In-Silico Optimisation of Tileable SiPM Based Monolithic Scintillator Detectors for SPECT Applications

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Abstract—Over the last decade one of the most significant technological advances made in the field of radiation detectors for nuclear medicine was the development of Silicon Photomultiplier (SiPM) sensors. At present a only small number of SiPM based radiation detectors for Single Photon Emission Computed Tomography (SPECT) applications has been explored, and even fewer experimental prototypes developed. An in-silico investigation into the optimal design of a Philips DPC3200 SiPM photosensor based monolithic scintillator detector for SPECT applications was undertaken using the Monte Carlo radiation transport modelling toolkit Geant4 version 10.5. The performance of the 20 different SPECT radiation detector configurations, 4 scintillator materials (NaI(Tl), GAGG(Ce), CsI(Tl) and LYSO(Ce)) and 5 thicknesses (1 to 5 mm), were determined through the use of six different figures of merit. For SPECT/X-ray CT applications it was determined that GAGG(Ce) was an optimal scintillator material, with crystal thicknesses of 3 mm and 5 mm being ideal for SPECT/X-ray CT systems with pinhole and parallel hole coded apertures respectively. Conversely for SPECT/MR applications it was determined that CsI(Tl) was an optimal scintillator material, with crystal thicknesses of 3 mm and 5 mm again being ideal for SPECT/MR systems with pinhole and parallel hole coded apertures respectively.

Index Terms—Radiation Instrumentation, Gamma-ray Detector, SPECT, SPECT/CT, SPECT/MR.

I. INTRODUCTION

Single Photon Emission Computed Tomography (SPECT) is one of the primary emission imaging modalities utilised in nuclear medicine. This imaging modality is based on the use of a direct or coded aperture to restrict the solid angle of gamma/x-rays incident upon the surface of a position-and-energy-resolving radiation detector [1], [2]. These two key system elements, the coded aperture and radiation detector, define the fundamental limit of any SPECT imaging system’s performance [3], [4]. The restriction of the solid angle via the coded aperture enables their tiling to create large surface area MRI compatible radiation detectors ideal for clinical SPECT applications. However at present only a small number of SPECT SiPM radiation detectors has been developed [19], [20], [21], [22], and a single simultaneous acquisition SPECT/MR clinical prototype constructed as part of the INSERT program [23], [24].

This work presents an in-silico investigation into the optimal design of a Philips DPC3200 SiPM photosensor based monolithic scintillator detector for SPECT applications. Four different monolithic scintillator crystal material types, NaI(Tl), GAGG(Ce), CsI(Tl) and LYSO(Ce) [25], directly bonded to the SiPM photosensor were explored for the primary gamma/x-ray emissions from $^{99m}$Tc, $^{123}$I, $^{131}$I and $^{201}$Tl as a function of crystal thickness over the range of 1 to 5 mm. Section II describes the developed simulation platform, detector response/readout modelling, and detection performance assessment/optimisation methodology. The results from this in-silico investigation, their discussion and an overall conclusion then follows in Section III, IV and V respectively.

II. METHOD

A simulation platform was constructed using the Monte Carlo radiation transport modelling toolkit Geant4 version 10.5 [26], [27], [28] to determine the optimal design of a Philips DPC3200 SiPM photosensor based monolithic scintillator detector for SPECT applications. The methodology of the investigation may be separated into four primary areas: 1) simulated detector geometry and materials, 2) physics and optical surface modelling, 3) photosensor response and SPECT detector readout modelling, and 4) radiation detector performance assessment/optimisation.

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1) Simulated Detector Geometry and Materials: A schematic of the simulated SPECT radiation detector geometry composed of a monolithic scintillator crystal coupled to a Philips DPC3200 Silicon Photomultiplier (SiPM) [17], [18] with a 100 µm layer of DELO photobond 4436 glue is shown in Fig. 1. The cross-sectional area of the coupled scintillator crystal surface was set to match the approximate active Philips DPC3200 SiPM photosensor region (32×32 mm), with the other five crystal surfaces made light-tight through the mounting of a layer of Vikuiti ESR foil via a 35 µm thick layer of DELO photobond 4436 glue. All 6 surfaces of the monolithic crystal were assumed to be polished, with four different scintillator crystal types, and its thickness varied as part of the optimisation process (see Section II-3 for more details). Implementation of the Philips DPC3200 SiPM photosensor followed the same approach as outlined in [29]. Here, the photosensor layer structure, dimensions and locations of the quartz light guide, glue layers, 8×8 and printed circuit board was based on version 1.1 of the unit manual. Finally, the density, elemental composition, and optical/scintillation properties of all materials can be found in Appendix A.

Fig. 1. A schematic of the SPECT radiation detector geometry constructed within the Geant4 simulation platform. Here a section of the monolithic crystal is removed to illustrate the implemented 8×8 Si pixel footprint of the Philips DPC3200 SiPM photosensor.

2) Physics and Optical Surface Modelling: X-ray, gamma-ray and electron transport was simulated using the Geant4 Option4 EM physics list (G4EmStandardPhysics_option4 [23]) with atomic deexcitation enabled, a maximum particle step length of 10 µm, and a low-energy cut off of 250 eV. Optical photon generation and transport was included for the processes of scintillation, absorption, refraction and reflection via the Geant4 implementation of the “Unified” model [30]. With the exception of the ESR foil-to-DELO-glue material interfaces (modelled as a dielectric to metal with reflectivity outlined in Appendix A), all other material optical interfaces were modelled as dielectric-to-dielectric. Finally, every surface interface between two materials was described as a ground surface with surface roughness of 0.1 degrees because it is not possible for surfaces to be “perfectly smooth” [31], [32].

3) Photosensor Response and Detector Readout Modelling: The implemented photosensor response model was taken from that developed and outlined in Brown et al. [29]. Here, the photosensor response was realised in two steps: 1) physical geometry, and 2) electronic response. The physical geometry of the SiPM was implemented through the definition of scoring boundaries that mimicked the shape and location of all 3200 59.4 µm × 64 µm Single Photon Avalanche Diodes (SPADs) [17], [18] in each of the 64 SiPM pixels. The electronic behaviour of the SiPM photosensor was modelled based on four assumptions: 1) the probability of a photoelectrically absorbed optical photon triggering a SPAD is proportional to the Photon Detection Efficiency (PDE) outlined in [17], 2) a given SPAD can only trigger once per simulated primary gamma/x-ray, 3) all SiPM pixels have a zero dark count rate and avalanche triggering probability, and 4) there is no SiPM photosensor onboard sub-pixel or validation trigger logic. Output of this photosensor response model was developed to approximate the unit output: an 8×8 array of values representing the total number of SPAD triggers per SiPM pixel. Finally, to enable a more in-depth “dead-time” analysis of the radiation detector design under investigation, each 8×8 SiPM pixel SPAD trigger count was also accompanied by a full list of their respective timestamps relative to the first incoherent interaction time of the gamma/x-ray within the monolithic scintillator crystals.

The interaction position (X, Y) of each simulated gamma/x-ray within the monolithic scintillator crystals was determined through the use of a truncated Centre of Gravity (CoG) algorithm [20], [33]. Each estimated interaction position (X, Y) was determine using the photosensor response model output by:

\[ X = \frac{\sum_{i=1}^{8} \sum_{j=1}^{8} x_{i,j} n_{i,j,\alpha}}{\sum_{i=1}^{8} \sum_{j=1}^{8} n_{i,j,\alpha}} \]  
\[ Y = \frac{\sum_{j=1}^{8} \sum_{i=1}^{8} y_{i,j} n_{i,j,\alpha}}{\sum_{j=1}^{8} \sum_{i=1}^{8} n_{i,j,\alpha}} \]  

where \( n_{i,j,\alpha} \) is the truncated SPAD trigger counts of each SiPM pixel (i, j) at location (x, y), and:

\[ n_{i,j} - \alpha \sum_{i=1}^{8} \sum_{j=1}^{8} n_{i,j} \geq 0 \Rightarrow n_{i,j,\alpha} = n_{i,j} - \alpha \sum_{i=1}^{8} \sum_{j=1}^{8} n_{i,j} \]  
\[ n_{i,j} - \alpha \sum_{i=1}^{8} \sum_{j=1}^{8} n_{i,j} \leq 0 \Rightarrow n_{i,j,\alpha} = 0 \]  

for the raw number of SPAD trigger counts of each SiPM pixel \( n_{i,j} \) and a given truncation factor \( \alpha \). The truncation factor \( \alpha \) has been shown to improve the position of interaction/crystal identification [20], [34] and in this work its impact was investigated for values of 0 (i.e. no truncation), 0.02 and 0.04.

4) Detector Performance Assessment/Optimisation: Two physical properties were optimised to maximise the performance of the proposed SPECT radiation detector: monolithic scintillator crystal material, and monolithic scintillator crystal thickness. Four different scintillator types, NaI(Tl), GAGG(Ce), CsI(Tl) and LYSO(Ce), over a thickness range of 1 to 5 mm was explored as their scintillation spectra align strongly with the PDE of the Philips DPC3200 SiPM photosensor [17]. For each configuration 16 different pencil beam irradiation positions were simulated for five different gamma/x-ray energies (28, 72, 140, 159 and 365 keV) that...
represent the primary emissions from $^{99m}$Tc, $^{123}$I, $^{131}$I and $^{201}$Tl. These 16 irradiation positions were composed of a horizontal and diagonal sweep from the centre of the SPECT radiation detector starting at 1 mm and continuing in 2 mm steps to its edge (i.e. 1mm, 3mm, 5mm, ... 15 mm). At each location the pencil beam originated at the surface of the monolithic scintillator crystal with zero divergence and total of 50,000 events were simulated.

The performance of the 20 different SPECT radiation detector configurations was determined through the use of six Figures of Merit (FoM): gamma/x-ray photoelectric absorption fraction on the first interaction, photopeak Full Width at Half Maximum (FWHM) energy resolution, energy spectrum linearity, relative final SPAD trigger time per gamma/x-ray, FWHM of estimated gamma/x-ray irradiation locations, and linearity of estimated gamma/x-ray irradiation locations. All FWHM values were calculated assuming a Gaussian distribution, and the energy/spatial linearity assessed through the use the correlation coefficient ($R^2$) from linear regression with respect to known incident gamma/x-ray energies and irradiation locations. Furthermore, the FWHM and linearity of estimated irradiation locations was applied to gamma/x-rays that underwent photoelectric absorption on their first interaction within the scintillator crystal. Filtering the data in this manner, rather than using an energy window approach which typically also includes gamma/x-rays that deposit their total/near total energy in the scintillator crystals through multiple interactions, enables quantification of the “true” number of detector events/spatial resolution of the SPECT radiation detector (relevant in calculation of SPECT system sensitivity).

III. RESULTS

The gamma/x-ray photoelectric absorption fraction on the first interaction for each material as a function of incident energy and crystal thickness can be seen in Fig. 2. For all four materials the fraction of gamma/x-ray photoelectric absorption for a given energy increases as a function of material thickness and, with the exception of the 28 keV profiles in CsI(Tl) and LYSO(Ce), the maximum value of each gamma/x-ray photoelectric absorption profile scales with its energy. This lower than expected photoelectric absorption fraction on the first interaction at 28 keV in CsI(Tl) and LYSO(Ce) can be attributed to the interplay between two factors: 1) the non-negligible interaction cross-section of 28 keV gamma/x-rays in the ESR and glue layer at the front surface of each scintillator crystals, and 2) an over 95% contribution of photoelectric absorption towards the total interaction cross-section of CsI(Tl) and LYSO(Ce) at 72 keV [35]. Finally, the ranking from maximum to minimum value of the four materials with this FoM corresponds directly to the total relative photoelectric cross-section of each material (e.g. LYSO(Ce), GAGG(Ce), CsI(Tl) and NaI(Tl)).

Figure 3 presents the photopeak energy resolution (% FWHM) of the four different scintillator crystal materials as a function of incident gamma/x-ray energy and material thickness. All four materials display a direct relationship between both the incident gamma/x-ray energy and material thickness with respect to energy resolution. In addition for the impact of material thickness, all four materials have an energy resolution across the range of tested gamma/x-ray energies that approach a plateau in performance at a thickness of 4 mm. From these data it can be seen that CsI(Tl) possesses the best energy resolution performance on average for all tested gamma/x-ray energies, followed by NaI(Tl), GAGG(Ce) and LYSO(Ce). Here, the lower than expected performance of the GAGG(Ce) with respect to NaI(Tl), based on their optical photon yields per MeV (see Table II) and SiPM PDEs outlined in [17], can be attributed to the fact that GAGG(Ce) has a high level of self-absorption for its emitted optical scintillation photons resulting in a net loss in those which propagate the full distance from their emission site to the SiPM.

Energy linearity of each material for the 5 simulated gamma/x-rays as a function of thickness can be seen in Fig. 4. All four materials approach a near-perfect energy linearity for material thicknesses above 4 mm, with NaI(Tl) and CsI(Tl) performing worse than GAGG(Ce) and LYSO(Ce) at below 4 mm. This lower performance of NaI(Tl) and CsI(Tl) for thinner crystal thicknesses can be attributed to their higher probability of fluorescence x-ray escape after the photoelectric absorption of gamma/x-rays that distorts the shape and estimated centroid position of photopeaks in measured energy spectra [36]. However it should be stated that all four materials across the range of explored material thicknesses possessed a $R^2$ of over 0.998, indicating a very high level of energy linearity.

The mean and standard deviation of the relative final SPAD trigger times per first gamma/x-ray interaction for each material as a function of incident energy and crystal thickness can be seen in Fig. 5. With the exception of CsI(Tl), the three other materials exhibit inverse relationships between both these parameters (incident gamma/x-ray energy and crystal
Fig. 3. Energy resolution (FWHM) of the four different scintillator crystal materials, NaI(Tl), GAGG(Ce), CsI(Tl) and LYSO(Ce), as a function of incident gamma/x-ray energy and crystal thickness. The coloured dash lines correspond to a fitted negative exponential function for each incident gamma/x-ray energy to illustrate the general trend as a function of crystal thickness.

Fig. 4. Energy linearity of the four different scintillator crystal materials, NaI(Tl), GAGG(Ce), CsI(Tl) and LYSO(Ce), as a function of crystal thickness. The coloured dash lines correspond to a capped fitted 1st order polynomial function for each material to illustrate the general trend as a function of crystal thickness.

thickness) and the mean relative final SPAD trigger times per first gamma/x-ray interaction. Comparison of all four material data-sets enables for a clear ranking between the four materials from shortest to longest mean relative final SPAD trigger times per gamma/x-ray: LYSO, GAGG(Ce), NaI(Tl), and CsI(Tl). Finally if it is assumed that the maximum mean SPECT radiation detector count rate before pile up is dependent on scintillation crystal alone, then for all tested energies and thicknesses NaI(Tl), GAGG(Ce), CsI(Tl) and LYSO(Ce) would possess approximate maximum counts per second (cps) rates of 500,000 cps, 830,000 cps, 400,000 cps, and 4,000,000 cps respectively.

Figure 6 presents the mean and standard deviations of the irradiation spot x-axial and y-axial spatial resolution (FWHM) for all four materials as a function of incident gamma/x-ray energy, crystal thickness, and CoG truncation factor. For all four materials an inverse relationship can be observed between the incident gamma/x-ray energy and improvement of spot spatial resolution along both axes (i.e. with increasing gamma/x-ray energy the FWHM of each spot decreases along both axes). A similar relationship can be observed for all four materials between the crystal thickness and spot spatial resolution along both axes. However the impact of CoG truncation factor on spot spatial resolutions for all four materials is far more complex, with only a general trend that a non-zero CoG truncation factor appears to improve the spatial resolution along both axes. Overall Fig. 6 illustrates that the four material’s performance as a factor of incident gamma/x-ray energy, crystal thickness, and CoG truncation factor is similar, with CsI(Tl) and GAGG(Ce) performing slightly better at lower incident gamma/x-ray energies due to their higher optical photon yields per MeV (see Table II in Appendix A). The axial spatial linearity of irradiation spot locations for the four scintillator crystal materials as a function of incident gamma/x-ray energy, crystal thickness, and CoG truncation factor can be seen in Fig. 7. As with the axial spot spatial resolution (FWHM) seen in Fig. 6, an inverse relationship can be observed between crystal thickness and the spatial linearity for all four materials along both axes (i.e. with increasing crystal thickness the linear correlation coefficient ($R^2$) decreases). In contrast it appears that the relationship between incident gamma/x-ray energy and spatial linearity is both material and axial direction dependent. Further inspection of Fig. 7 illustrates that an axial asymmetry in spatial linearity as a function of incident gamma/x-ray energy and crystal thickness is present for all four materials, and that the extent of this axial asymmetry is suppressed proportionally with increasing CoG truncation factor. In fact for the highest tested energy...
Fig. 6. Mean and standard deviations of the irradiation spot x- and y-axial spatial resolution (FWHM) for the four different scintillator crystal materials, NaI(Tl), GAGG(Ce), CsI(Tl) and LYSO(Ce), as a function of incident gamma/x-ray energy, truncation factor \(\alpha = 0\) circle, \(\alpha = 0.02\) square, and \(\alpha = 0.04\) diamond marker) and crystal thickness. The coloured dash lines \((\alpha = 0\) dashed, \(\alpha = 0.02\) dot-dashed, and \(\alpha = 0.04\) dotted) correspond to a fitted 1st order polynomial function for each incident gamma/x-ray energy to illustrate the general trend as a function of crystal thickness.

CoG truncation factor \((\alpha = 0.04)\) there is minimal difference between the four materials along both axes.

IV. DISCUSSION

The in-silico optimisation of a Philips DPC3200 SiPM photosensor based monolithic scintillator detector for SPECT applications was undertaken through the use of six FoMs. For the gamma/x-ray photoelectric absorption fraction on the first interaction FoM, the ranking of the four tested materials corresponded directly to the total relative photoelectric cross-section of each material (e.g. LYSO(Ce), GAGG(Ce), CsI(Tl) and NaI(Tl)). Assessment of the material types based on phototube energy resolution (FWHM) saw CsI(Tl) and NaI(Tl) performing on average better than the other two over the tested energy range, with all four materials also showing a high level of energy linearity regardless of crystal thickness. Of the four materials LYSO(Ce) was determined to possess the highest maximum count rate before saturation regardless of incident gamma/x-ray energy or material thickness, followed by GAGG(Ce), NaI(Tl), and CsI(Tl). Assessment of the spatial resolution saw CsI(Tl) and GAGG(Ce) performing better than the other two materials at lower gamma/x-ray energies, with little difference between the performance of the four materials at higher incident gamma/x-ray energies. Finally, the outcome of the assessment of the spatial linearity of the four materials as a function of incident gamma/x-ray energy, crystal thickness, and CoG truncation factor \((\alpha)\) illustrated that at higher values of \(\alpha\) there was minimal difference between the four material’s performance.

Based on these FoM results it is difficult to select one scintillator material over the other three to construct a single
Philips DPC3200 SiPM photosensor based monolithic scintillator detector applicable to every SPECT application. Further consideration is also needed for the scintillator material selection that includes the target image task and the SPECT systems methodology of acquiring supporting patient anatomical information. In the case of SPECT/X-ray CT systems GAGG(Ce) or LYSO(Ce) are viable choices, with GAGG(Ce) most likely being selected in the majority of cases due to its superior energy resolution [1], [3], [4]. For SPECT/MR systems CsI(Tl) or LYSO(Ce) would be logical choices due to their MR compatibility [25], with CsI(Tl) most likely being selected due to its superior energy resolution and the fact that it does not suffer from non-proportional scintillation yields at incident gamma/x-ray energies below 100 keV [57].

With these two base unit designs for SPECT/X-ray CT and SPECT/MR, optimisation of their crystal thickness requires consideration of each system’s coded aperture design to minimise the trade off between spatial resolution, sensitivity and energy resolution. In the case of a pinhole based coded aperture with a large field of view, i.e. typically used in small animal and brain imaging systems [1], [38], [39], the ideal crystal thickness for both the GAGG(Ce) SPECT/X-ray CT and CsI(Tl) SPECT/MR radiation detectors would be 3 mm. This thickness would maximise SPECT system spatial resolution via reducing the impact of Depth of Interaction (DoI) effects at a minimal cost to detection efficiency and reduction in energy resolution. Whereas with a parallel hole based coded aperture, i.e. typically used for whole body and cardiac imaging systems [3], [4], [40], the crystal thickness of both the GAGG(Ce) SPECT/X-ray CT and CsI(Tl) SPECT/MR radiation detectors be could increased to 5 mm. This thickness maximises both the energy resolution and detection efficiency without significantly degrading the effective system spatial resolution as the impact of DoI effects is suppressed for this coded aperture configuration [1], [3], [4].

This investigation is part of a larger research program to develop a novel multiple radiomolecular tracer platform for head and neck imaging within the Department of Radiation Science and Technology at the Delft University of Technology (The Netherlands). As the first phase of this new imaging platform will use a parallel hole collimator, two experimental Philips DPC3200 SiPM photosensor based monolithic scintillator detector prototypes using 5 mm thick GAGG(Ce) and CsI(Tl) crystals have begun construction. The performance of these units will be explored not only as a function of incident gamma/x-ray energy, but also as a function of unit temperature, Philips DPC3200 SiPM photosensor trigger setting, and readout algorithm to determine the ideal unit for the imaging platform.

V. CONCLUSION

An in-silico investigation into the optimal design of a Philips DPC3200 SiPM photosensor based monolithic scintillator detector for SPECT applications was undertaken using the Monte Carlo radiation transport modelling toolkit Geant4 version 10.5. The performance of the 20 different SPECT radiation detector configurations, 4 scintillator materials (NaI(Tl), GAGG(Ce), CsI(Tl) and LYSO(Ce)) and 5 thicknesses (1 to 5 mm), were determine through the use of six FoMs. For SPECT/X-ray CT applications it was determine that GAGG(Ce) was an optimal scintillator material, with crystal thicknesses of 3 mm and 5 mm being ideal for SPECT/X-ray CT systems with pinhole and parallel hole coded apertures respectively. For SPECT/MR applications it was determine that CsI(Tl) was an optimal scintillator material, with crystal thicknesses of 3 mm and 5 mm again being ideal for SPECT/MR systems with pinhole and parallel hole coded apertures respectively. Further work is underway to construct SPECT/X-ray CT and SPECT/MR units based on these specifications for a novel parallel hole based coded aperture multiple radiomolecular tracer platform for head and neck imaging within the Department of Radiation Science and Technology at the Delft University of Technology (The Netherlands).

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APPENDIX A

GEANT4 SIMULATION PLATFORM MATERIAL PROPERTIES

The following appendix contains the density, elemental composition, and optical/scintillation properties of all materials utilised in the developed Geant4 simulation platform. Material data relating to the world volume, bonding glue, Vikuici ESR foil, and implemented Philips DPC3200 SiPM is outlined in Table I and Fig. 8. Material data relating the four explored scintillator types, NaI(Tl), GAGG(Ce), CsI(Tl) and LYSO(Ce), can be seen in Table II and Fig. 9.

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### Table I

| Material | Density (g/cm³) | Elemental Composition | Refractive Index | Optical Reflectivity / Absorption | Reference |
|----------|-----------------|----------------------|------------------|-----------------------------------|-----------|
| Air      | 1.29×10⁻³       | C (0.01%), N (75.52%), O (23.19%), Ar (1.28%) | 1                | -                                 | Geant4 Material Database 25 |
| DELO glue | 1.92           | H₂₅Ce₂O₆        | 1.5              | -                                 | [40]     |
| Vikuiti ESR | 1.29         | H₂₅Ce₂O₆        | -                | 98% / 2%                          | [42]     |
| DPC3200 PCB | 1.86        | SiO₂ (52.8%), H₂₃Ce₃O₁ (47.2%) | -                | 0% / 100%                         | [29], [41] |
| DPC3200 Glass | 2.203       | SiO₂            | See Fig. 8       | See Fig. 8                        | [29], [41] |
| DPC3200 Pixel | 2.33          | Si               | See Fig. 8       | See Fig. 8                        | [43]     |

**Density, elemental composition, and optical material properties of the world volume, bonding glue, Vikuiti ESR foil and Philips DPC3200 SiPM implemented in the Geant4 simulation platform.**

### Table II

| Material | Density (g/cm³) | Elemental Composition | Refractive Index | Optical Yield, Emission Spectrum, Absorption Length | Optical Decay Time Constants (ns) | Resolution Scale (at 511 keV) | Reference |
|----------|-----------------|----------------------|------------------|-----------------------------------------------------|---------------------------------|--------------------------------|-----------|
| NaI(Tl)  | 3.67            | NaI (6.5% Tl doping) | See Fig. 9       | 41 Photons per eV, See Fig. 9                       | Fast: 220 (96%), Slow: 1500 (4%) | 3.50                           | [44]     |
| GAGG(Ce) | 6.63            | Gd₃Al₂Ga₃O₁₀₂ (1% Ce doping) | See Fig. 9    | 50 Photons per eV, See Fig. 9                      | Fast: 87 (90%), Slow: 255 (10%) | 3.08                           | [44]     |
| CsI(Tl)  | 4.51            | CsI (0.08% Tl doping) | See Fig. 9       | 54 Photons per eV, See Fig. 9                      | 1000 (100%)                     | 3.50                           | [44]     |
| LYSO(Ce) | 7.4             | La₁₋ₓYₓO₃₋ₓ(SiO₅) (0.5% Ce doping) | See Fig. 9   | 30 Photons per eV, See Fig. 9                     | Fast: 7.1 (7%), Slow: 33.3 (93%) | 4.17                           | [40]     |

**Density, elemental composition, and optical properties of the four scintillator materials, NaI(Tl), GAGG(Ce), CsI(Tl) and LYSO(Ce), implemented in the Geant4 simulation platform.**

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Fig. 8. DPC3200 quartz glass (SiO₂) and pixel (Si) material refractive index (solid line) and attenuation length (dashed line) data sets implemented in the Geant4 simulation platform.

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Fig. 9. NaI(Tl), GAGG(Ce), CsI(Tl) and LYSO(Ce) scintillator crystal material refractive index’s (solid line), attenuation lengths (dashed line) and normalised scintillation photon emission intensities (dotted line) data sets implemented in the Geant4 simulation platform.

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