Performance of thin long scintillator strips of GSO:Ce, LGSO:Ce and LuAG:Pr for low energy $\gamma$-rays

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Abstract

Interest in fibers or strips of single crystalline scintillators is increasing for their possible applications in fine-segmented particle detectors for particle physics experiments as well as $\gamma$-ray detectors for medical diagnoses. We compared 2 $\times$ 2 $\times$ 100 mm$^3$ strips of Gd$_2$SiO$_5$(GSO):Ce, Lu$_{1.9}$Gd$_{0.1}$SiO$_5$(LGSO):Ce, and Lu$_2$Al$_2$O$_7$(LuAG):Pr single crystals for 0.511 MeV $\gamma$-rays with respect to the effective light attenuation length $\lambda_{a}$, light yield $Y$, FWHM energy resolution $\Delta E/E$, and rms position resolution $\sigma(z)$ of the injection position $z$ along the length. The obtained result was ($\lambda_{a}$, $Y$, $\Delta E/E$, $\sigma(z)$) = (128 mm, 380 phe/MeV, 17.7%, 8.7 mm) in GSO:Ce, (151 mm, 760 phe/MeV, 12.2%, 10.9 mm) in LGSO:Ce, and (171 mm, 660 phe/MeV, 15.0%, 8.9 mm) in LuAG:Pr. The $\sigma(z)$ position was obtained independently from the pulse height ratio as well as the timing difference between both ends of the strip. The latter method gave comparable or even smaller $\sigma(z)$ than the former only in LGSO:Ce having both large $Y$ and fast rise time. The $\lambda_{a}$ in the 100 mm long GSO:Ce strip was found to be twice as large as that in the 200 mm long one [1] with the same cross-section. To obtain good $\Delta E/E$ and $\sigma(z)$, large light yield, fast rise time, and moderately large attenuation length are important for the scintillators.

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1. Introduction

Single crystalline scintillators in fibers or strips have attracted increasing interest in these years [1–3] for their possible applications in fine-segmented particle detectors for particle physics experiments as well as $\gamma$-ray detectors for medical diagnoses [1,4,5]. In most of the applications, high-quality fibers or strips as long as 100–200 mm are required. Several scintillator strips were evaluated in the past, including 3.2 $\times$ 3.2 $\times$ 100 mm$^3$ (Lu$_2$Y$_{2}$SiO$_{12}$LYSO:Ce) and YAlO$_3$(YAP):Ce [6], 3 $\times$ 3 $\times$ 100 mm$^3$ LYSO:Ce [5], 1 $\times$ 1 $\times$ 43 mm$^2$ and 1 mm diameter, 69 mm length LYSO:Ce [4], and 2 $\times$ 2 $\times$ 200 mm$^3$ GSO:Ce [1].

In our previous work [1], we evaluated a 2 $\times$ 2 $\times$ 200 mm$^3$ GSO:Ce 1.5 mol% strip for 0.511 MeV $\gamma$-rays. Employing photomultiplier tube (PMT) readout at both ends, we obtained the effective attenuation length $\lambda_{a}$ = 67 mm, FWHM energy resolution $\Delta E/E$ = 35–24% depending on the longitudinal position $z$, and the rms position resolution $\sigma(z)$ ~ 10 mm almost independently of $z$. While GSO:Ce should be promising, there may be better materials for fibers among heavy, fast response, and efficient scintillators.

With this motivation, we compared in the present work GSO:Ce, LGSO:Ce and LuAG:Pr, all having the same size of 2 $\times$ 2 $\times$ 100 mm$^3$. The scintillator characteristics of these materials are compared in Table 1. The reason why we chose GSO:Ce was mentioned in Ref. [1]. It is one of dense, fast-response, and efficient scintillators with good balance [7,8], and has been widely used in particle detectors [9–11]. Its light yield (LY), however, is not large enough compared with some other Ce-activated scintillators such as Lu$_2$SiO$_5$(LSO):Ce, LY:LSO:Ce, LGSO:Ce, etc. It is then interesting to evaluate scintillator strips with higher LYs.

As for LSO:Ce, the internal non-uniformity has mostly been solved [12]. To overcome the remaining instability completely in both crystal growth and properties of grown crystals, mixed crystals of LSO:Ce with small concentrations of Y$_2$SiO$_5$ (LYSO:Ce [13]) or GSO (GSO:Ce [14,15]) have been successfully developed in these years. Since LYSO:Ce and LGSO:Ce have the same crystal structure without cleavage and similar scintillation properties, we chose LGSO:Ce for the present study. The crystal structure is of LSO:Ce type (monoclinic structure, C2/c space group) if Lu:Gd molar ratio is larger than 0.2:0.8 [16]. The present sample with Lu:Gd = 0.95:0.05 is close to LSO:Ce in almost all aspects. Besides the main emission peak at 410 nm, an additional peak at 310 nm occupies 18% of the total LY (Fig. 1). This peak, coming from the 4f–4f spin-forbidden transitions of Gd$^{3+}$, remains because the

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Gd–Gd energy migration to Ce\(^{3+}\) should be weak due to small concentration of Gd\(^{3+}\). Since the 310 nm component should be slow enough with a decay constant \(\tau\approx\) ms, its existence should hardly disturb the present measurement.

We also included LuAG:Pr\(^{3+}\) for the present study. Compared with GSO:Ce, it has a similar density, a little larger \(Z_{\text{eff}}\) (62.9 compared to 59.4), and rather different scintillation properties (Table 1). The emission peak sits at 350 nm, much shorter compared to 59.4 nm. The radioluminescence spectra of GSO:Ce, LGSO:Ce and LuAG:Pr are shown in Fig. 1. The emission peak sits at 310 nm for LGSO:Ce and 350 nm for LuAG:Pr. The overlap of the excitation and emission spectra in the tails is as large as or even larger than in GSO:Ce (see Fig. 2). Self-absorption may limit the obtainable LYSs in the strips.

All the single crystalline strips studied in the present work were cut from Czochralski-grown ingots of high quality. Since single crystalline fibers commercially available are limited in materials as well as size, it was not easy to get fiber samples of a fixed size with the scintillation properties as good as bulk single crystals.

Production of single crystalline fibers has been developed [2] with several methods including (1) micro-pulling-down (µPD), (2) edge defined film-fed growth (EFG), (3) laser-heated pedestal growth (LHPG), and (4) internal crystallization method (ICM). Among them, µPD method has been expected to be promising in growing long fibers at a reasonable cost. To the authors’ knowledge, GSO:Ce fibers of the present length (100 mm) have not yet been realized. This may be related to the cleavage of this crystal. LGSO:Ce fibers are not yet available, different from LYSO:Ce. In a pioneering work for a small PET (positron emission computed tomography) scanner [4], LYSO fibers with a cross-section of about 1 mm\(^2\) and a length of 70 mm were grown by the µPD method, and evaluated with respect to the scintillation properties. A clear LSO:Ce fiber of 0.5 mm diameter and 20 mm length [27] was also grown with the LHPG method. The situation as mentioned above may indicate a possibility of growing LGSO:Ce fiber in the near future.

In contrast to GSO:Ce and LGSO:Ce, LuAG:Pr fibers have already been grown successfully at a few laboratories and companies [28,3]. In Furukawa Co., one of the present authors (Y.U.) has successfully grown single crystal fibers of LuAG:Pr 2.5 mol% longer than 200 mm with a cross-section of 2 × 2 mm\(^2\) by the µPD method. The grown fiber was clear with the cross-section uniform. However, we had some difficulty in cutting both ends at a precise length; small cracking occurred probably due to the stress remaining in the crystal even after annealing. The reason why this difficulty does not occur in LuAG:Ce fiber but in LuAG:Pr remains to be clarified in the future. For the present experiment, we abandoned crystal fiber of LuAG:Pr, and cut the strip from a Czochralski-grown ingot.

For most of the applications mentioned above, the energy deposit of injected particle in a strip should be as small as a few MeV. We therefore evaluated each crystal strip for 0.511 MeV γ-rays, which can be easily obtained from the back-to-back annihilation of a positron from \(^{22}\)Na on an electron. A narrow γ-ray beam can be obtained by a tagging technique [1,29].

Table 1

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>GSO:Ce(^{3+}) (1.5 mol%)</th>
<th>LGSO:Ce(^{3+}) (Lu 95%)</th>
<th>LSO:Ce(^{3+})</th>
<th>LuAG:Pr(^{3+})</th>
<th>LuAG:Ce(^{3+})</th>
<th>LuCeO(_5) (BGO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, g/cm(^3)</td>
<td>6.71</td>
<td>7.3</td>
<td>7.40</td>
<td>6.73</td>
<td>6.73</td>
<td>7.13</td>
</tr>
<tr>
<td>Radiation length cm</td>
<td>1.38</td>
<td>1.16</td>
<td>1.14</td>
<td>1.45</td>
<td>1.45</td>
<td>1.12</td>
</tr>
<tr>
<td>Effective atomic number (Z_{\text{eff}})</td>
<td>59.4</td>
<td>66.1</td>
<td>66.4</td>
<td>62.9</td>
<td>62.9</td>
<td>75.2</td>
</tr>
<tr>
<td>µ(^2) at 511 keV, cm(^{-1})</td>
<td>0.71</td>
<td>0.88</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>0.98</td>
</tr>
<tr>
<td>Emission peak, nm</td>
<td>310</td>
<td>410</td>
<td>310, 365</td>
<td>520</td>
<td>480</td>
<td></td>
</tr>
<tr>
<td>Excitation peak, nm</td>
<td>310, 350</td>
<td>410</td>
<td>270, 300</td>
<td>470</td>
<td>280</td>
<td></td>
</tr>
<tr>
<td>LY(^{e}), phe/MeV</td>
<td>8000</td>
<td>23,000</td>
<td>18,000</td>
<td>18,000</td>
<td>18,000</td>
<td>18,000</td>
</tr>
<tr>
<td>Decay constant (\tau), ns</td>
<td>28 (87%) [3,260 (13%)]</td>
<td>40</td>
<td>17 (35%), 119 (14%), 69 (40%)</td>
<td>300</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(\tau\) is the time for the intensity to fall to the background level.

\(\tau\) is the time for the intensity to fall to 0.41 of the initial value.

\(\tau\) is the time for the intensity to fall to 10% of the initial value.

\(\tau\) is the time for the intensity to fall to 90% of the initial value.

References: [1,7,17,8,17,18,8,19,20,21,21,22]
The main aim of the present paper is to compare $l_a$, $LY$, $DE/E$, and $s(z)$ for the three crystals. After description of the measuring method in the next section, the obtained results are given in Section 3. Section 4 is devoted to discussions on $l_a$, $LY$, energy and position resolutions before coming to a summary in Section 5.

2. Experimental

A GSO:Ce 1.5 mol% strip with $2 \times 2 \times 100$ mm$^3$ was cut from a longer strip of $2 \times 2 \times 200$ mm$^3$, which came from the same ingot as the 200 mm long strip evaluated in Ref. [1]. The whole surface was polished to the optical grade by chemical etching. Compared with the standard Ce$^{3+}$ concentration of 0.5 mol%, the present crystal should give 80% of light intensity [1], a shorter $\tau$ of 28 instead of 53 ns, and a faster rise time (10–90%) of 8 instead of 13 ns [17].

A single crystal of LGSO:Ce with a diameter of 50 mm was grown by Hitachi Chemical Co. with $Lu:Gd$ molar ratio = 0.95:0.05 and Ce$^{3+}$ concentration of 0.15 mol% in the melt. A strip of $2 \times 2 \times 100$ mm$^3$ was cut from the ingot and polished by chemical etching.

A LuAG:Pr single crystal was grown by Furukawa Co. with the Czochralski method using an Ir crucible. The Pr$^{3+}$ concentration was 2.5 mol% in the melt, while 0.2 mol% in the crystal. The small segregation coefficient of 0.062 should be due to the significant mismatch in the ion radii between Lu$^{3+}$ (0.85 Å) and Pr$^{3+}$ (1.06 Å). A strip of $2 \times 2 \times 100$ mm$^3$ was cut from the ingot and polished by chemical etching.

The experimental setup as sketched in Fig. 3 was placed in a light-shielded box. Each scintillator strip was directly coupled to a PMT on both ends (called $A_1$ and $A_2$) with optical grease Oken 6262. The strip without reflector wrapping nor coating was mechanically supported only by a 7 mm thick bakelite holder at each PMT window. For each PMT, one of the 16 anodes of position sensitive PMT (Hamamatsu H6568MODIII, UBA, QE = 41% max at 350 nm, borosilicate glass window) was assigned. The fixed channels on the fixed PMTs were used for different scintillators by remounting them.

The 0.511 MeV $\gamma$-rays were injected to a small spot on the scintillator strip by using a tagged $\gamma$-ray injector [1]. The injector consists of a $^{22}$Na $\gamma$-ray source (1 mm diameter) and a needle of Lu$_{1.96}$Y$_{0.04}$SiO$_5$(LYSO):Ce$^{3+}$ scintillator with $1 \times 1 \times 20$ mm$^3$. Lu-rich LYSO:Ce [13] has similar scintillation characteristics as LSO:Ce (Table 1). Both the LYSO needle and the scintillator strip were placed at a distance of 100 and 50 mm, respectively, from the $^{22}$Na source on the opposite side. Two $\gamma$-rays emitted back to back were detected by the needle and the scintillator strip in coincidence. The $\gamma$-ray beam profile on the strip was scanned with another $1 \times 1 \times 20$ mm$^3$ LYSO:Ce needle at the scintillator strip position. The obtained 1-dimensional distribution of the $\gamma$-rays gave a Gaussian shape of 0.68 mm rms.

The scintillator strip mounted on an optical stand was moved along the direction of its length, taken as $z$-axis, while the $\gamma$-ray injector was fixed in position. Referring to Fig. 3, $z$ gives the $\gamma$-ray injection position along the $z$-axis, increasing from $z=0$ at A1 toward $L/2$ at A2, here $L$ being the strip length of 100 mm.

A sketch of the setup. PMTs as well as their pulse heights on both ends of crystal strip are called $A_1$ and $A_2$. The distance $z$ of the injection position of 0.511 MeV $\gamma$-rays on the strip measured from its center ($z=0$) increases from $-L/2$ at $A_1$ toward $L/2$ at $A_2$, here $L$ being the strip length of 100 mm.

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We carried out measurement for seven injection points $z = -40, -20, 0, 10, 20, 30,$ and $40$ mm using standard NIM-CAMAC circuits. The outputs of the LYSO needle and the scintillator strip were first amplified in a preamplifier (KN2104, Kaizu-Works Co., gain ~4), and fed to a charge-sensitive ADC (14 bit, Hoshin C009H) within a...
350 ns gate (300 ns net for integration). The ADC signals or light yields of the PMTs A1 and A2 are also called A1 and A2, respectively, throughout the present paper. The timings of the A1 (denoted as T1) and A2 (T2) were registered with a TDC (12 bit for 100 ns, Philips 7187) with respect to the LYSO as the start.

Data taking was done under a triggering condition of hits in the LYSO and at least “A1 or A2” (for GSO:Ce), or both “A1 and A2” (for LGSO:Ce and LuAG:Pr) in coincidence. “A1 or A2” and “A1 and A2” should not make any sizable differences in event selection, since the threshold in both A1 and A2 was set a little below the single photoelectron (phe) level.

The pulse height spectrum of the LYSO needle was similar to Ref. [1]. The 0.511 MeV total absorption peak with 16.5% FWHM occupied 34% of the total LY, and was well separated from the Compton-scattering plateau. While we did not require the LYSO pulse height to be in the total absorption peak in triggering and data analysis because of the following reason: when the two γ-rays from 22Na are detected by the LYSO needle and the scintillator strip, the reaction of Compton scattering or total absorption of one of the γ-rays in the former detector is irrelevant to the reaction of the other γ-ray in the latter.

3. Results

The obtained results on LY, \( \lambda_{\text{a}} \), \( \Delta E/E \) and \( \sigma(z) \) from pulse height measurement are first given separately for three crystals in Sections 3.1–3.3. Then in Section 3.4, the timing difference \( T_1 - T_2 \) as well as the calculated \( \sigma(z) \) will be compared for all the crystals. Typical results obtained for the injection at \( z=0 \) are summarized in Table 2.

### 3.1. GSO:Ce strip

Pulse height spectrum of A1 (or A2) consists of 0.511 MeV total absorption peak and Compton-scattering plateau. While we followed similar data analysis as in our previous work [1], the analysis was simpler this time because the separation of the total absorption peak from the Compton tail was much better due to the shorter strip.

Since the PMT gain, including preamplifiers, may be different for A1 and A2, we first normalized both gains by injecting the γ-rays at the center (\( z=0 \)), and comparing the total absorption peak channels. All the results are given after this left and right normalization and pedestal subtraction.

A typical pulse height spectrum of the sum of A1 and A2 obtained at \( z=0 \) is given in Fig. 4 in comparison with the other crystals. Typical results obtained for the injection at \( z=0 \) are summarized in Table 2.

### Table 2

Summary of the obtained result for 0.511 MeV γ-ray injection at \( z=0 \). LY and \( \Delta E/E \) are for the sum of A1 and A2. The 200 mm long GSO:Ce [1] is also added for comparison.

<table>
<thead>
<tr>
<th>Scintillator strip</th>
<th>GSO:Ce</th>
<th>LGSO:Ce</th>
<th>LuAG:Pr</th>
<th>GSO:Ce [1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size, mm³</td>
<td>2 × 2 × 100</td>
<td>2 × 2 × 100</td>
<td>2 × 2 × 100</td>
<td>2 × 2 × 200</td>
</tr>
<tr>
<td>Attenuation length, ( \lambda_{\text{a}} ), mm</td>
<td>128</td>
<td>509</td>
<td>171</td>
<td>67</td>
</tr>
<tr>
<td>Light yield LY, phe/MeV</td>
<td>380</td>
<td>1758</td>
<td>691</td>
<td>114</td>
</tr>
<tr>
<td>FWHM energy resolution, ( \Delta E/E )</td>
<td>0.177</td>
<td>0.122</td>
<td>0.150</td>
<td>0.35</td>
</tr>
<tr>
<td>RMS position resolution ( \sigma(z) ), mm</td>
<td>8.9</td>
<td>16.8</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>From A1/A2</td>
<td>42</td>
<td>14.3</td>
<td>19.2</td>
<td>32</td>
</tr>
<tr>
<td>Combined</td>
<td>8.7</td>
<td>10.9</td>
<td>8.9</td>
<td>9.5</td>
</tr>
</tbody>
</table>

Fig. 4. Pulse height spectra of A1 + A2 for 0.511 MeV γ-rays injected at \( z=0 \) in GSO:Ce, LGSO:Ce and LuAG:Pr strips under the triggering condition given in Section 2.2. The pedestal is already subtracted. Solid curve gives a Gaussian fit for the total absorption peak. Although the PMT high voltages (HVs) were 750, 700 and 720 V for GSO:Ce, LGSO:Ce and LuAG:Pr, respectively, so as to avoid saturation in PMT, the spectra are presented after gain normalization to the same HV. The bin width is 50 ch. in (a) and (c), while 100 ch. in (b).

\[
A_1 \sim \exp(-z/\lambda_{\text{a}}) \quad \text{and} \quad A_2 \sim \exp(z/\lambda_{\text{a}})
\]
with $\lambda_a \sim 122$ mm for A1 and 129 mm for A2. The $z$-dependences of A1 and A2 are similar to each other, indicating the approximate uniformity of the strip along the length with respect to the emission intensity and attenuation. While the sum of A1 + A2 could be fit well with the sum of two exponentials

$$f_{\text{sum}}(z) = \text{const} \cdot [\exp(z/\lambda_a) + \exp(-z/\lambda_a)]$$

(2)

this function is poorly sensitive to $\lambda_a$. Then, instead of fitting, the solid curve on the A1 + A2 data is simply drawn with $f_{\text{sum}}(z)$ by substituting $\lambda_a$ with 129 mm obtained in the fit of A2. The agreement between $f_{\text{sum}}(z)$ with data is visibly good as expected. The situation is the same for $\Delta E/E$, which is given by the ratio of the FWHM width of A1 + A2 to A1 + A2. If we assume that $\Delta E/E$ should be dominated by the statistical fluctuation of LY, it should have a $z$ dependence of

$$f_{\text{res}}(z) = \text{const} \cdot \left[\exp\left(z/\lambda_a\right) + \exp\left(-z/\lambda_a\right)\right]^{1/2}.$$

(3)

Since this function is not sensitive to $\lambda_a$, the solid curve on the $\Delta E/E$ data is simply drawn with $f_{\text{res}}(z)$ by substituting in it a fixed $\lambda_a = 129$ mm again. The agreement between $f_{\text{res}}(z)$ with data is visibly good again as expected.

The injection position $z$ of $\gamma$-rays can be obtained by comparing the pulse heights of A1 and A2. We can define for each event

$$R = \log_e(A2/A1).$$

(4)

A typical spectrum of R is presented in Fig. 6 for events in the total absorption peak. Since the separation between the total absorption peak and the Compton tail was always good (see Fig. 4), the cut between them was straightforward in any of the pulse height spectra of A1, A2, and A1 + A2. The spectrum of R obtained in each run for a fixed injection position $z$ showed a sharp peak as seen in Fig. 6. The peak was fit with a single Gaussian to obtain its mean $R(z)$ and width $\sigma(R)$. The $R(z)$ is plotted versus $z$ in Fig. 5b with $\sigma(R)$ as its error bar. Substituting Eq. (1) into Eq. (4), we have the following approximate relation:

$$R(z) = 2z/\lambda_a.$$

(5)

Actually the $R(z)$ spectrum can be fit well with a straight line Eq. (5) with $\lambda_a = 129$ mm, which is consistent with 129 and 122 mm obtained in the fit of A2 and A1, respectively. Eq. (5) gives the position resolution $\sigma(z)$ as

$$\sigma(z) = \lambda_a \sigma(R)/2.$$

(6)

Then, from $\lambda_a = 129$ mm and $\sigma(R)$ as shown in Fig. 6, we obtain $\sigma(z) \sim 8.9$ mm almost independently of $z$ (Fig. 5c). Here, we note that $\sigma(R)$ can be written as

$$\sigma(R) = \left[\sigma(A1)/A1^2 + \sigma(A2)/A2^2\right]^{1/2}.$$

(7)

This gives a relation of $\sigma(R) \sim 2\sigma(A1 + A2)/(A1 + A2)$ for the injection at $z=0$, where $A1 \sim A2$ holds. Actually for GSO:Ce at $z=0$, we obtained $\sigma(R)=0.146$ in Fig. 6, and $2\sigma(A1 + A2)/(A1 + A2) \sim 0.148$ in Fig. 4a.

Fig. 6. A typical spectrum of $R$ for total absorption events in GSO:Ce at the injection position $z=0$. The solid curve gives a Gaussian fit. The triggering condition is the same as in Fig. 4.
While the asymmetry parameter $A = (A_2 - A_1)/(A_2 + A_1)$ [1] should be similarly useful as $R$ to obtain $\sigma(z)$, $R$ is more convenient since it gives a simple expression of Eq. (6) for $\sigma(z)$.

### 3.2. LGSO:Ce

Data analysis was similar to GSO:Ce. A typical pulse height spectrum of the sum of $A_1$ and $A_2$ for $z=0$ is given in Fig. 4. The LY was 4.63 times GSO:Ce at $z=0$ from comparison of the total absorption peak position.

Fig. 7a gives the $z$-dependences of the $A_1$, $A_2$, $A_1 + A_2$ and $\Delta E/E$. The dependence of $A_2$ (or $A_1$) on $z$ can be fit well with Eq. (1) with $\lambda_a = 518$ mm (or 485 mm). The $z$-dependences of $A_1$ and $A_2$ are similar to each other, indicating the approximate uniformity of the strip with respect to the emission intensity and attenuation. Due to the same reason as mentioned for GSO:Ce, $A_1 + A_2$ and $\Delta E/E$ are poorly sensitive to $\lambda_a$. Instead of fitting, therefore, the solid curves on the $A_1 + A_2$ and $\Delta E/E$ data in Fig. 7a are simply drawn with $f_{\text{sum}}(z)$ of Eq. (2) and $f_{\text{rel}}(z)$ of Eq. (3), respectively, by substituting $\lambda_a = 500$ mm, an average value obtained in the fit of $A_1$ and $A_2$.

The injection position $z$ can be obtained from $R$ of Eq. (4). The spectrum of $R$ for the events in the total absorption peak in each run for a fixed $z$ showed a single peak similar to Fig. 6. The peak was fit well with a single Gaussian to obtain $R(z)$ and $\sigma(R)$. The obtained $R(z)$ is plotted versus $z$ in Fig. 7b with $\sigma(R)$ as its error bar. Based on Eq. (5), $R(z)$ was fit well with $2z/\lambda_a$ with $\lambda_a = 509$ mm, which is consistent with 518 and 485 mm obtained...
in the fit of A2 and A1, respectively. From the obtained $\lambda_0$ and $\sigma(R)$, the position resolution $\sigma(z)$ is given by Eq. (6) to be 16.8 mm almost independently of $z$ (Fig. 7c).

3.3. LuAG:Pr

Data analysis was again similar to GSO:Ce. The LY was 1.82 times GSO:Ce from Fig. 4. Fig. 8a gives the $z$-dependences of the A1, A2, A1+A2 and $\Delta E/E$. The $z$-dependence of A2 (or A1) can be well fit with a single exponential of Eq. (1) with $\lambda_0 \sim 170$ mm (or 161 mm), indicating the approximate uniformity of the strip with respect to the scintillation intensity and attenuation. Since $A1 + A2$ and $\Delta E/E$ are poorly sensitive to $\lambda_0$, fitting was not done. The solid curves on the data points were calculated from $f_{\text{sum}}(z)$ of Eq. (2) and $f_{\text{res}}(z)$ of Eq. (3), respectively, by substituting the typical value of $\lambda_0 = 170$ mm obtained in the fit of A2. To calculate the position resolution $\sigma(z)$, the spectrum of $R$ for the total absorption events was first fit with a single Gaussian to obtain its mean $R(z)$ and the width $\sigma(R)$. If the $z$-dependence (Fig. 8b) of the obtained $R(z)$ and its error bar $\sigma(R)$ was fit with Eq. (5), we obtained $\lambda_0 = 171$ mm, which was close to 170 and 161 mm obtained in the fit of A2 and A1, respectively. Substituting the obtained $\lambda_0$ and $\sigma(R)$ into Eq. (6), we obtained $\sigma(z) \sim 10.0$ mm almost independently of $z$ (Fig. 8c).

3.4. Resolution $\sigma(z)$ in timing difference method

We measured the $T_{1 \text{ (stop)}} - T_{2 \text{ (start)}}$ spectra similarly as in our previous work [1]. While the obtained result was qualitatively similar to Ref. [1], the timing resolution $\sigma(T_{1 \text{ (stop)}} - T_{2 \text{ (start)}})$ was much smaller in the present work as shown in Fig. 9. For GSO:Ce, this improvement should come from the significantly larger LY registered in PMTs due to shorter strip length of 100 mm instead of 200 mm in Ref. [1]. For LGSO:Ce and LuAG:Pr, not only larger LY but also faster rise and decay should improve the timing resolution.

As a typical example, $T_{1 \text{ (stop)}} - T_{2 \text{ (start)}}$ spectra in LGSO:Ce are compared in Fig. 9b for $\gamma$-ray injection at $z = 40$, 0 and +40 mm. We obtained $\sigma(T_{1 \text{ (stop)}} - T_{2 \text{ (start)}})$ of 0.25 ns rms almost independently of $z$ between −40 and +40 mm. The timing resolution between two LSO:Ce crystals was reported to be 0.207 ns rms for the crystal of $3 \times 3 \times 30$ mm$^3$ [30] and 0.191 ns rms for $3 \times 3 \times 20$ mm$^3$ [18]. Compared with these results, the obtained resolution of 0.25 ns rms for the LGSO:Ce strip should be good if the following two differences are taken into account: first, the crystal is much longer, and second, the LY in each PMT was smaller by half due to the readout at both ends of the strip.

The $T_{1 \text{ (stop)}}$ and $T_{2 \text{ (start)}}$ can be written as

$$ T_1 = (5L + z)/c_{\text{eff}} + t_1 $$
$$ T_2 = (5L - z)/c_{\text{eff}} + t_2 $$

where $L = 100$ mm is the strip length, $z$ is the injection position (Fig. 3), and $c_{\text{eff}}$ the effective light velocity along the $z$-axis. The additional delays $t_1$ and $t_2$ depend on the scintillators and PMT. The delay due to the mean transit time of PMT should be approximately canceled out in $T_{1 \text{ (stop)}} - T_{2 \text{ (start)}}$. The transit time spread of PMT is independent of scintillator and $z$, and may be included in the measuring errors of both $T_1$ and $T_2$.

The $c_{\text{eff}}$ terms in Eq. (8) should originally come from the geometry and refractive index of the strip, being independent of the scintillation characteristics of the crystal. On the contrary, the $t_1$ and $t_2$ depend on the scintillation LY as well as the rise and decay times. They should be actually determined by the time elapsed before the occurrence of the first phe in the PMT. The first phe is important because the discriminator thresholds were set slightly below the single phe level. For simplicity we will here ignore $t_1$ and $t_2$ and discuss their effects later in Section 4.3. Neglect of $t_1$ and $t_2$ means that their effects should be effectively
included in c_{eff}, making c_{eff} depend not only on the LY but also on the rise and decay times. Under this approximation, Eq. (8) is reduced to the following simple relation:

\[ z = 0.5c_{eff}(T_1 - T_2). \]  

(9)

From Fig. 9b, we see that the peak position shifts by 1.4 ns as \( z \) changes by 80 mm in the LGSO:Ce strip. Eq. (9) then gives \( c_{eff} = 11.4 \) cm/ns. The position resolution is derived from Eq. (9) as

\[ \sigma(z) = 0.5c_{eff}\sigma(T_1 - T_2). \]  

(10)

Substitution of \( c_{eff} = 11.4 \) cm/ns and \( \sigma(T_1 - T_2) = 0.25 \) ns at \( z = 0 \) obtained already into Eq. (10) gives \( \sigma(z) = 14.3 \) mm at \( z = 0 \) (Table 3).

The quantities \( c_{eff}, \sigma(T_1 - T_2), \) and \( \sigma(z) \) for GSO:Ce and LuAG:Pr strips were obtained in the similar way as for LGSO:Ce, and compared in Table 3: \( \sigma(z) \) was 40 and 19.2 mm in GSO:Ce and LuAG:Pr, respectively. The \( c_{eff} = 6.54 \) for GSO:Ce and 8.54 cm/ns for LuAG:Pr are significantly less than 11.4 cm/ns for LGSO:Ce, as expected from the smaller LY and/or slower rise and decay.

### 4. Discussions

#### 4.1. Effective light attenuation length \( \lambda_a \)

The obtained \( \lambda_a \) of 509 mm for LGSO:Ce was much longer than 128 mm for GSO:Ce and 171 mm for LuAG:Pr (Table 2). We have not expected this since the overlap between the excitation and emission peaks in LGSO:Ce is similarly large as in GSO:Ce (Fig. 2), suggesting possible significant self-absorption. The obtained result may indicate that the internal transparency and/or total reflection on the walls may be much better in LGSO:Ce than GSO:Ce. According to Dr. Ishibashi [31], the internal attenuation length of LGSO:Ce was as large as 300 cm at 420 nm in the best samples. To our measurement the corresponding quantity of GSO:Ce 1.5 mmol% was around 30 cm at 450 nm in a typical crystal of \( 2 \times 2 \times 20 \) cm\(^3\).

Another result to be noted is that the \( \lambda_a \) of 128 mm in the 100 mm long GSO:Ce strip was roughly twice as large as that of 67 mm [1] in the 200 mm long one with the same cross-section of \( 2 \times 2 \) mm\(^2\). Both strips were cut from the same large ingot. The length/width (or thickness) ratio, called the aspect ratio [1], is 50 or 100 in them. If the aspect ratio is much larger than typically 10, direct photons from the \( \gamma \)-ray injection point (\( z = 0 \)) to PMT would give only a small contribution to the PMT pulse height due to small solid angle, making the contribution of the photons which experienced total reflection on the strip walls much more important. Then we can approximate that \( \lambda_a \) should be determined by internal attenuation and incomplete total reflection on the walls, and that the light reflected back from the PMT window as well as from the strip surfaces could be ignored. Under these approximations, \( \lambda_a \) should hardly depend on the strip length, because the light transmission from the \( \gamma \)-ray injection point to the PMT becomes essentially one directional. The \( \lambda_a \) should be locally the same anywhere in the strip. The increase in \( \lambda_a \) for shorter strips may be due to any of the three quantities which are neglected in the above approximation: (1) the light reflected back from the other end of strip, (2) the reflected light from the strip surfaces due to incomplete total reflection, (3) the reflected light from the strip surfaces for the injection angles outside the total reflection.

While we estimated each contribution, we cannot explain the large difference of \( \lambda_a \) between the two strip lengths. We still need to fully understand the mechanism for the significant dependence of \( \lambda_a \) on the strip length at the present stage. To further understand the roles of internal attenuation and the times of total reflection, comparison of two 100 mm long GSO:Ce strips with the same cross-section area but different sizes of \( 2 \times 2 \) mm\(^2\) (the present sample) and \( 1 \times 4 \) mm\(^2\) (another sample cut from the same large ingot) is under way.

#### 4.2. Light yield LY and energy resolution \( \Delta E/E \)

The LY ratios of the three scintillator strips of GSO:Ce:LGSO:Ce:LuAG:Pr were 1:4.63:1.82 from the 0.511 MeV \( \gamma \)-ray peak positions in Fig. 4. To estimate the LY in number of photoelectrons (phe), we measured the single phe peak for both PMTs A1 and A2 at all the HVs (700, 720 and 750 V) in the same setup as in the data taking. Removing the scintillator strip, laser light (410 nm, 33 ps duration) was injected at a constant rate to the PMT through a pinhole prepared in front of the window. A neutral density optical filter was inserted until the single phe peak was identified. Since the single phe peak was most clearly identified at the highest voltage 750 V which was applied for GSO:Ce, we first calculated the LY of GSO:Ce in phe, and then for the other scintillators by using the LY ratios given in the beginning of the present section. The LYs of GSO:Ce, LGSO:Ce, and LuAG:Pr at \( z = 0 \) were 380, 1758 and 691 phe/MeV, respectively (Table 2).

We compared the obtained LY in phe/MeV with expectation. The LY at \( z = 0 \) can be given by a product of the nominal LY of scintillator (LY\(_{0}\)) in phe/MeV and four efficiencies [1]: (1) attenuation of photons through 50 mm transmission along the length due to internal absorption and incomplete total reflection on the walls, (2) geometrical efficiency \( f_{geo} \) for the light transportation from the source (\( z = 0 \)) to the strip end and refraction into PMT window under an assumption that total reflection on the walls should be complete, (3) \( (QE)_{on} = QE \) of PMT averaged for the emission spectrum of scintillator, and (4) \( f_{gate} = \) fraction of LY within the ADC gate width \( f_{gate} = 300 \) ns to the total one. Then we obtain the following relation:

\[ LY(in \ phe/MeV) = (LY_{0})_{exp}\exp(-50 \ mm/\lambda_a)\frac{(QE)_{on}}{f_{geo}}f_{gate}. \]  

(11)

The parameters are listed in Table 4. \( (LY)_{0} \) and \( \lambda_{0} \) were taken from Tables 1 and 2, respectively, \( f_{geo} = 0.19 \) for GSO:Ce based on a Monte Carlo calculation [1]. The corresponding value of 0.196 for LGSO:Ce and 0.158 for LuAG:Pr was calculated in the similar way as for GSO:Ce. \( (QE)_{on} \) was calculated by folding the nominal QE of PMT supplied by its manufacturer with the radioluminescence spectrum (Fig. 1). \( f_{gate} \) should be close to unity for LGSO:Ce, whose decay (\( t = 40 \) ns) is much faster than \( f_{gate} = 300 \) ns. For GSO:Ce 1.5 mmol%, the decay of two components listed in Table 1 gives \( f_{gate} \) of 96%. For LuAG:Pr, the decay process is more complicated. According to our measurement, fast components consist of

### Table 3

Comparison of the effective light velocity \( c_{eff} \) and timing resolution \( \sigma(T_1 - T_2) \) at \( z = 0 \) for different scintillator strips.

<table>
<thead>
<tr>
<th>Scintillator strip</th>
<th>GSO:Ce</th>
<th>LGSO:Ce</th>
<th>LuAG:Pr</th>
<th>GSO:Ce [1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size, mm(^3)</td>
<td>(2 \times 2 \times 100)</td>
<td>(2 \times 2 \times 100)</td>
<td>(2 \times 2 \times 100)</td>
<td>(2 \times 2 \times 200)</td>
</tr>
<tr>
<td>(c_{eff}), cm/ns</td>
<td>6.54</td>
<td>11.4</td>
<td>8.54</td>
<td>3.0</td>
</tr>
<tr>
<td>(\sigma(T_1 - T_2)) at (z = 0), ns</td>
<td>1.28</td>
<td>0.25</td>
<td>0.45</td>
<td>2.12</td>
</tr>
<tr>
<td>(\sigma(2)), mm</td>
<td>42</td>
<td>14.3</td>
<td>19.2</td>
<td>32</td>
</tr>
</tbody>
</table>

### Table 4

Comparison of estimated and measured LY (see text).

<table>
<thead>
<tr>
<th>Crystal</th>
<th>((LY)_{0}), phe/MeV</th>
<th>(\lambda_{0}), mm</th>
<th>(f_{att})</th>
<th>(f_{geo})</th>
<th>((QE)_{on})</th>
<th>(f_{gate})</th>
<th>LY, phe/MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSO:Ce</td>
<td>8000 [1]</td>
<td>128</td>
<td>0.6766</td>
<td>0.190</td>
<td>0.31</td>
<td>0.96</td>
<td>306</td>
</tr>
<tr>
<td>LGSO:Ce</td>
<td>23,000</td>
<td>509</td>
<td>0.9064</td>
<td>0.196</td>
<td>0.34</td>
<td>1</td>
<td>1390</td>
</tr>
<tr>
<td>LuAG:Pr</td>
<td>18,000</td>
<td>171</td>
<td>0.7465</td>
<td>0.158</td>
<td>0.39</td>
<td>0.78</td>
<td>646</td>
</tr>
</tbody>
</table>
\[ \tau_1 = 17 \text{ ns for 35\%}, \tau_2 = 119 \text{ ns for 14\%}, \text{ and } \tau_3 = 1633 \text{ ns for 51\%.} \]

Much slower components, including \( \tau_4 = 9000 \text{ ns} \) [21] and phosphorescence observed with \( \tau_5 = 0.2 \text{ ms} \) are not useful and have to be suppressed electronically for most of applications. We take useful fast component to be about 18,000 phe/MeV for \( \Delta E \) at 1 µs (Table 1) based on our measurement result of three times fluorescence observed with Eq. (6), the improving effect of the increased LY for improvement in shorter strip should indicate that, referring to useful fast component to be about 18,000 phe/MeV for resolution. This is because the large light injected at \( \text{LY} \) 0. It may also be due to the contribution of the light reflected back from the other end of the strip, as mentioned in the previous section. Should this contribution be finite, it would increase \( f_{\text{att}} \) in Eq. (11).

The FWHM energy resolution \( \Delta E/E \) of 0.51 MeV γ-rays injected at \( z = 0 \) was 17.7% in GSO:Ce, 12.2% in LGSO:Ce and 15.0% in LuAG:Pr (see Table 2). If the resolution is due only to the statistical origin, the obtained LY in Table 2 gives FWHM resolution of 16.9% in GSO:Ce, 7.86% in LGSO:Ce and 12.5% in LuAG:Pr. These numbers are a little smaller than the experimental resolutions, suggesting additional instrumental width of 5–9% FWHM.

For GSO:Ce, we can compare the present result for 100 mm long strip (LY = 380 phe/MeV and \( \Delta E/E = 17.7\% \)) with that for 200 mm long one (114 phe/MeV and 35%) [1]. The improvement of \( \Delta E/E \) by 17.7%/35% = 0.51 times is almost consistent with the (LY ratio) \( 1/2 \). This is because the large \( \lambda_p \) of 509 mm reduced the difference of \( \Delta E/E \) from unity, thereby reducing its sensitivity to \( z \).

The \( \sigma(z) \) of GSO:Ce was improved from 10 mm in the 2 × 2 × 200 mm3 strip to 8.9 mm in the 2 × 2 × 100 mm3 one. This improvement in shorter strip should indicate that, referring to Eq. (6), the improving effect of the increased LY for \( \sigma(R) \) outweighed the degrading effect of longer \( \lambda_p \).

Second, \( \sigma(z) \) obtained from T1 – T2 according to Eq. (10) is compared in Table 2 with that from A2/A1. We see that \( \sigma(z) \) from T1 – T2 is poorer than that from A2/A1 except in LGSO:Ce. Eq. (10) shows that \( \sigma(z) \) is given by half of the \( c_{\text{eff}} \) times \( \sigma(T1 – T2) \). We will below examine these two equations:

1. Geometrical effects on \( c_{\text{eff}} \). Since the local light velocity is equal to \( c/n \) with \( c \) the light velocity in vacuum and \( n \) the refractive index of scintillator, the \( c_{\text{eff}} \) in Eq. (8) can be approximately given by dividing it by the ratio \( k \) of the average light path length along zigzag motion to its projection on the z-axis.

In the LGSO strip, the total reflection angle is 33.12° on the surface for \( n = 1.83 \) (Table 1). For a rough estimation of \( k \), we make the following simplifications; the strip cross-section is circular, the light is emitted uniformly from a point on the z-axis at a distance \( \zeta \) to PMT, and reaches the PMT window directly or after complete total reflection on the strip surface.

Taking a phase space average within the cone of an opening angle of twice 56.88° (= 90° – 33.12°), we obtain the average light path length of 1.332 \( \zeta \) instead of \( \zeta \). Then we obtain \( k \approx 1.332 \) and \( c_{\text{eff}} = c/\langle nk \rangle = 0.41 \approx 12.3 \text{ cm/ns} \), which is not far from the experimental value of 11.4 cm/ns.

The situation is different for both GSO:Ce and LuAG:Pr. Similar estimation for GSO:Ce (\( n = 1.85 \)) gives \( k \approx 1.339 \) and \( c_{\text{eff}} = 0.40c = 12.0 \text{ cm/ns} \), which is significantly larger than the experimental value of 6.54 cm/ns. Estimation for LuAG:Pr (\( n = 1.99 \)) gives \( k \approx 1.383 \) and \( c_{\text{eff}} = 0.36c = 10.9 \text{ cm/ns} \), which is still sizably larger than the experimental value of 8.54 cm/ns.

Smallness of the observed \( c_{\text{eff}} \) for GSO:Ce and LuAG:Pr may be attributed to the effects of the delays \( r1 \) and \( r2 \) in Eq. (8). Neglect of \( r1 \) and \( r2 \) in Eq. (9) must have resulted in reduction of \( c_{\text{eff}} \) when the LY is not large enough and/or the rise and decay time is not fast enough. This conjecture will be examined qualitatively in the following paragraphs.

2. Effects of the delays \( r1 \) and \( r2 \) on T1 – T2 and \( c_{\text{eff}} \). As mentioned in Section 3.4, the \( r1 \) and \( r2 \) should represent the time elapsed before the occurrence of the first peak and in the PMT. While they should occur within the rise time in many scintillators, no photoelectrons may be produced within the rise time if the scintillation LY and/or rise time should be too small. In such a case, the delays should occur in the decay time of the scintillation pulse. The delays should be small if the LY is sufficiently large and the rise time is small as in LGSO:Ce. Otherwise, the delays should become substantial as in GSO:Ce.

When the LY is not large enough and/or the rise and decay times are not fast enough, T1 – T2 can be overestimated, then \( c_{\text{eff}} \) from Eq. (9) underestimated, and finally \( \sigma(z) \) from Eq. (10) underestimated. To obtain an intuitive picture for the effects of LY and rise time on \( c_{\text{eff}} \), we compare two injection points, one at the center \( z = 0 \), and the other close to \( A2 \) \( z = 40 \text{ mm} \).

For the injection at \( z = 0 \), \( r1 \) and \( r2 \), which give event by event fluctuations of T1 and T2, respectively, should be of the same level, keeping the mean of T1–T2 distribution unchanged. For the injection point at \( z = 40 \text{ mm} \), the A2 pulse height should be increased while the A1 decreased. If the LY is small and the rise time is large, \( r2 \) should be decreased compared with \( z = 0 \) advancing T2 (start), while \( r1 \) should be increased delaying T1 (stop). As the result, T1 – T2 should be increased more than the geometrical contribution given by the \( c_{\text{eff}} \) terms of the right-hand side of Eq. (8). Then, \( c_{\text{eff}} \) should be underestimated according to Eq. (9).

Since the light intensity registered in the PMT depends on \( z \) through light attenuation, \( r1(r2) \) should also depend on \( z \). Smaller LY and larger rise time tend to increase both \( r1 \) and \( r2 \), thereby increasing T1 – T2 and \( \sigma(T1 – T2) \), and then decreasing \( c_{\text{eff}} \). If we write the increase factor of T1 – T2 by \( \eta, c_{\text{eff}} \) is reduced by \( \eta^{-1} \) according to Eq. (9). Since \( \sigma(T1 – T2) \) should be increased by a factor \( \eta^{1/2} \), that comes from the fluctuation of \( \eta, \sigma(z) \) of Eq. (10) should be finally decreased by \( \eta^{-1/2} \).

As an example, we compare 100 and 200 mm long GSO:Ce strips. Since the LY of the latter is as small as 30% of the former (Table 2), T1 – T2 in the latter should be increased by a factor \( \eta = 6.54/3.0 = 2.18 \) (Table 3), which is given by the inverse ratio of \( c_{\text{eff}} \) for the two strips. Then \( \sigma(z) \) should be finally decreased by \( \eta^{-1/2} = 0.68 \text{ times in the 200 mm long strip in rough agreement with the experimental result of 32 mm/42 mm = 0.76 times} \) (Table 3).

4.4. Application of single crystalline scintillator strips or fibers

Among the three crystals evaluated, LGSO:Ce gave the largest LY, the best \( \Delta E/E \), the longest \( \lambda_p \) and the poorest \( \sigma(z) \). GSO:Ce gave the smallest LY, the poorest \( \Delta E/E \), the shortest \( \lambda_p \) and the best \( \sigma(z) \), while LuAG:Pr was in between. The cost of raw materials may be the lowest for GSO:Ce.

For the applications in particle physics experiments, choice of optimum crystals should depend on the requirements of specific particle detectors, since the characteristics of scintillator strips depend not only on the material but also on the length, cross-section and surface texture. The length should be one of the most
important factors which determine the obtainable $\Delta E/E$ and $\sigma(z)$, while the cross-section should limit the lateral position resolution. Choice of scintillators may be various since the scintillator size is of wide variety depending on the detectors.

For the applications to axial PET scanners, however, the scintillator size should not have large variety; the cross-section should limit the lateral position resolution properties to each other (see Table 1). Promising properties of strip will be within 1–10 mm², and the length within 10–30 cm. Both energy and position resolutions should be the most important. Then optimum scintillators could be chosen once the geometries of the PET scanners are defined. To compete with conventional human PET scanners using BGO, $\Delta E/E$ as small as 25% and $\sigma(z)$ as small as or smaller than 10 mm should be considered [1]. All the strips of GSO:Ce, LGSO:Ce and LuAG:Pr studied in the present work satisfy the requirements mentioned above, and appear promising (Table 2).

If the longitudinal position $z$ of injected $\gamma$-rays should be measured only from the pulse height ratio at both ends so as to simplify the electronics, only LGSO:Ce fails to satisfy the requirement of $\sigma(z) < 10$ mm, while the $\Delta E/E$ is by far better than 25% (see Table 2). Since the poor $\sigma(z)$ is due to too long $\lambda_p$, $\sigma(z)$ may be improved by reducing $\lambda_p$ at a cost of degrading the LY and $\Delta E/E$. For example, we may reduce $\lambda_p$ by half to 255 mm by appropriate surface treatment or reflector wrapping [6]. Then the LY for the $\gamma$-ray injection at $z=0$ should decrease to 1584 phe/MeV by a factor of $k=\exp(-50/509)=0.906$, and $\Delta E/E$ increase to 12.8% FWHM by $k^{-0.5}=1.05$. Then, $\sigma(R)$, which should be approximately proportional to $\Delta E/E$, is increased again by a factor of 1.05. As the result, $\sigma(z)$ of Eq. (6) would be improved from 16.8 to 8.82 mm.

If we consider $2 \times 2 \times 200 mm^3$ strips for the PET scanners with the axial length of 200 mm, GSO:Ce was found to be marginal due to $\Delta E/E$ as large as 35% [1]. For LGSO:Ce and LuAG:Pr, we assume that $\lambda_p$ should decrease to half of the $2 \times 2 \times 100$ mm strips similarly as in GSO:Ce. Then the LY for $\gamma$-rays injected at the center $z=0$ can be estimated in the similar way as above. As the result, we can predict $\Delta E/E=14.1\%$ and $\sigma(z)=9.7$ mm for LGSO:Ce, and $\Delta E/E=23.2\%$ and $\sigma(z)=7.7$ mm for LuAG:Pr. This indicates that both LGSO:Ce and LuAG:Pr should be promising candidates.

LYSO:Ce and LGSO:Ce have similar physical as well as scintillation properties to each other (see Table 1). Promising properties were reported for LYSO:Ce strips with 3.2 × 100 mm² [6]; for 0.511 MeV $\gamma$-rays injected to the centre $z=0$, the $\lambda_p$ was 420 mm, the LY 1173 phe/MeV, $\Delta E/E$ 14.6% FWHM, and $\sigma(z)$ 14.4 mm. The present result on LGSO:Ce with $2 \times 2 \times 100$ mm³ gave similar, or even better result; $\lambda_p$ was 500 mm, LY 1758 phe/MeV, $\Delta E/E$ 12.2% FWHM and $\sigma(z)$ 10.9 mm (Table 2).

Axial PET scanners have not yet been realized. One of the reasons may be the difficulty in producing high-quality single crystalline scintillator fibers at a reasonable cost in spite of many progresses achieved [2]. Further progress is waited for producing fibers having as high quality as bulk single crystals with a cross-section of a few mm square and a length as large as 100-300 mm.

5. Conclusion

The obtained result can be summarized as follows:

(1) We compared $2 \times 2 \times 100$ mm³ strips of GSO:Ce 1.5 mol%, LGSO:Ce 0.15 mol% and LuAG:Pr 2.5 mol% for 0.511 MeV $\gamma$-rays. The $z$ dependences of LY at each end can be fit well by a single exponential $\exp(-z/\lambda_p)$ with $\lambda_p=128$, 500 and 171 mm for GSO:Ce, LGSO:Ce and LuAG:Pr, respectively.

(2) Sum of the pulse height at both ends for the $\gamma$-ray injection at $z=0$ gave (LY, $\Delta E/E$ in FWHM)=(380 phe/MeV, 17.7%), (1758 phe/MeV, 12.2%), and (691 phe/MeV, 15.0%) in GSO:Ce, LGSO:Ce and LuAG:Pr, respectively.

(3) $\sigma(z)$ of the injection position $z$ obtained from the pulse height ratio at both ends was 8.9, 16.8, and 10.0 mm rms in GSO:Ce, LGSO:Ce and LuAG:Pr, respectively. While $z$ was also measured from the timing difference at both ends, comparable or even smaller $\sigma(z)$ (14.3 mm) was obtained only in LGSO:Ce, which has large LY and fast rise time.

(4) To obtain good $\Delta E/E$ and $\sigma(z)$ at the same time, large LY, fast rise time, and moderately large $\lambda_p$ are important for scintillator strips. All the tested crystals appear promising depending on their applications in fine-segmented particle detectors as well as axial PET scanners.

(5) The $\lambda_p$ in the 100 mm long GSO:Ce strip was twice as large as that in the 200 mm long one with the same cross-section.

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References