, but without external radioactivity, and single counts were recorded. All measurements were performed with standard LabPET digital data acquisition electronics [16].

B. Gamma Spectroscopy Measurements

To assess the intrinsic performance of the crystals, measurements were performed on individual pixels from the modules. Whereas results from these needle-like crystals with an unfavorable form factor ($2 \times 2 \times 11.9/13.3 \text{ mm}^3$ with a 55° slant plane) will be degraded relative to small cubic crystals ($3 \times 3 \times 3 \text{ mm}^3$) commonly used in spectroscopic studies [17], these

TABLE II
SPECTROSCOPIC MEASUREMENTS ON INDIVIDUAL CRYSTALS

	LGSO _{47ns}	LGSO _{31ns}	LGSO _{LabPET}	LYSO _{LabPET}
Decay time (ns)	47.1 ± 0.2	30.7 ± 0.1	83 ± 3 (78%) 22 ± 1 (22%)	43 ± 1
Photoelectron yield (phe ⁻ /MeV)	28000±2000	18000±2000	19600±300	30700±400
Initial emission rate at 511 keV (phe ⁻ /(MeV ns))	620±40	590±80	302±5	770±10
Timing resolution (ns)	1.5 ± 0.1	1.7 ± 0.1	3.0 ± 0.2	1.8 ± 0.1
Energy resolution (%)	11.0±0.5	11.6±0.3	8.3±0.2	10.6±0.3
Peak emission wavelength (nm)	432	420	426	422
Window fraction $f_{250-650}$	0.62	0.65	0.57	0.63
Form factor	0.084	0.075	0.075	0.084

measurements allow direct comparison with similar crystals in the *phoswich* modules.

Several physical characteristics were inspected, namely the decay time, the photoelectron yield, the energy and timing resolutions, the peak emission wavelength and the crystal form factor (defined as the ratio of the detection surface area to the crystal volume). The decay time was measured by collecting 10 000 signals from the scintillators coupled to a fast PMT (RCA 4802-1) using a digital oscilloscope at 2 GSa/s (DSO6034 A, Agilent Technologies). The signals were averaged and the decay part of the curve was fitted using a single or double exponential regression. To evaluate the peak emission, UV-excited luminescence spectra were obtained using a spectrofluorometer (Hitachi F2000).

Four different scintillator types were investigated: LGSO_{LabPET} and LYSO_{LabPET} from the current LabPET module and LGSO_{31ns} and LGSO_{47ns} from the Type I module. Four samples of each scintillator were measured. All experiments were performed with the crystals coated with Bicon BC-620 white paint, with the exception of the photoelectron yield measurements that have been performed with scintillators wrapped in > 6 layers of PTFE tape. All crystals were optically coupled to a $4 \times 4 \text{ mm}^2$ UV-enhanced c7532 APD (Excelitas) operated at a gain of 120. The APD was connected to a custom low-noise charge-sensitive preamplifier (RCA 3.0) followed by an ORTEC 452 spectroscopy amplifier employed for all light yield and energy resolution measurements with a shaping time of 0.25 μs . The APD gain was calibrated by direct irradiation of the APD with 9 keV X-rays from a ^{67}Ga radiation source with the APD operated at low gain. The absolute light yield was then estimated by comparing to a reference pulse injected by a precision pulser at the input of the preamplifier through a calibrated 1 pF test capacitor. The intrinsic timing performance of the crystals coupled to an APD was assessed by coincidence against a fast PMT (RCA 4802-1) and plastic scintillator (NE102-A1-15c6 V) detector using a zero-cross time circuit connected to a time-amplitude converter (Ortec 467). For timing measurements, the signal from the APD-crystal detector was shaped with a fast filter amplifier (Ortec 474) having a 20 ns time constant and used to trigger a constant fraction discriminator with a 40% fraction and 4 ns (LGSO_{31ns}), 8 ns (LYSO_{LabPET} and LGSO_{47ns}) or 20 ns (LGSO_{LabPET}) delay. All data were acquired at ambient temperature ($\sim 21.0 \pm 0.5^\circ\text{C}$) in a temperature controlled room.

III. RESULTS

A. Gamma Spectroscopy Measurements

Spectroscopic measurements for the individual crystals are reported in Table II and are in fair agreement with the scintillators physical characteristics (Table I). The results indicate excellent decay time uniformity between the four LGSO-90%Lu samples of each type. However, the tested LGSO_{31ns} samples did not possess a higher photoelectron yield than the LGSO_{LabPET} and LYSO_{LabPET}, as reported earlier [7], indicating that the crystal production may not be stable and that better results could be expected later on. The LGSO_{47ns} also presented a slightly lower photoelectron yield than the LYSO_{LabPET}. The lower light yield of the LGSO_{31ns} and LGSO_{47ns} could also be due to self-absorption, but the UV emission and excitation spectra did not show significant overlap. Comparison with current LabPET crystals suggests that modules made of LGSO-90%Lu will have a slightly degraded energy resolution. The LGSO_{LabPET} achieves a better energy resolution despite its lower light yield because there is likely less competition between Ce1 and Ce2 luminescence centers in this scintillator [18]. The LGSO_{31ns} and LGSO_{47ns} timing resolution is equivalent to LYSO_{LabPET} resolution (~ 1.7 ns) and significantly better than LGSO_{LabPET} resolution (~ 3.0 ns). Emission wavelengths are very similar for all the scintillators. To enable the comparison of detection efficiency with a 250–650 keV energy window, the window fraction $f_{250-650}$ defined in Eq. (1) is also reported

$$f_{250-650} = \frac{\text{counts} \in \text{photoelectric window}(400 - 600\text{keV})}{\text{counts} \in 250 - 650\text{keV window.}} \quad (1)$$

B. Module Measurements

To characterize the new LGSO_{47ns}/LGSO_{31ns} LabPET modules as a replacement for the current LabPET module, *phoswich* crystal identification is a prerequisite. At first glance, the discrimination with the new *phoswich* combination, having a 16 ns decay time difference, appears more challenging than with the current module having a 25 ns difference. Decay time discrimination was performed using the same procedure as in the LabPET data processing chain [16].

TABLE III
MODULES PERFORMANCE

	Type I		Type II		LabPET	
	LGSO _{31ns}	LGSO _{47ns}	LGSO _{31ns}	LGSO _{47ns}	LGSO _{LabPET}	LYSO _{LabPET}
Energy resolution (%)	21 ± 2	17 ± 2	18 ± 3	17 ± 2	18 ± 1	20 ± 2
Timing res. (250 keV) (ns)	5.2 ± 0.5	4.6 ± 0.3	5 ± 1	4.6 ± 0.3	10 ± 3*	6 ± 2*
Light output ratio (slow/fast)	1.4 ± 0.1		1.2 ± 0.1		0.8 ± 0.1	
Discrimination error (%)	7 ± 1		8 ± 3		5 ± 2	

* obtained with a LabPET8 scanner

Fig. 2. Detection efficiency ratio. The measurement was performed using a 662 keV source, 40 cm away from the detectors.

Fig. 3. Intrinsic ¹⁷⁶Lu spectra for current LabPET and Type I modules.

Table III reports the module performance as a comparison between the Type I, Type II and [LGSO/LYSO]_{LabPET} modules. Contrary to what was observed in the spectroscopic measurements on individual crystals, the energy resolution is similar in all configurations, with a slight advantage with the Type II assembly. This could be explained by the different reflectors used in the two modules; the reflectivity of the silver foil used in the current LabPET module is 85%, while the reflectivity of the 3M ESR used in the Type I and II modules is about 98% above 400 nm. LGSO_{47ns} clearly shows better results than LGSO_{31ns}, regardless of the configuration, mostly due to its higher light yield. The expected relative light yield between the two scintillators (LGSO_{47ns}/LGSO_{31ns}) is 1.6 ± 0.2 , obtained from Type I spectroscopic measurements. The relative light output

estimated from the photopeak positions in the module measurements yields 1.4 ± 0.1 for the Type I configuration and 1.2 ± 0.1 for the Type II configuration. The Type II configuration is slightly more balanced than Type I as it is closer to one and the two crystals should exhibit similar performance.

The average time resolution in coincidence was 4.6 ± 0.3 ns for LGSO_{47ns} in both configurations and 5.2 ± 0.5 ns for LGSO_{31ns} in Type I and 5 ± 1 ns in Type II. The time resolution of both assemblies is similar to the results obtained in a LabPET8 scanner for LYSO_{LabPET} (6 ± 2 ns) and better than results obtained for LGSO_{LabPET} (10 ± 3) [19]. The LGSO_{47ns} scintillator yields the best timing performance in both configurations as its higher light yield compensates for its slower decay time.

The ratio of the new module detection efficiency ϵ_{new} to the LabPET module detection efficiency ϵ_{LabPET} was defined as

$$\frac{\epsilon_{\text{new}}}{\epsilon_{\text{LabPET}}} = \frac{\text{singles}_{\text{LGSO}_{31\text{ns}}} + \text{singles}_{\text{LGSO}_{47\text{ns}}}}{\text{singles}_{\text{LGSO}_{\text{LabPET}}} + \text{singles}_{\text{LYSO}_{\text{LabPET}}}} \quad (2)$$

where the singles rates from a 662 keV source are measured above an energy threshold. The ratios are found to be identical for Type I and Type II modules (the crystal composition is the same), ranging from 1.15 ± 0.05 to 1.21 ± 0.07 with increasing the energy threshold from 200 to 600 keV (see Fig. 2), which corresponds to a ratio of 1.3–1.5 in coincidence.

Fig. 3 shows the spectra obtained without an external radioactive source to evaluate the intrinsic radioactivity of the lutetium. The ¹⁷⁶Lu isotope (2.6% abundance, 3.78×10^{10} years half-life) decays by β^- emission, followed by the emission of γ -ray(s) of 307 keV (94%), 202 keV (78%), and 88 keV (15%) [20]. Since the identification algorithm is less efficient at lower energy, the interaction crystal is poorly discriminated and it is preferable to compare the results at the *phoswich* level rather than the crystal level. Therefore, the two signals were added. From Fig. 3, the background count rate due to natural radioactivity is found to be almost twice higher with the LGSO_{31ns}/LGSO_{47ns} module than with the standard LabPET module, due to the higher Lu content. This could be a problem for SPECT imaging using PET detectors [21], since this unwanted signal must be subtracted.

C. Sensitivity Improvement

A calculation was performed to compare the sensitivity of a PET system based on the new LGSO to the standard LabPET module. To estimate the sensitivity ratio, the first step was to evaluate the photoelectric detection efficiency ϵ of both modules using

$$\epsilon = 1 - e^{-\mu \cdot P(\tau) \cdot L} \quad (3)$$

TABLE IV
PREDICTED IMPACT ON LABPET8 SCANNER PERFORMANCE (250–650 keV)

	Current module	New module
ϵ_w short crystal	43%	43%
ϵ_w long crystal	38%	49%
Relative solid angle*	1	0.96
Sensitivity improvement (%)		+33%
Coincidence time window	20 ns	10 ns
NEC improvement (mouse)		1.4×
NEC improvement (rat)		1.5×

* 3M ESR reflector ($\sim 75 \mu\text{m}$) thicker than silver foil ($\sim 25 \mu\text{m}$)

where μ is the linear attenuation coefficient at 511 keV, $P(\tau)$ is the photoelectric probability and L the crystal length (measured in the middle of the tapered crystals, respectively 11.9 and 13.3 mm for the shorter and longer components of the *phoswich* [see Fig. 1(b)]. The sensitivity comparison is based on a 250–650 keV energy window. This window was chosen to be compliant with LabPET standard acquisition mode and to overcome any possible light crosstalk mostly due to the cut-off frequency around 400 nm of the 3M ESR reflector [22]. Because this energy window was chosen rather than the photopeak only, a window fraction specific to each crystal, $f_{250-650}$, must be added in Eq. (3) to adequately compare the sensitivity. The windowed detection efficiency ϵ_w is defined as

$$\epsilon_w = (1 - e^{-\mu \cdot P(\tau) \cdot L}) / f_{250-650}. \quad (4)$$

The ratio $f_{250-650}$ was assessed using the spectroscopic samples and the results were reported in Table II, which completes the data needed to compare the modules sensitivities. Overall, the LGSO-90%Lu scintillators have more stopping power than $\text{LGSO}_{\text{LabPET}}$ and $\text{LYSO}_{\text{LabPET}}$. Moreover, the photoelectric probability is higher, especially compared to the $\text{LGSO}_{\text{LabPET}}$. The calculated windowed detection efficiencies, ϵ_w , are displayed in Table IV. To evaluate the sensitivity ratio S_r between the two modules, we used

$$S_r = \frac{(\epsilon_w \text{LGSO}_{31\text{ns}} + \epsilon_w \text{LGSO}_{47\text{ns}})^2}{(\epsilon_w \text{LGSOLabPET} + \epsilon_w \text{LGSOLabPET})^2}. \quad (5)$$

The theoretical sensitivity ratio S_r is 1.29, using values from Table I and the window fraction $f_{250-650}$ obtained from spectroscopic measurements (Table II). Even with the slightly smaller packing fraction resulting from the slightly thicker reflector (by a 0.96 factor), the sensitivity would still be improved. Using the theoretical S_r , it is possible to compare with the experimental ratio (Fig. 2). Since the ratio of detection efficiencies was 1.16 ± 0.05 for a 250 keV lower energy limit, the experimental sensitivity improvement will be 1.36 ± 0.06 for a 250–650 keV window. The two values (1.29 and 1.36) are slightly different, mostly because of the imprecision coming from the $f_{250-650}$ ratio in the theoretical evaluation. The mean values of the two different estimations are 1.15 ± 0.05 for the singles ratio and 1.33 ± 0.06 for the coincidence rates ratio.

D. Noise Equivalent Count Rate Improvement

A standard width for the coincidence time window is about $2 \times$ the FWHM time resolution to ensure the recovery of 98% of the coincidence events, assuming a Gaussian coincidence time distribution. Since the time resolution of both crystals in the new module is about half of the $\text{LGSO}_{\text{LabPET}}$ resolution, the coincidence time window can be reduced by up to a factor of 2 with the new detectors, leading to a reduction by a factor of 2 in the random rates. Considering that the LabPET peak noise equivalent count rate (NEC) occurs at a specific total count rates, the peak NEC activity for the new module would be slightly lower than for the current module, corresponding to the ratio of the detection efficiencies (~ 1.15). The NEC improvement can be calculated using

$$\text{NEC improvement} = \frac{\text{NEC}_{\text{LGSO-90\%Lu}} @ [\text{peak activity} / 1.15]}{\text{NEC}_{\text{LabPET}} @ [\text{peak activity}]}, \quad (6)$$

where

$$\text{NEC}_{\text{LGSO-90\%Lu}} @ [\text{peak activity} / 1.15] = \frac{1.33 \times R_T^2}{R_T + R_S + 0.5 R_R} \quad (7)$$

and where R_T is the true rate, R_S is the scatter rate and R_R is the random rate of the LabPET modules. The improved detection efficiency, along with the random rates reduction, would result in an estimated NEC amelioration of $1.4 \times$ for a mouse phantom and $1.5 \times$ for a rat phantom. This was calculated using the LabPET8 scanner data [13].

IV. DISCUSSION

In the present work, the same electronic settings and firmware as for $\text{LGSO}_{\text{LabPET}}$ and $\text{LYSO}_{\text{LabPET}}$ were employed without any modifications. Signal processing could be adapted to the specific characteristics of the LGSO-90%Lu signal shapes.

As confirmed by all the measurements, the use of LGSO-90%Lu in the LabPET modules would be beneficial in many respects. Table IV summarizes the predicted impact on scanner performance using a 250–650 keV energy window, notably a $33 \pm 6\%$ increase in sensitivity and a NEC improvement of a $\sim 1.4 \times$ factor for mouse imaging and $\sim 1.5 \times$ for rat imaging. The results obtained in this work confirm that the proposed all LGSO-based detector module can be manufactured with highly reproducible performance characteristics, as demonstrated by the small standard deviation in all measured data, and hence can be readily implemented in LabPET scanners. Whereas these scintillators performed well in a side-by-side *phoswich* like LabPET detector, they can be expected to perform even better in dual-layer assemblies for DOI detectors. The data reported in Table I suggest that the light yield could be improved if the crystal production was stabilized. If this was the case, this application would benefit from the good light yield of $\text{LGSO}_{47\text{ns}}$, given the unavoidable light loss at the *phoswich* crystal interface. This higher light yield would also open the way to better detection of lower energy signals in applications such as intercrystal recovery in high resolution PET [23], SPECT imaging using PET detectors [24] and counting CT imaging [25].

V. CONCLUSION

The new high lutetium LGSO scintillators with tunable decay time based on cerium concentration offer a great potential for simplifying detector assembly and improving PET imaging performance, by a simple replacement of the LabPET detector modules. These new crystals provide excellent timing resolution while still supporting *phoswich* discrimination. They are expected to improve the LabPET scanner sensitivity and count rate performance, while significantly reducing random rates.

ACKNOWLEDGMENT

The authors would like to thank M. Toshinori Takeyama of Marubeni Specialty Chemicals Inc. (White Plains, NY) and Dr. H. Ishibashi of Hitachi Chemical Co., Ltd. (Ibaraki, Japan) for supplying the LGSO crystal samples.

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