Comparison between YAP : Ce and CsI(Tl) multipillar matrices

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Abstract

The characteristics of segmented CsI(Tl) and YAP : Ce scintillators coupled to a position-sensitive photomultiplier tube (PSPMT Hamamatsu R2486) have been measured and compared to evaluate the potential use of such scintillators as precise X- and γ-ray imagers. For such configurations, we obtained good spatial resolution and linearity over their entire 40 × 40 mm² Fields of View (FOVs). The scintillating matrices consist of orthogonal arrays of crystal pillars with 0.6 × 0.6 mm² cross sections and thicknesses of 3 and 10 mm. The 3 mm thick CsI(Tl) matrix shows a light yield of 44% compared to NaI(Tl), an energy resolution of 22% FWHM at 122 keV, a single pillar spatial response of 0.5 mm FWHM, and a spatial resolution of 0.83 mm. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: YAP : Ce; CsI(Tl); Multipillar structure; Position-sensitive photomultipliers; Segmented crystal scintillators; Gamma-ray imager

1. Introduction

Previous studies have shown that position-sensitive photomultiplier tubes (PSPMTs) coupled to segmented crystal scintillators are particularly suitable for γ-ray imaging applications in which a good spatial resolution and a reasonable energy resolution are required. Particular attention has been paid to accurate X- and γ-ray imagers for nuclear medicine [1–3] and astrophysics applications [4,5]. In the past few years, YAP : Ce and CsI(Tl) have been the scintillating crystals investigated most frequently when arranged in multipillar configurations [6,7] because they have good mechanical and scintillating properties. Moreover, recent works demonstrated that small, optically isolated segmented crystals show significant advantages with respect to continuous crystals, especially when submillimeter spatial resolution and good spatial linearity over the entire FOV are required [4,8].

In this paper, results obtained using two CsI(Tl) matrices and a YAP : Ce one, when illuminated by 122 keV γ-rays, are reported, discussed and compared. Our results demonstrate that 0.6 × 0.6 × 3 mm³ CsI(Tl) pillars show a good light yield and...
an energy resolution acceptable for nuclear medicine purposes.

2. Equipment and method

The miniature γ-ray imagers investigated in this work consist of a multipillar gamma detector (an array of scintillating crystal pillars) optically coupled to a Position Sensitive PMT Hamamatsu R2486. This is a specially selected PMT [9] having uniform sensitivity (the response uniformity is about 12.6% defined as the standard deviation from the mean value). It has a bialkali photocathode, a useful 50 mm diameter area, 11 multiplication dynodes, 1 reflective dynode, and a multiwire anode with 16 wires for each axis. Each multiplication dynode consists of an hexagonal focusing mesh and parallel bars 0.7 mm apart. Two supporting bars 20 mm from each other, support the whole dynode structure.

The multipillar matrices that were studied have a 40 × 40 mm² detection area and consist of scintillating crystal pillars optically isolated from each other by an adequate reflective or diffusive layer. Two different types of scintillating crystals were compared: YAP : Ce supplied by Preciosa Crytur (Czech Republic) and CsI(Tl) from Hilger Analytical (Great Britain).

The YAP : Ce multipillar matrix consists of about 67 × 67 orthogonally arranged pillars whose dimensions are 0.6 × 0.6 × 10 mm³. Each pillar is covered by a 5 μm thick reflective diffusive layer with a total dead zone of 10 μm and a light transmission of less than 5% [7]. The characteristics of YAP : Ce are well described in other works [10,11], but they can be summarized as follows. It has a light yield of about 50–60% compared to NaI(Tl) [12], an average Z of 39, a density of 5.37 g/cm³, an average scintillation decay time of 25 to 30 ns, and an emission peak at about 370 nm with an attenuation length of 14.7 ± 0.3 cm [13]. Moreover, it is not hygroscopic, has high hardness (8.6 Mho), and lacks a cleavage plane. These properties allow YAP : Ce crystals to be machined down to a thickness of about 0.1 mm.

We have further investigated two CsI(Tl) multipillar matrices with thickness of 3 and 10 mm, respectively. They consist of 44 × 44 orthogonally arranged pillars whose cross sections are 0.6 × 0.6 mm². Each pillar is covered by a diffusive white layer (epoxy) with a total dead zone between two adjacent elements of about 230 μm. CsI(Tl) characteristics are well known. It has a density of 4.51 g/cm³, a refractive index of 1.78, an output light yield of 45–50% relative to NaI(Tl) (typical PMT response with bialkali photocathode), an emission peak at about 550 nm, and a scintillation decay time of about 900 ns. Its main mechanical properties are a slight hygroscopicity, a low hardness, and a lack of cleavage plane. Because of its ductility, it is rather simple to arrange matrices with a small pixel size (0.5 × 0.5 mm²) and a relatively thin interpixel diffusive layer (150–300 μm).

The gamma camera acquisition system has 32 independent electronic chains (consisting of a preamplifier and an amplifier) to read out the PSPMT’s 32 anode wires. For each interaction event the outputs are multiplexed, digitized by two 10-bit amplitude ADCs, and then sent to a FIFO. From the FIFO, data are transmitted to a PC486 through a dedicated parallel interface with a transfer rate of about 100 kbytes/s. Finally, data are processed off line by dedicated software in Fortran 90 at a rate of about 200 kbytes/s. After data storage, the total energy spectrum is evaluated by summing up the charge collected for each event by the 32 anode wires. An energy window is set to select the events belonging to the spectrum Full Energy Peak (FEP). If the energy value of a detected gamma photon falls in the window, the interaction position of that event is calculated as the centroid of the charge distribution sampled from the anode wires.

Spatial linearity and resolution tests were performed with Tc⁹⁹m (140 keV) and ⁵⁷Co (122 keV) collimated sources. Their positioning was obtained through means of a precise servo assisted mechanical system driven by step motors and monitored by encoders along the two orthogonal axes parallel to the detection area. The mechanical system was driven by dedicated hardware and software allowing an accurate scanning of the matrix with a positioning accuracy of about 2–3 μm. Particular care was taken in aligning the collimators with the pillar axis in order to avoid unwanted irradiation of the neighboring crystal pillars.
The detector responses relative to the whole active area were analyzed by irradiating the multipil- lar matrices (both YAP : Ce and CsI(Tl)) with a $^{57}$Co point-like source in flood-field condition.

As Fig. 1 shows, energy resolution and light yield measurements were accomplished by arranging an appropriate setup. The crystal matrices were coupled to a traditional phototube (Philips X2020Q) and the output signals were integrated with a charge ADC (LeCroy 2249W). The integration time was set with gate pulses of 200 ns and 4 $\mu$s width for YAP : Ce and CsI(Tl), respectively. Finally, the matrices were irradiated by means of a $^{57}$Co collimated source (1 mm collimating diameter).

3. Results and discussion

3.1. Light yield

By the means of a conventional PMT, we measured the light yield values, relative to NaI(Tl), of a 10 mm thick YAP : Ce matrix and of two CsI(Tl) matrices of 3 and 10 mm thickness, respectively. The pillars were irradiated by a $^{57}$Co source. The results, illustrated in Table 1, are listed in the following. The YAP : Ce pillar light yield value is 11% and the light yield values of the 10 and 3 mm thick CsI(Tl) pillars are 14 and 44%, respectively. To date, these are the first light yield measurements of pixellated CsI(Tl) matrices coupled to photomultiplier tubes.

The YAP : Ce crystal matrix analyzed in this work has a greater light yield than the old YAP : Ce matrices. Indeed, the 11% light yield value obtained with the new 10 mm thick matrix is higher than the 9% value achieved with an old YAP : Ce matrix with pillars of the same size and only 7 mm length [1]. This result is in agreement with an intrinsic crystal light yield improvement from 40% to 50–60% announced by the crystal supplier due to the care taken during the crystal growth process [12]. Owing to this improvement, the light yield values of the YAP : Ce and the CsI(Tl) matrices relative to the same pillar thickness of 10 mm are quite similar, even though they are lower than the intrinsic crystals values.

It is worth noting that the 3 mm thick CsI(Tl) matrix has a 44% light yield, a value close to the 45–50% intrinsic value of the CsI(Tl) crystal.

3.2. Energy resolution

The YAP : Ce and CsI (Tl) matrices energy resolutions were measured with both a PMT and a PSPMT by using a 1 mm collimated source. The results are reported in Table 1.

The measurements were performed by irradiating the center of the detection area of the PSPMT in order to avoid the distortion introduced by the dynodes' bars [14].

As Fig. 2 shows, the energy resolution values of 10 mm thick YAP : Ce and CsI(Tl) matrices, coupled to the PSPMT and irradiated by a Tc$^{99m}$ collimated source, are 43% FWHM and 40% FWHM, respectively. As with the light yield measurements, the two matrices have similar energy resolution values.

The energy resolution relative to the 3 mm thick CsI(Tl) matrix improves up to 32% FWHM due
Table 1
Comparison between YAP:Ce and CsI(Tl) multicrystal matrices measurements

<table>
<thead>
<tr>
<th></th>
<th>YAP:Ce</th>
<th>CsI (Tl) 0.6 x 0.6 x 10 mm³</th>
<th>CsI (Tl) 0.6 x 0.6 x 3 mm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light yield (relative to NaI(Tl) (%))</td>
<td>11</td>
<td>14</td>
<td>44</td>
</tr>
<tr>
<td>Energy resolution (% FWHM)</td>
<td>PSPMT 43 (Tc⁹⁹m)</td>
<td>40 (Tc⁹⁹m)</td>
<td>32 (⁵⁷Co)</td>
</tr>
<tr>
<td></td>
<td>PMT 30 (⁵⁷Co)</td>
<td>—</td>
<td>22 (⁵⁷Co)</td>
</tr>
<tr>
<td>Spatial resolution (mm FWHM)</td>
<td>ϕ = 1 mm</td>
<td>1.42 [15]</td>
<td>1.5⁵</td>
</tr>
<tr>
<td></td>
<td>Intrinsic²</td>
<td>0.6-0.8 [15]</td>
<td>1.1-1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.4-0.6</td>
<td></td>
</tr>
<tr>
<td>DRF width (mm FWHM)</td>
<td>9.70</td>
<td>10.95</td>
<td>11.20</td>
</tr>
</tbody>
</table>

²Measured along the x-axis (see text).

³Not measurable as the peak FWHM relative to the spatial response of the detector when irradiated by a 1 mm diameter photon beam.

⁴Single pillar spatial response.

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Fig. 2. CsI(Tl) and YAP:Ce energy spectra comparison. The 10 mm thick multipillar matrices are irradiated by a Tc⁹⁹m collimated source whose diameter is 1 mm. Energy resolution: 43% FWHM for YAP:Ce and 40% FWHM for CsI(Tl).

The energy resolution of the latter matrix, in the above mentioned experimental conditions when coupled to the PMT, improves up to 22% FWHM. The great difference in the energy resolution values measured when the 3 mm thick CsI(Tl) matrix is coupled to the PSPMT (32% FWHM) and to the PMT (22% FWHM) is due mainly to the different signal processing we performed. Whereas for the PMT we used a single electronic chain to process the anode charge signal, for the PSPMT we collected the charge using 32 anode wires and the signals processed by 32 independent electronic chains. Although each of the chains has a threshold, they introduce a higher noise, and by doing so affect the energy resolution; nevertheless its basic and fundamental usefulness is in allowing the calculation of the photon interaction position.

It is worth noting that the above-mentioned energy resolution difference is also evident when comparing the values obtained by irradiating the 10 mm thick YAP:Ce matrix coupled to the PSPMT (43% FWHM) and to the PMT (30% FWHM).

3.3. Detector response homogeneity

A 1 mm step scanning was performed by irradiating the 10 mm thick CsI(Tl) matrix with a collimated ⁵⁷Co source having a 1 mm collimating diameter in order to analyze the energy response fluctuations of the detector. The result is shown in Fig. 3, where the CsI(Tl) energy response is compared to the YAP:Ce energy response measured in a previous work [15].

The CsI(Tl) energy response is similar to that obtained with the YAP:Ce showing higher values at the matrix boundaries and lower ones near the two zones corresponding to the dynodes’ bars.

As shown in Fig. 4, due to these fluctuations, the energy resolution relative to the entire 3 mm thick CsI(Tl) matrix, irradiated with a ⁵⁷Co point-like source in flood field condition, is rather large: 49% FWHM. However, as illustrated in a previous work [14], this result can be improved by means of a correction procedure capable of bringing the
Fig. 3. Full energy peak channel vs. irradiating position of CsI(Tl) and YAP:Ce [15] multipillar matrices. 1 mm step scanning performed with a $^{57}$Co 1 mm collimated source.

Fig. 4. CsI(Tl) energy spectrum obtained by irradiating the 40 mm $\times$ 40 mm $\times$ 3 mm CsI(Tl) matrix with a $^{57}$Co point-like source in flood field condition. Comparison between the uncorrected spectrum (energy resolution: 49% FWHM) and the corrected one (energy resolution: 30% FWHM).

The 30% FWHM energy resolution achieved with the pixellated CsI(Tl) crystal is quite a good result compared to the 25% FWHM value obtained over the full area of a planar CsI(Tl) crystal, 4 mm thick, measured with a Hamamatsu R2487 PSPMT [5]. To date, there are no other energy resolution measurements of pixellated CsI(Tl) matrices coupled to PSPMTs.

Fig. 5 displays the spatial homogeneity response comparison between the 10 mm thick YAP:Ce matrix and the 3 mm CsI(Tl) one when irradiated by a $^{57}$Co point-like source in flood field condition. The image distortion introduced by the dynodes’
bars is evident in both images. Moreover, the
strong discretization effect in the CsI(Tl) image is
evident, in that we can clearly distinguish the spa-
tial response of the single pillars.

3.4. Spatial resolution

The evident pillars discretization visible in the
CsI(Tl) image of Fig. 5 is due to the high intrinsic
spatial resolution shown by the 3 mm thick CsI(Tl)
pillars in this experimental condition. In other
words, the spatial response of single 3 mm thick
CsI(Tl) pillars is narrower than the inter-axis dis-
tance between two adjacent pillars. As it is in this
case, the spatial resolution definition implicitly
used up to now (the FWHM of the image peak
when a detector is irradiated with a gamma col-
limated spot), no longer has meaning. Then, it is
useful to consider the pitch of the matrix as resolu-
tion indicator. Using this latter point of view, the
3 mm thick CsI(Tl) matrix used in this study has
a spatial resolution of 0.83 mm.

We measured the 10 mm thick CsI(Tl) matrix
spatial resolution values by irradiating the matrix
with a 1 mm step scanning (i.e. along the Y-axis)
using a collimated $^{57}$Co source with a 1 mm col-
limating diameter. The CsI(Tl) spatial resolution
values are presented in Fig. 6, whereas the mean
values are reported in Table 1. In Fig. 6 and in
Table 1, for comparison, we also added the 10 mm
thick YAP : Ce spatial resolution measurements,
already reported in an another work [15].

The 10 mm thick CsI(Tl) matrix has
a (1.5 $\pm$ 0.2) mm FWHM (Fig. 6a) and a (1.6 $\pm$ 0.3)
mm FWHM (Fig. 6b) mean spatial resolution in the
X-axis (orthogonal to the scanning direction)
and Y-axis (parallel to the scanning direction), re-
spectively. The last result is clearly affected by the
presence of the dynodes' bars that worsen the spa-
tial resolution along the direction parallel to the
scanning as already reported and explained, for the
YAP : Ce matrix, in a previous work [15].

In order to measure the intrinsic spatial resolu-
tion, or more precisely the “single pillar spatial
response”, of the 3 and 10 mm thick CsI(Tl) pillars,
the CsI(Tl) matrices were irradiated using a col-
limated $^{57}$Co source with a 0.2 mm collimating
diameter. The intrinsic spatial resolution results,
reported in Table 1, can be summarized as follows.
The 10 mm thick CsI(Tl) matrix gives values
ranging from 1.1 to 1.2 mm FWHM and the 3 mm
thick CsI(Tl) matrix values range from 0.4 to
0.6 mm FWHM.

Furthermore, in order to evaluate the anode
charge spatial distribution we measured the De-
tector Response Function (DRF) of both YAP : Ce
and CsI(Tl) matrices coupled to the PSPMT. The
results are reported in Table 1.

Comparing the single pillar spatial responses
of the two matrices with 10 mm thickness, the higher
CsI(Tl) value with respect to the YAP : Ce one can
be partially explained by taking into account the
DRF width results. The DRF width values
achieved for the 10 mm thick YAP : Ce and CsI(Tl)
matrix are 9.70 and 10.95 mm FWHM, respectively, when a 1 mm collimated source is used. In contrast, when considering the 3 mm thick CsI(Tl) matrix, although the DRF width value is greater than the previous ones (11.20 mm FWHM), the single pillar spatial response is very good (0.4–0.6 mm FWHM) due to a much higher light yield and a more precise photon interaction position determination as expected from the statistical theory.

The (0.5 ± 0.1) mm FWHM single pillar spatial response is the best value achieved with pixelated crystals coupled to PSPMTs. Similar measurements were carried out by Truman et al. [6] using a pixelated CsI(Tl) matrix coupled to a PSPMT Hamamatsu R2487. They achieved a 0.9 mm FWHM single pillar spatial response by using the CsI(Tl) matrix composed by pillars of 1.2 mm in size and 0.25 mm crystal separation. The best result achieved with a YAP : Ce matrix, in the same experimental conditions, is (0.7 ± 0.1) mm FWHM [15].

3.5. Spatial linearity

Fig. 7 shows the spatial linearity response obtained by irradiating the 10 mm thick CsI(Tl) matrix with a 1 mm step scanning using a collimated $^{57}$Co source with 1 mm collimating diameter. Along the scanned direction, the detector shows a good position linearity response, similar to that obtained when irradiating the YAP : Ce matrix in the same experimental conditions [15]. The two curves are compared in Fig. 8, where the displacements from the theoretical linearity curve are drawn in order to evaluate the standard deviation which is 0.52 mm for the YAP : Ce curve and 0.64 mm for the CsI(Tl) one.

Obviously, the greater value of CsI(Tl) linearity standard deviation, due to the larger fluctuations, is justified by the thicker septum between two pillars and therefore a greater matrix pitch, that is the distance between two pillar axes.

In order to study the spatial linearity response of the single pillars so as to analyze the spatial resolution behavior, a more accurate scanning with a 0.25 mm step and a 0.3 mm diameter collimator was carried out on the 3 mm thick CsI(Tl) matrix. Fig. 9 displays the fine linearity response as well as the related spatial resolution values obtained in the above mentioned experimental conditions.

As already found when analyzing the 10 mm thick YAP : Ce pillars covered by a diffractive reflective multilayer [15], the 3 mm thick CsI(Tl) pillars with diffusive surfaces show a nonlinear spatial response. As a consequence, similar to the YAP : Ce matrix, the multipillar CsI(Tl) matrix behaves as a discrete sampling device.

3.6. Detection efficiency

In order to extend the comparison between the YAP : Ce and the CsI(Tl) multipillar matrix, the
Full-Energy Peak (FEP) efficiency at 140 keV and the contribution given by the reabsorption of Compton-scattered photons were calculated by means of a Monte Carlo simulation. The results are reported in Table 2. The YAP : Ce matrix FEP efficiency is 67% whereas for the CsI(Tl) matrix with the same thickness is 96%, due to the CsI(Tl) higher atomic number and consequently, a shorter attenuation length. By reducing the CsI(Tl) matrix thickness down to 3 mm, a 63% FEP efficiency value is obtained, and this result is comparable to the 10 mm thick YAP : Ce matrix value (67%).

The FEP efficiency of a single pillar takes into account only primary gamma photons that undergo photoelectric absorption or single (or multiple) Compton scattering followed by photoelectric absorption of the scattered photon inside the same pillar (let’s call it “central pillar”). For multipillar crystals, the two above mentioned events are indistinguishable in terms of both energy deposit and interaction position. It is important to consider a different interaction process that takes place when a primary gamma photon undergoes single (or multiple) Compton scattering followed by photoelectric absorption inside a pillar different from the “central pillar”. Such an event gives a false position indication of the primary gamma interaction even though it belongs to the detector energy spectrum FEP. Since nuclear medicine is based on the selection of the events belonging to the detector FEP, the latter represents an almost irreducible background for the image. The total amount of such a background can be evaluated by means of a Monte Carlo calculation. So, we can say that about 33% of the matrix FEP events (the ones selected in the image formation process) do not refer to the real radioactivity distribution when the 10 mm thick YAP : Ce matrix is used. A similar calculation made for the 10 mm thick CsI(Tl) matrix and the 3 mm thick CsI(Tl) one yields 8 and 9%, respectively. This means that CsI(Tl) matrices have a greater percentage of “true events”, that is, the position calculated as the anode charge center-of-gravity corresponds to the source position (disregarding the discrete effect) and, therefore, CsI(Tl)

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Table 2
Monte Carlo calculation of YAP : Ce and CsI(Tl) multicrystal matrices detection efficiencies

<table>
<thead>
<tr>
<th></th>
<th>YAP : Ce</th>
<th>CsI(Tl)</th>
<th>CsI(Tl)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.6 × 0.6 × 10 mm³</td>
<td>0.6 × 0.6 × 10 mm³</td>
<td>0.6 × 0.6 × 3 mm³</td>
</tr>
<tr>
<td>FEP efficiency (%)</td>
<td>One pillar</td>
<td>45</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td>Matrix (40 × 40 mm²)</td>
<td>67</td>
<td>96</td>
</tr>
<tr>
<td>Reabsorption of Compton scattered photons (%) ⁴</td>
<td>33</td>
<td>9</td>
<td>8</td>
</tr>
</tbody>
</table>

⁴Percentage (relative to the FEP photons) of the Compton photons reabsorbed inside the 40 × 40 mm² matrix, but outside the pillar where the first interaction occurred.
matrices show a better image signal-to-noise ratio than YAP:Ce ones. These results give another explanation for the strong image discretization observed with the thinner CsI(Tl) matrix. Indeed, both the high light yield and the low Compton photon reabsorption lead to events being preferentially reconstructed towards the center of each pillar in the matrix, with the consequence that the image takes on a very pixellated appearance.

4. Conclusions

We have presented encouraging results on a small area γ-ray imager suitable for nuclear medicine purposes (e.g. new radiopharmaceuticals’ research) as well as for astrophysics applications. We have shown that a 40 × 40 mm² area CsI(Tl) matrix made up of 0.6 × 0.6 × 3 mm³ pillars has a light yield of 44%, which is very close to the crystal intrinsic value, a FEP efficiency of 63%, a single pillar spatial response of (0.5 ± 0.1) mm FWHM, and an energy resolution over the entire FOV of 30% FWHM at 122 keV. Moreover, we have measured a 43% FWHM energy resolution at 140 keV with a 10 mm thick YAP:Ce matrix consisting of 0.6 × 0.6 mm² size pillars.

For multipillar crystals showing a single pillar spatial response narrower than the matrix pitch, standard resolution computations do not adequately communicate the resolution of such matrices. In such conditions, it is useful to consider the pitch of the matrix as a resolution indicator. Using this latter point of view, the 3 mm thick CsI(Tl) matrix used in this study has a spatial resolution of 0.83 mm. Because this matrix employs 230 μm thick diffusive optical isolation among the pillars, it is expected that matrices with better resolution can be developed as it is expected that matrices with thinner diffusive optical isolation can be fabricated. The resolution of such newly fabricated matrices would be finer as the pitch of such matrices would be finer.

On the other hand, the 10 mm thick YAP:Ce matrix has a 10 μm thick reflective optical coating among the pillars that leads the matrix pitch to 0.61 mm. Moreover, this matrix shows a single pillar spatial response (0.7 mm FWHM [15]) larger than the matrix pitch due to its relatively low light output (11% against 44% of the 3 mm thick CsI(Tl) matrix). This is the main reason why the 10 mm thick YAP:Ce matrix shows no image discretization effect. On the contrary, the 3 mm thick CsI(Tl) matrix produces a visibly pixellated image because its single pillar spatial response is narrower than the matrix pitch.

References

