Geometry and reflection effects on pulse shapes within plastic scintillators using Geant4

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Introduction

Portal monitors for use in nuclear security typically use large volume detectors such as plastic scintillator detectors fabricated from polyvinyl toluene (PVT). Recent advancements in plastic scintillators have produced new scintillator materials which respond to both neutron and gamma radiation. These materials show pulse shape discrimination (PSD) properties which can be used to distinguish between the fast neutron and gamma events. However, it is observed that PSD performance generally degrades with increasing scintillator size. In this work, we aim to understand the optical transport processes in PSD-sensitive plastic scintillators and how these are potentially important for future portal monitors.

Geant4 is a Monte Carlo radiation transport toolkit which is often used to model energy deposition in detector systems [1]. However, it also has the ability to track optical photons and tally their arrival time at a collecting surface. In addition, the performance of the reflective coating and of the scintillator geometry can be altered to study different detector configurations. Optical photons generated in a scintillation event can be sampled from a distribution with multiple exponential decay constants allowing the dependency of PSD on material properties to be studied. This poster will demonstrate Geant4 modelling of optical photon arrival times for a variety of material properties and geometries of plastic scintillator. These phenomena directly effect the time profiles and shapes of the detected optical pulses. We will discuss the effect of optical photon transport on the PSD performance of plastic scintillator, and the underlying causes of reduced PSD performance in large volume scintillators.

Geant4 Optical Photons

Geant4 has the ability to simulate and track optical photons. For simulations of scintillators, the optical photons are generated along the incident radiations track where energy deposits would occur in the material. The modelled scintillator material can be solid such as plastic scintillators or liquids. The number of optical photons generated (light yield) for different particle interactions can also be applied alongside time constants of the emission, this allows for PSD to be modelled [2].

Currently, the Geant4 scintillation code is limited to two decay time constants for the photon emission. However, PSD plastic scintillators, such as EJ-299 and EJ-276, are documented to have three or more time constants [3]. The simulations presented here use a primary action generator which is based on G4Scintillation to produce photons independent from the initial particle interaction and is capable of having three or more time constants.

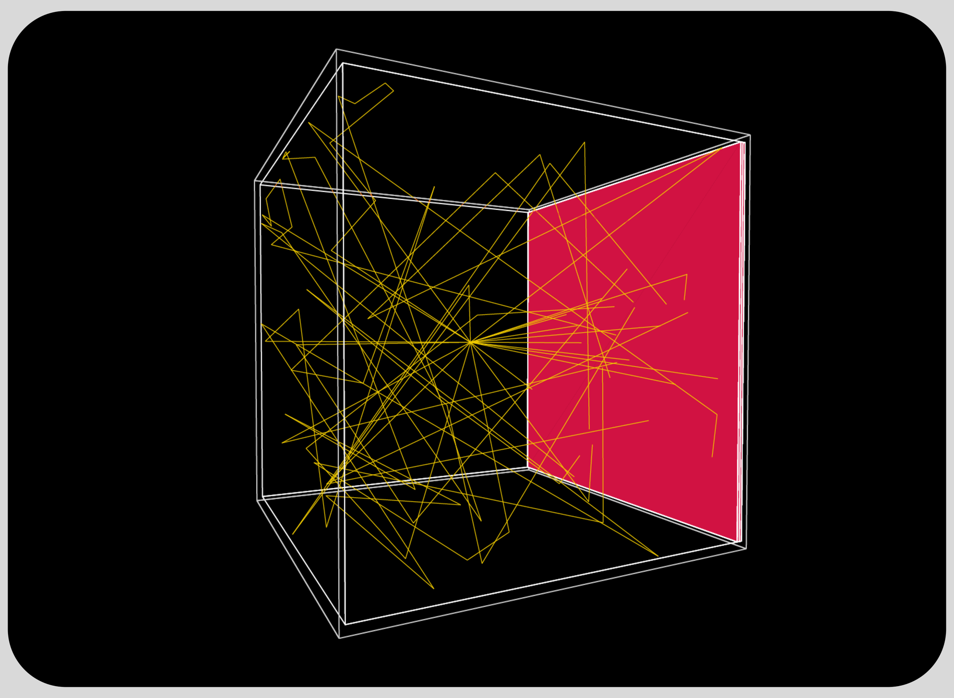

Figure 1. Simulation of a scintillation event. Optical photons emitted from the centre of a plastic scintillator cube with EJ-200 properties.

Optical photon directionality

When optical photons are emitted during the scintillation process their individual arrival time will be distributed based upon geometry and reflection parameters. Increasing the distance from the emission point to the photodetector will increase the time at which the distribution starts. When modelled the optical photons appeared to come from two distinct distributions based on emission direction. The behaviour was seen in all reflectivity models tested; specular, diffuse and specular+diffuse. However the distributions are most prominent in the specular model, this is shown in Figure 2.

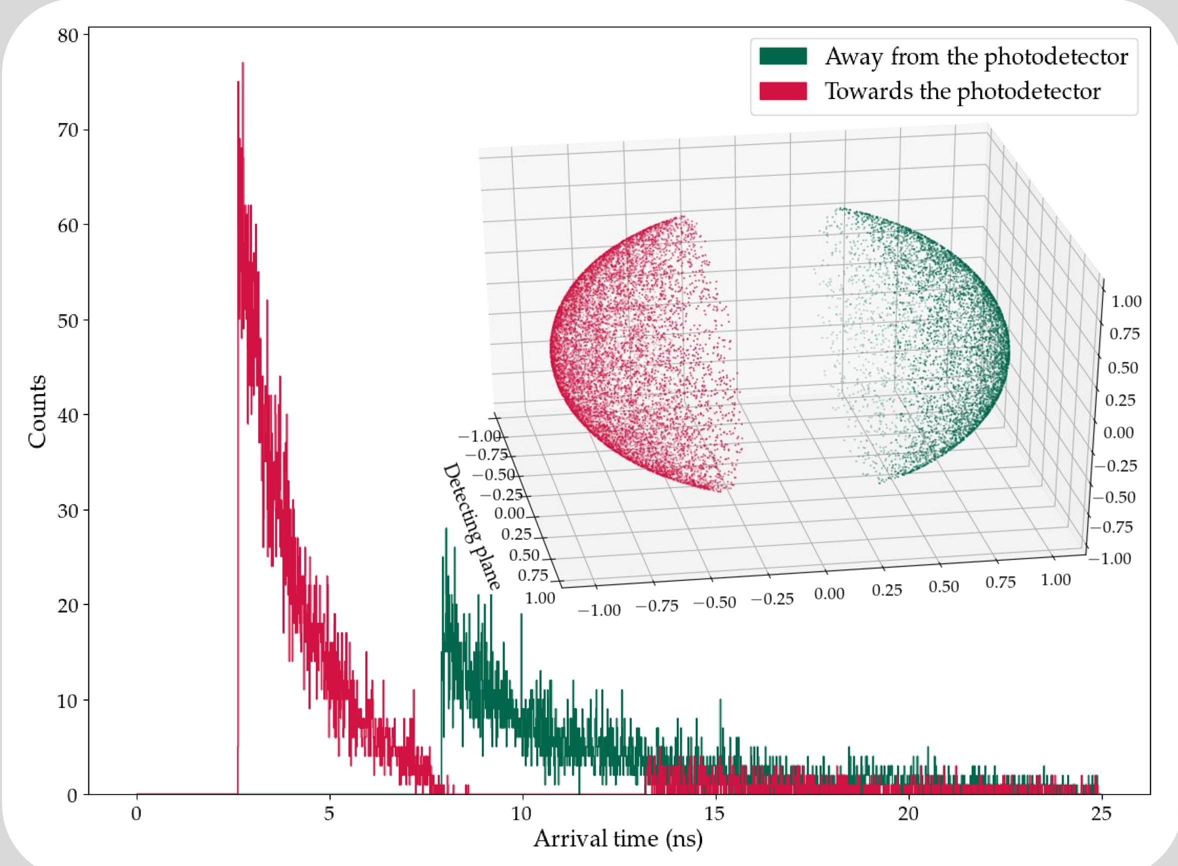

Figure 2. Arrival time of individual optical photons released at t=0 in the centre of a scintillator cube with 1m side length and using the specular reflection model. There are two distinctive distributions, one for emission towards and the other away from the photodetector.

Pulse shape modelling

The ability to distinguish the incident radiation in scintillators is due to the distribution of the optical photons generated from the interaction event. The model chosen for PSD plastic scintillator simulation includes three time constants and this is shown in Equation 1.

$$f(t) = Ae^{-t/\tau_1} + Be^{-t/\tau_2} + Ce^{-t/\tau_3}$$

Equation 1. Triple time constant pulse model.

The literature lacks what specifically changes during emission whether it is the induvial time constants, their specific weightings or both. Different systems have been modelled however it was ultimately chosen to use values where both changed as the values were from a published source [3], the values are located in Table 1.

Particle	A	τ_1(ns)	B	τ_2(ns)	C	τ_3(ns)
Gamma	0.74	4.3	0.14	18	0.12	140
Neutron	0.58	4.5	0.18	20	0.24	170

Table 1. Parameters used for pulse shape modelling based upon data from [3].

In a perfect, scenario the convolution of the geometry and reflection distributions of optical photons would keep the pulse shapes indistinguishable with little artefacts added. However, this isn't the case as seen in Figure 2 there is a directionality effect. The effect is observed most in large scintillator simulations, an example is in Figure 3. In individual pulses the effect cannot be seen clearly due to low photon count, therefore averaging a large amount shows the artefact.

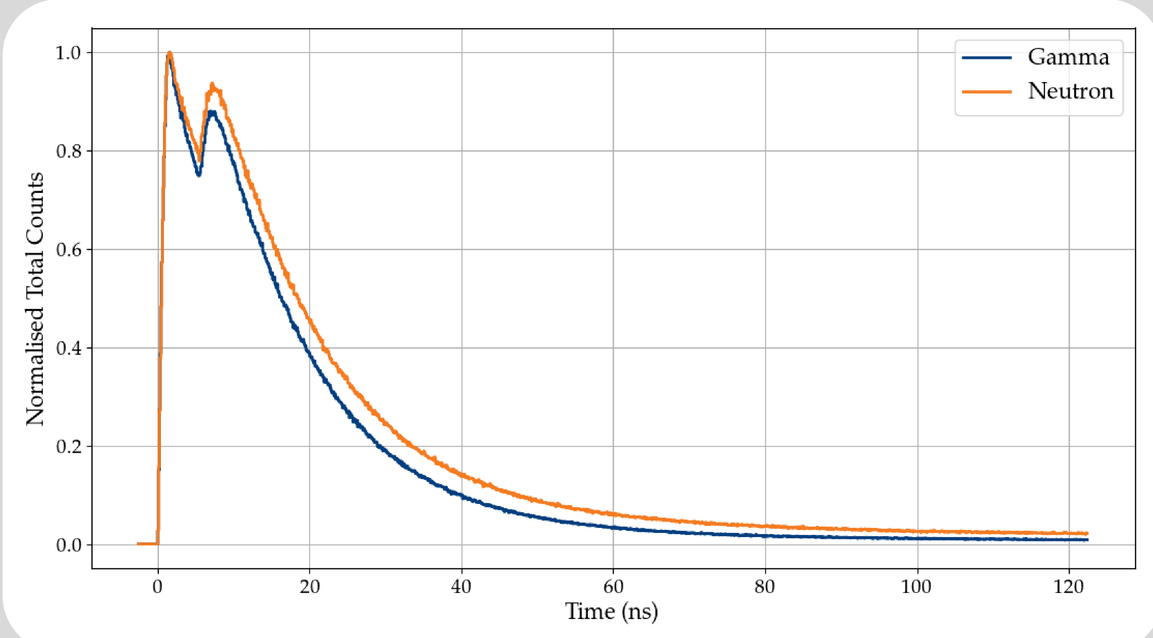

Figure 3. Detected pulse shape for scintillator cube with 1m side length with directional effects. Reflection model includes both specular and diffuse reflections. Pulses are averaged from 5000 events to show features hard to decipher from low statistics.

Realistically a 1m cube of plastic scintillator is not very feasible. Therefore smaller sizes were modelled and the directionality effect was observed to occur in the rising edge. Comparing increasing sizes shows a shift in the decay, and due to increased time of flight, the convolution changes with size as shown in Figure 4.

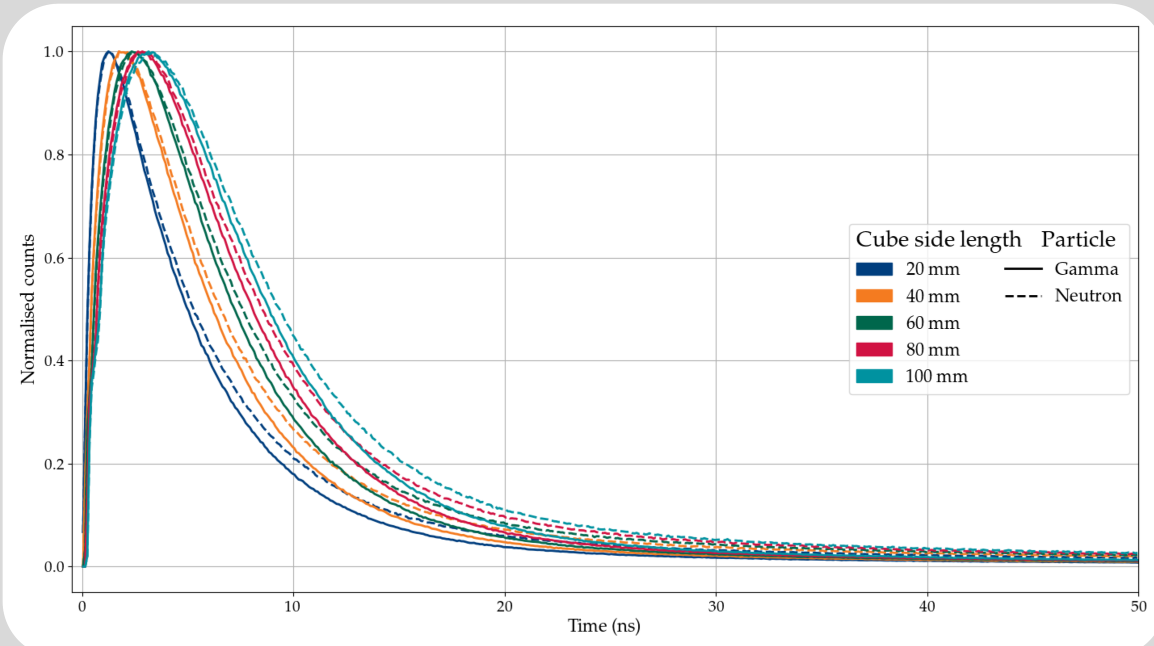

Figure 4. Detected pulse shape evolution with varying cube side length. The time of peak maximum increases with cube size, thus shifting the decay of the pulse.

Pulse Shape Discrimination

To perform pulse shape discrimination (PSD) on simulated data the arrival time at the photodetector is used to fill histogram creating a pseudo pulse shape, i.e. a pulse without any further convolution from the detector readout. From this, a PSD discrimination parameter is calculated. The Charge Comparison Method was used for this analysis and is defined in Equation 2.

$$\mathrm{CCM} = 1 - Q_s/Q_l$$

Equation 2. CCM parameter definition. Where Q_l is the long gate integral (area under the whole pulse) and Q_s is the area under a region at the start of the pulse to a defined point.

The PSD parameter and long gate integral is then used to fill a 2D histogram and a projection is made to show separation between two regions belonging to different pulses. The figure of merit (FoM) is calculated which shows how well the two types of pulses are separated, this is shown in Figure 5.

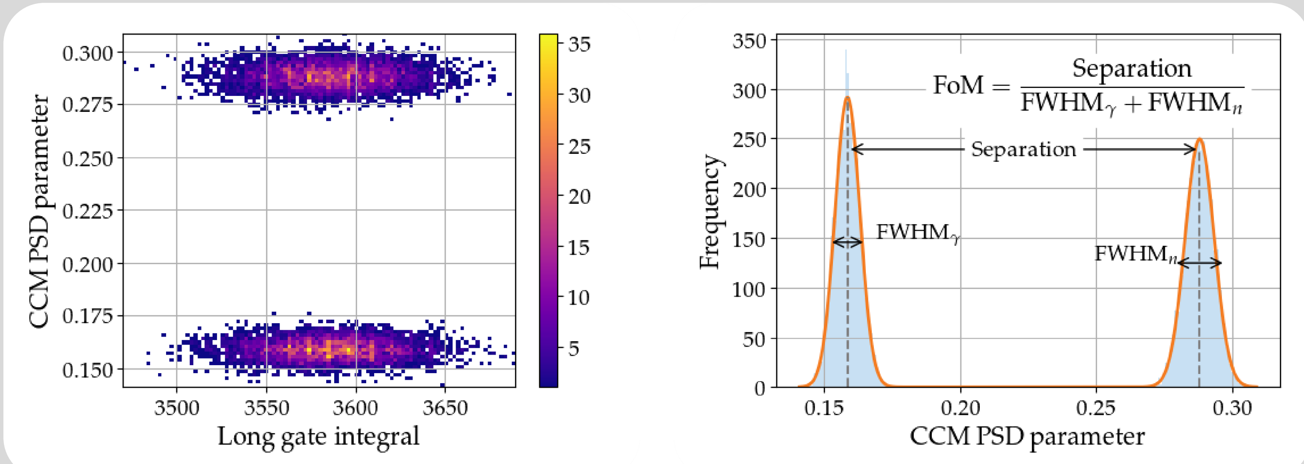

Figure 5. The PSD parameter is used to populate a 2D histogram. Then projections of the y-axis are made at different energies. From here the Figure of Merit (FoM) is calculated, which gives a distinction between the two particles. A FoM of 1.27 and above indicates good separation.

Different cube sizes were simulated and the FoM compared (Figure 6). This shows a decrease in FoM which is seen experimentally with increasing scintillator size. The cause is shown in Figure 7, where the parameters in the denominator have a larger percentage increase leading to a decrease in FoM.

$$\mathrm{FoM}\downarrow = \frac{\mathrm{Separation}\uparrow}{\mathrm{FWHM}_\gamma\uparrow + \mathrm{FWHM}_n\uparrow}$$

Equation 3. Cause of FoM decrease due to a larger increase in the denominator.

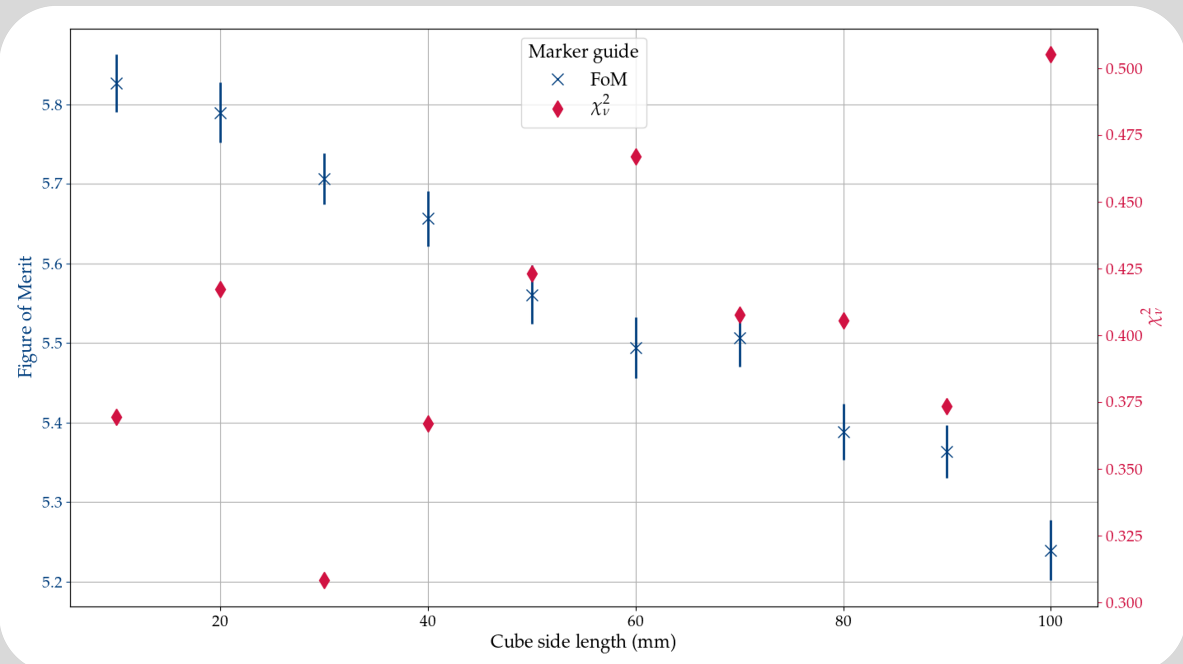

Figure 6. FoM decreasing with increasing cube sizes. The reduced chi-square statistic is used to determine how well the double gaussian fit is applied to the data for use in FoM calculations. The value is less than 1 indicating overestimated analytical uncertainties.

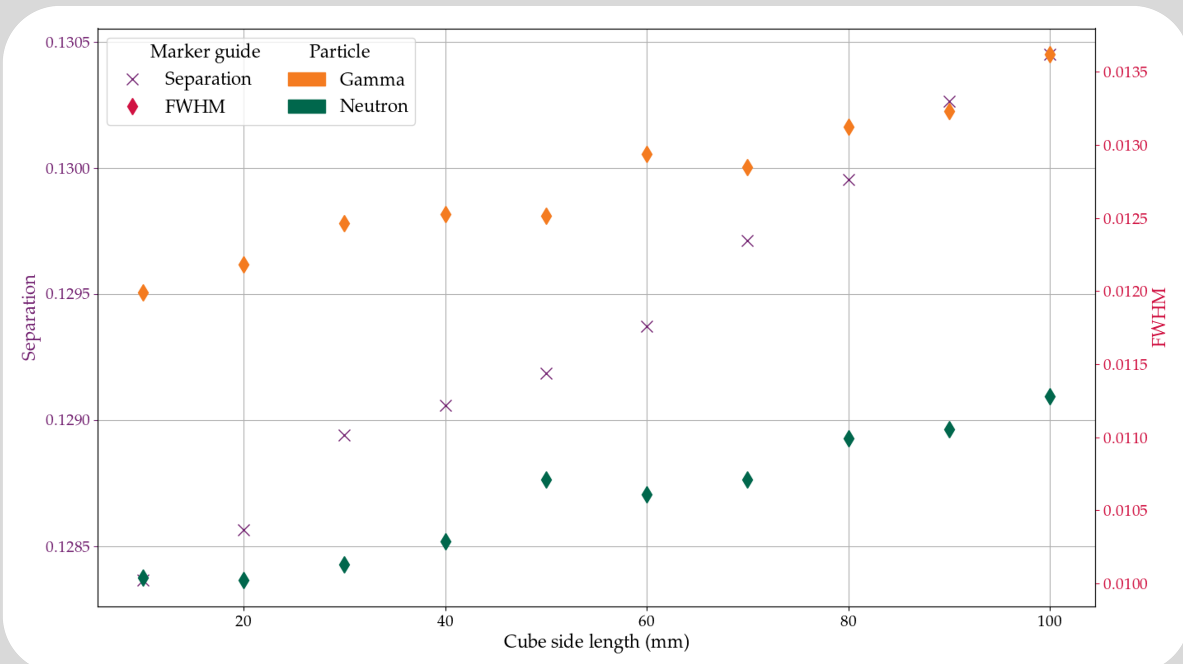

Figure 7. The individual components in the FoM calculations dependence with increasing cube size. The FWHM show ~10% increases whereas the separation only has ~2% increase. Leading to an overall decrease in FoM as seen in Equation 3.

Summary & Outlook

These early simulation results show promise for the cause of PSD diminishing with increasing scintillator size due to changes in certain parameters. The simulation model will need to be experimentally validated. This will then allow for further simulations to have merit. Further geometries and different photodetector configurations will be tested to see if the directionality has an impact on their PSD performance.

References:
[1] J. Allison et al. Nucl. Instrum. Meth. A **835** (2016) 186-225
[2] Z. S. Hartwig, P. Gumplinger. Nucl. Instrum. Meth. A **737** (2014) 155-162
[3] J. Iwanowska-Hanke et al. JINST **9.06** (2014) P06014

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