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Optical photon transport and geometry contributions to time response of scintillation detectors

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The sensitivities of both time and energy resolutions of a typical scintillation detector to major optical parameters (i.e. paint reflectivity, quantum efficiency of photomultiplier tube and attenuation coefficient) have been estimated using a dedicated Monte Carlo (MC) optical photon transport (OPT) simulation code, PHOTRACK, and the OPT capabilities of general-purpose code, FLUKA. Both cylindrical and parallelepiped geometries have been considered for the scintillator cell and lightguide. The results determine the scintillation light wavelength regions that the energy and time resolution represent enhanced sensitivities to small change/uncertainty in optical parameters.

Keywords: Scintillator; PHOTRACK; FLUKA; sensitivity; time resolution.

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1. Introduction

Two critical types of information can be drawn from the Monte Carlo (MC) simulation of OPT in scintillators; (a) the OPT contributions of time[1] and energy[2] resolutions and (b) the influence of scintillator cell/lightguides surface type on the response of detector.[3] Such crucial information can be solely derived with the OPT simulation in which all wavelength-dependencies are included.

In most MC OPT simulation codes (e.g. PHOton TRACKing FORTRAN program, PHOTRACK[4]), either the spatial distribution of energy deposition points (i.e. scintillation centers) may be imported to the program if the OPT is a sub-program of a simulation package (e.g. MCNPX-PHOTRACK,[5] FLUKA-PHOTRACK[6]), or the scintillation centers are produced homogeneously inside the sensitive region of the scintillator according to the user requirements. Normally, the emission of produced scintillation photons are well approximated to be isotropic. Demonstrated by a 3D parametric equation, the scintillation light photon intersects the scintillator/lightguide surface obtained by putting the line into the cylinder equation.[1] The optical reflections are generally categorized as mirror-type or diffuse when the light is reflected from polished and painted surfaces, respectively. The simulation procedure is terminated when the optical photons meet the photo-sensitive surface (i.e. photocathode) in the photomultiplier tube (PMT). The optical parameters (i.e. emission curve, paint reflectivity, attenuation coefficient, etc.) used in the OPT modeling process were assumed as constants but actually they all vary with wavelength so that they sometimes drastically alter as the wavelength changes.[4]

The effects of different surface coverings of scintillator and Perspex lightguide on the energy resolution have previously been reported.[1] Moreover, the sensitivity of energy resolution with respect to the variation of optical properties has been calculated.[7] In both studies, the geometries of scintillator cell and lightguide are assumed to be cylindrical as it is commonly used in most applications.

In this paper, using both PHOTRACK and FLUKA MC codes, the time response of scintillator with two commonly-used geometries (i.e. parallelepiped or cylindrical) has been studied and compared. Moreover, the influence of different optical parameters on the scintillator timing behavior has been estimated using sensitivity analysis. The results of these simulation studies are extremely important in precise timing measurements such as time-of-flight and neutron-gamma discriminations in the mixed neutron-gamma fields.[8]

The verifications of PHOTRACK code have been given in Sec. 2 and the use of sensitivity analysis in determining the importance of different optical parameters in time resolution of scintillators with both PHOTRACK and FLUKA has been explained in Sec. 3. Section 4 closes the paper with suggestions for further research.

2. Materials and Methods

In the MC PHOTRACK code,[4] the destination of every scintillation photon is recorded after tracking them via every optical process they have gone through. The absorption probabilities and the detection are determined later by simulating numerous light transport events. The major stages in OPT modeling are as follows: (1) to locate the light-generating points in the scintillator sensitive volume, which are in most cases randomly distributed, however; the program can receive any spatial distribution as input data; (2) to randomly select the direction of the light emission; (3) to track the traveling optical photons through the scintillator or lightguide whose attenuation is of exponential decay form; (4) to trace reflections in the scintillator or lightguide facets and (5) to tally up the photons that enter the PMT. The surface of the scintillator/lightguide can be partially or fully polished (uncovered), painted or metalized. For a precise modeling, every wavelength dependence in all above-named processes has to be taken into account.

Since the main objectives of the OPT simulation studies are pulse-height (i.e. energy) or/and timing analyses, any precise MC OPT simulation has to be benchmarked with both energy and time measurements/simulations. The simulation studies undertaken by Schölermann and Klein[9] who obtained the optimum energy resolution of a right cylindrical scintillator by using partial painting of lightguide has been accepted by many researchers as a good benchmark over the years. The simulation results of PHOTRACK code and those of Schölermann and Klein have been compared to prove excellent mutual agreement.[10] The scintillator in their studies has a 51 mm diameter by 51 mm high attached to a 25 mm length lightguide via a 4 mm so-called glass window. The scintillator surface has been fully covered by reflective paint, while the lightguide surface has been polished or partially painted. The variation of light collection efficiency against its generation vertical position can quantitatively determine how the scintillator/lightguide surface coverings affect the energy resolution.

A variety of successful studies have been conducted on light collection behavior of the cylindrical scintillator, a few of them reported on the parallelepiped scintillator. Belmont–Moreno and Menchaca–Rocha considered a $60\,\text{mm} \times 60\,\text{mm} \times 186\,\text{mm}$ NE102A plastic scintillator (H/C = 1.104, Refractive index = 1.581) and performed both simulation and experimental studies to obtain the light collection efficiency for different surface coverings.[11] Their geometry and surface coverings have been calculated for OPT simulation with PHOTRACK code. The numbers of scintillation centers and optical photons considered in this simulation are 10000 and 1000, respectively, which means 10^7 OPT have been undertaken for every data point. Also, here the MC tally is the average optical photon weight recorded at the PMT window. It has been decided to model the reflection from aluminized surface as a weighted mixture of specular (80%) and almost perfect (i.e. with 0.98 reflectivity) diffuse (20%) reflections.

Figure 1 compares the simulation data of PHOTRACK code and experimental results of Ref. 11 in which the horizontal axis, Z, is the light generation point distance from the photocathode center. The comparison represents an overall agreement despite the lack of complete set of optical characteristics of the experimental setup (e.g. the wrapping style of aluminum foil, the PMT type, etc.) may

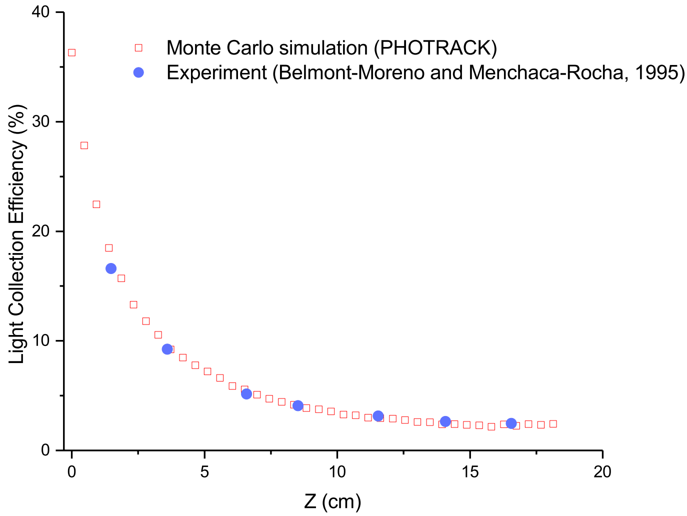


Fig. 1. (Color online) Variation of scintillation light collection efficiency versus the light generation axial position; A comparison between PHOTRACK data and the measurements performed by Belmont–Moreno and Menchaca–Rocha.

result in small discrepancies. In timing studies using MC OPT simulation, it is assumed that the speed of light photon is $C/n(\lambda)$, where C is the speed of light in vacuum, $n(\lambda)$ is the refractive index of the medium as a function λ and λ is the wavelength of scintillation photon.[12] The mean and standard deviations of the

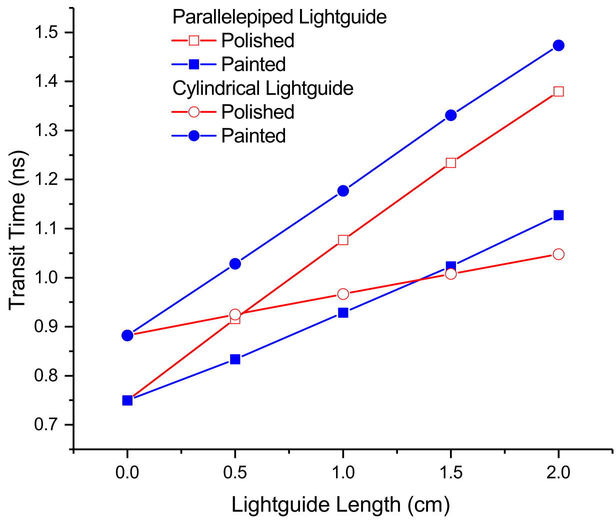


Fig. 2. (Color online) MC predictions for variation of mean transit time versus lightguide length for parallelepiped (51 mm × 51 mm × 51 mm dimensions; rectangular exit window) and cylindrical (51 mm diameter by 51 mm high; circular exit window) scintillators with polished and painted surfaces. The plastic scintillator is Saint-Gobain BCF-92.

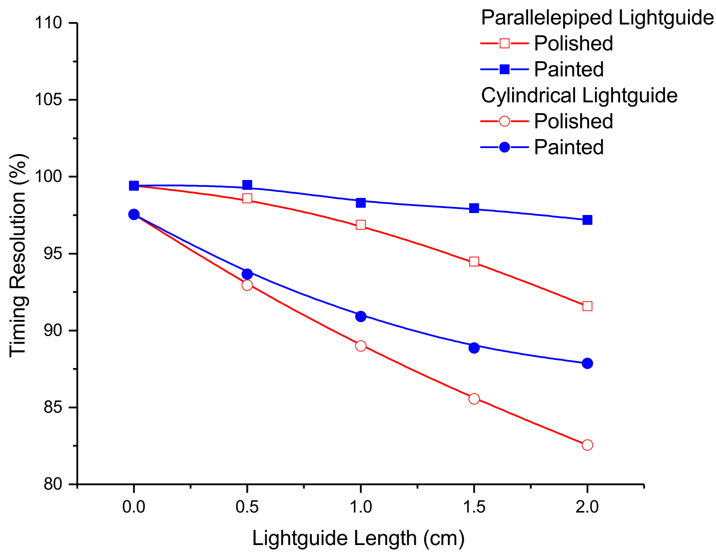


Fig. 3. (Color online) MC predictions for variation of time resolution versus lightguide length for parallelepiped (51 mm × 51 mm × 51 mm dimensions; rectangular exit window) and cylindrical (51 mm diameter by 51 mm high; circular exit window) scintillators with polished and painted surfaces. The plastic scintillator is Saint-Gobain BCF-92.

transit times (i.e. the times that the light photons spend while moving between their generation point and the photocathode surface) for a large number of computation runs give the transit time and time spread values of the detector; hence, the time resolution (i.e. time spread divided by average transit time).

It has been shown that the variation of optical parameters (e.g. paint reflectivity, quantum efficiency, etc.) relative to the photon wavelength will affect the transit time spread.[1,13] In the current study, PHOTRACK is used to compare the effect of lightguide length on the plastic scintillators time response with parallelepiped geometry (51 mm × 51 mm × 51 mm dimensions; rectangular exit window) to that of cylindrical shape (51 mm diameter × 51 mm high; circular exit window) (Fig. 2). Also, the time resolution has been illustrated in Fig. 3. In Fig. 3, the time resolution is improved as the lightguide length increases (this result coincides with experimental data as well,[8] but the improvement is greater for cylindrical scintillators to prove that they are more appropriate than parallelepiped scintillators as far as timing measurement is concerned.

3. Results and Discussion

3.1. *Sensitivity analysis of timing characteristics*

Sensitivity analysis examines the proportional uncertainty in the model output (numerical or otherwise) to various sources of uncertainty in the input.[14] If the parameter f is a function of g and g a function of x, i.e. $f(g(x))$, the variation diagram

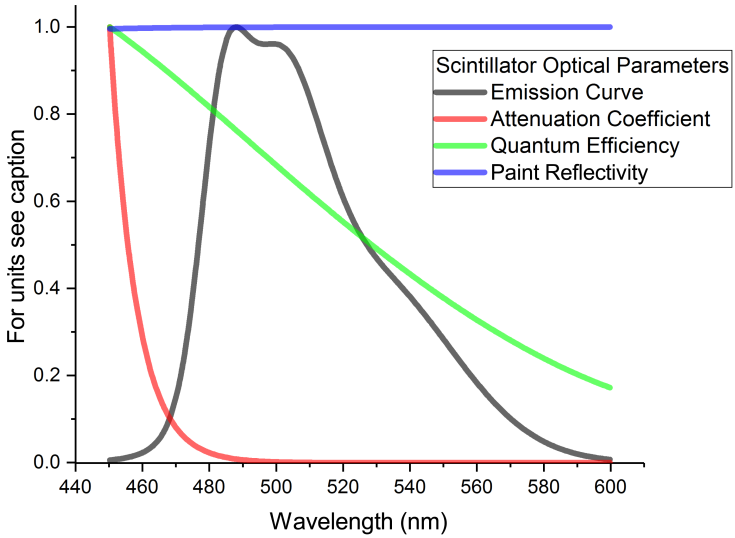


Fig. 4. (Color online) Wavelength-dependencies of some important parameters used in light transport simulation: Attenuation coefficient (cm^{-1}), Emission probability curve, Quantum efficiency normalized to its maximum value within the wavelength of interest (450–600 nm) and TiO_2 paint reflectivity probability. The scintillator is Saint-Gobain BCF-92.

of $(\triangle f/f)/(\triangle g/g)$ against x (i.e. sensitivity profile) determines the exact values of x around which the relative variation of g may have more/less effect on f. This information becomes important when the variation of g against x suffers from some uncertainties.

The primary results of sensitivity analysis on energy resolution of scintillation detectors as the optical parameters variation against light wavelength have been reported in 2008[7] where the wavelength regions of high sensitivities have been identified for three optical parameters in cylindrical scintillators. The subsequent enquiry is whether the scintillator shape will affect the sensitivity of energy resolution with respect to optical parameters. To examine this question, a parallelepiped scintillator has been considered with 51 mm × 51 mm × 51 mm size made of plastic scintillator with wavelength-dependent optical parameters shown in Fig. 4.

The sensitivity profiles can be obtained through the procedure shown in Table 1. A set of wavelengths is taken from the scintillator emission curve (The typical

Table 1. The sensitivity analysis calculation procedure used in sensitivity profiles.

Wavelength	Reflectivity	Resolution	Sensitivity	
λ_1	REF_1	RES_1	$\left(\frac{RES_2-RES_1}{RES_1}\right)/\left(\frac{REF_2-REF_1}{REF_1}\right)$	$\left(\frac{RES_3-RES_2}{RES_2}\right)/\left(\frac{REF_3-REF_2}{REF_2}\right)$
λ_2	REF_2	RES_2		
λ_3	REF_3	RES_3	$\left(\frac{RES_4-RES_3}{RES_3}\right)/\left(\frac{REF_4-REF_3}{REF_3}\right)$	
λ_4	REF_4	RES_4		

values for a plastic scintillator are from 450 to 600 nm as shown in Fig. 4). Then the relative change in energy/time resolution (i.e. $(\mathrm{RES}_{i+1} - \mathrm{RES}_i)/\mathrm{RES}_i$) divided by the relative change in one of the optical parameters (here, paint reflectivity) is calculated (e.g. $(\mathrm{REF}_{i+1} - \mathrm{REF}_i)/\mathrm{REF}_i$ for reflectivity) as a discrete function of wavelength.

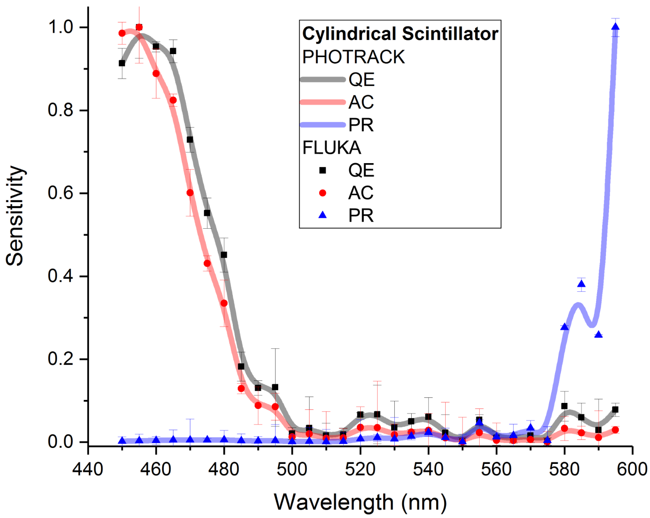
3.2. *FLUKA simulations*

The above-mentioned calculations can be undertaken either with a dedicated OPT code, like PHOTRACK, or with the OPT capability of general-purpose codes, like FLUKA[15] and GEANT4.[16] In order to verify the sensitivity profiles calculated with PHOTRACK in this study, a set of comparisons with FLUKA results has also been undertaken. The simplicity and OPT features of FLUKA code in all required details have inspired the use of this MC code.

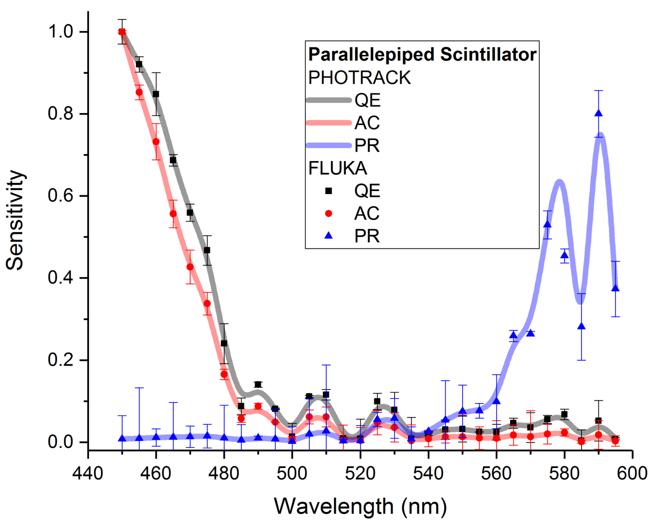
The FLUKA (version 2011.2c.6, updated in August 2017) can treat optical photons either as a result of ionizing radiation interactions (e.g. Čerenkov radiation or scintillation) or as a primary particle. Having considered the scintillator cell as a volume source of optical photons, one may calculate the average transit times of optical photons for a given wavelength through FLUKA USRDUMP card. Providing a FORTRAN routine, *mgdraw.f*, the USRDUMP normally generates a so-called collision file in which the interaction Cartesian coordinates at each boundary-crossing event, (XSCO,YSCO,ZSCO), together with atrack (a so-called particle age or transport time), is provided via ENTRY BXDRAW. From this entry, the mean and standard deviation of transit times can be easily calculated when the refraction index of the medium is provided. However, one has to define the optical properties of scintillator/lightguide by inserting OPT-PROP card. The FLUKA routines *rfrndx.f*, *rflctv.f*, *queffc.f* and *abscff.f* can be used to define the refractive index, the paint reflectivity (PR), the quantum efficiency (QE) of the PMT and the absorption (i.e. attenuation) coefficients (AC) of scintillator/lightguide for a given wavelength, respectively.

Following Table 1, the energy resolution sensitivity profiles for cylindrical- and parallelepiped-geometry scintillators have been obtained (Figs. 5(a) and 5(b)). As it can be seen in Fig. 5, there are two sets of wavelengths with distinct sensitivities: small wavelengths (from 450 to 500 nm) in which the sensitivity to both QE and AC is dominant and large wavelengths (from 570 to 600 nm) where the sensitivity to PR dominates. The comparison between FLUKA and PHOTRACK sensitivity profiles shows a good agreement especially for small wavelengths. Almost similar behavior can be seen in time resolution sensitivity profiles except for the sensitivity to PR at large-wavelength region where relatively large fluctuations exist.

As shown in Figs. 6(a) and 6(b), once more, FLUKA and PHOTRACK results exhibit excellent agreement for both parallelepiped and cylindrical scintillators. However, unlike PR case where a very low sensitivity is seen for small- and high-sensitivity for large wavelengths, the sensitivities of time resolution to AC and QE



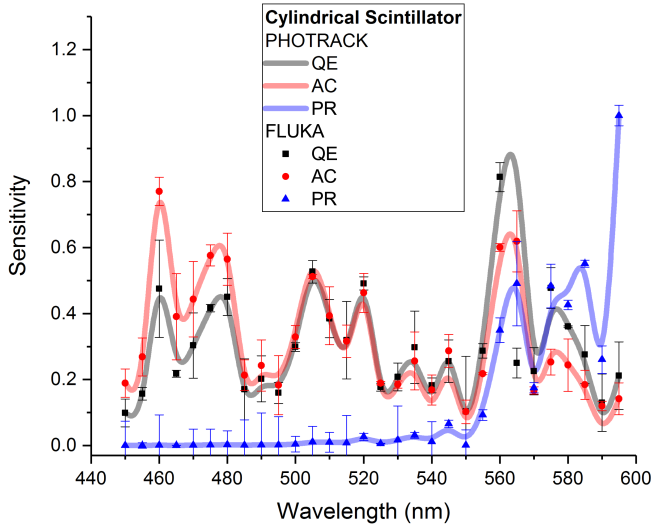
(a)



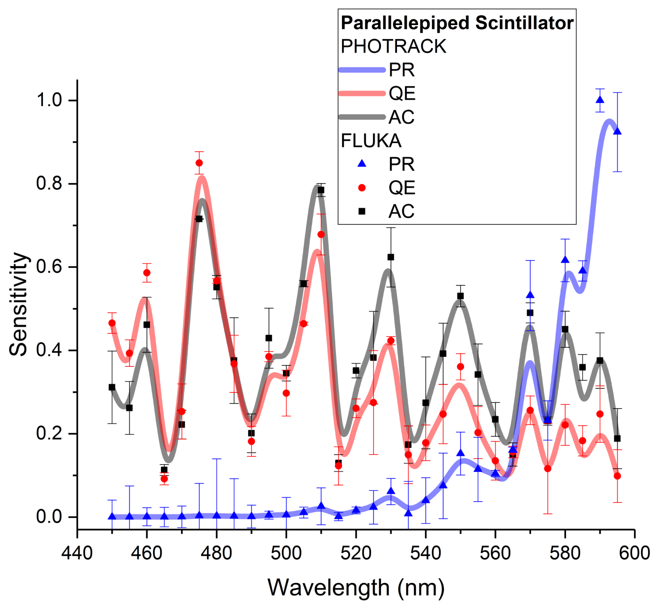
(b)

Fig. 5. (Color online) The energy resolution sensitivities to wavelength-dependent optical parameters (QE: Quantum Efficiency, AC: Attenuation Coefficient and PR: Paint Reflectivity) calculated with PHOTRACK and FLUKA MC codes, for: (a) cylindrical scintillator (25.5 mm diameter by 51 mm high) and (b) parallelepiped scintillator (51 mm × 51 mm × 51 mm). The scintillator is Saint-Gobain BCF-92.

represent oscillating behavior. These results confirm that in precise timing measurements the painting configurations of scintillator cell and lightguide have to be carefully taken into account, while the QE and AC wavelength specifications and uncertainties are of less importance.



(a)



(b)

Fig. 6. (Color online) The time resolution sensitivities to wavelength-dependent optical parameters (QE: Quantum Efficiency, AC: Attenuation Coefficient and PR: Paint Reflectivity) calculated with PHOTRACK and FLUKA MC codes, for: (a) cylindrical scintillator (25.5 mm diameter by 51 mm high) and (b) parallelepiped scintillator (51 mm $\times$ 51 mm $\times$ 51 mm). The scintillator is Saint-Gobain BCF-92.

4. Conclusions

Two different MC codes, FLUKA and PHOTRACK, have been used to study the timing behavior of scintillators of two different geometries, cylindrical and parallelepiped. The sensitivities of energy and time resolutions with respect to wavelength-dependent optical parameters of scintillation detector have been calculated using well-known sensitivity analysis technique.

The sensitivity analysis results also support that the geometry does not necessarily contribute to the sensitivity of energy and time resolutions. Besides, among different wavelength-dependent parameters, the paint reflectivity represents meaningful effects on the sensitivity of time resolution. In other words, special care has to be taken by developers of scintillators, to painting configurations while designing or constructing the scintillators for precise timing studies.

The studies on timing characteristics of scintillation detectors show that the scintillators with parallelepiped shapes have relatively long transit times and poor time resolution, therefore they seem inappropriate for timing measurements. But, since, the parallelepiped scintillators are more preferred in dosimetry studies,[17] the MC simulations sound an interesting research to undertake to obtain an optimum shape in order to fulfil both timing and dosimetry requirements.

Note should be taken that in the present study the scintillation photons are homogeneously generated within the scintillator cell which is clearly inappropriate in such applications as medical imaging where low-energy gamma rays deposit most of their energies close to the entrance surface. Therefore, one has to use an event-by-event simulation procedure in order to have a more accurate OPT simulation for energy and timing sensitivity analyses.

References

1. N. Ghal-Eh, *Radiat. Phys. Chem.* **80**, 365 (2011).
2. P. Lecoq, A. Gektin and M. Korzhik, *Energy Resolution and Non-Proportionality of Scintillators, in Inorganic Scintillators for Detector Systems* (Springer, International Publishing, 2017).
3. M. J. Safari, H. Afarideh, N. Ghal-Eh and F. A. Davani, *Nucl. Instrum. Methods A* **737**, 101 (2014).
4. N. Ghal-Eh, *Modelling Photon Transport in Scintillators* (LAP LAMBERT Academic Publishing, 2013)
5. M. Tajik, N. Ghal-Eh, G. R. Etaati and H. Afarideh, *Nucl. Instrum. Methods A* **704**, 104 (2013).
6. M. Tajik and N. Ghal-Eh, *Nucl. Instrum. Methods A* **791**, 65 (2015).
7. N. Ghal-Eh and R. Koohi-Fayegh, *J. Lumin. A* **128**, 11 (2008).
8. Z. B. Bash, N. Ghal-Eh, E. Bayat and G. R. Etaati, *Radiat. Phys. Chem.* **82**, 1 (2013).
9. H. Schölermann and H. Klein, *Nucl. Instrum. Methods* **169**, 25 (1980).
10. N. Ghal-Eh, M. C. Scott, R. Koohi-Fayegh and M. F. Rahimi, *Nucl. Instrum. Methods A* **516**, 116 (2004).
11. E. Belmont–Moreno and A. Menchaca-Rocha, *J. Phys. D: Appl. Phys.* **28**, 835 (1995).
12. M. Born and E. Wolf, *Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light* (Elsevier, 2013).

13. C. Thalhammer, Ph.D. thesis, Improving the light yield and timing resolution of scintillator-based detectors for position emission tomography. Humboldt-Universitt zu Berlin, Mathematisch-Naturwissenschaftliche Fakultät (2015).
14. A. Saltelli, K. Chan and E. M. Scott, eds., *Sensitivity Analysis*, Vol. 1 (Wiley, New York, 2000).
15. A. Ferrari, P. R. Sala, A. Fasso and J. Ranft, FLUKA: A multi-particle transport code, No. INFN-TC-05-11 (2005).
16. S. Agostinelli *et al.*, *Nucl. Instrum. Methods A* **506**, 250 (2003).
17. J. Nilsson, V. Cuplov and M. Isaksson, *Appl. Radiat. Isot.* **103**, 15 (2015).