Optimising Detecting Geometry for Improved Pulse Shape Discrimination Performance in Plastic Scintillators

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Abstract*—Pulse Shape Discrimination (PSD) is a technique used extensively for the detection and analysis of neutron emissions in mixed fields of ionising radiation. Extensive work has been carried out on optimising PSD through improvements in digital signal processing, however few works focus on the physical geometry of the detection medium and how this influences discrimination. This work uses GEANT4 to model the ratio of energy deposition from incident gamma and neutron isotropic radiation fields (100 keV – 10 MeV range) in a series of EJ276 plastic scintillator geometries. The general shape types simulated are cylindrical and conical geometries in a series of dimensions. Simulated results indicate that over the specified energy range (100 keV – 10 MeV) and the series of volumes simulated, conical volumes displayed a higher percentage of optical photon energy being absorbed from neutrons than γ-rays, than for comparable cylindrical detector volumes. Conical geometries have shown more than double the neutron--γ-ray efficiency over cylindrical volumes for 10 MeV particles. Though modest, this difference would stimulate greater production of optical photons with a slower decay times which enhance the ability of digital signal processors to discriminate between the signals produced by the γ -rays and neutrons.

***Keywords* — Pulse shape discrimination, neutron detection, Monte Carlo simulation.**

I. Introduction

PULSE shape discrimination (PSD) is a technique that is used for the analysis of mixed neutron-gamma fields. PSD uses electronics to distinguish between optical photons produced by neutron interactions from those of γ-ray interactions within a detection media, typically an organic scintillator. Photons produced by neutrons in organic scintillators have a longer decay time than those produced by gamma-rays. Adding a mix-field analyser (MFA) to the back-end electronics can separate the pulses generated in the photomultiplier tube based on the difference in decay times, and as such be able to discriminate the gamma-rays and allow analysis of the identified neutrons.

To improve the performance of PSD, the majority of works have focused on the development and refinement of the pulse processing circuitry, this has included, the digitization of pulse signals, increasing the sampling rate of counters and MFAs, and development of real-time pulse shape systems, [1]–[3] are examples. Other areas of work include the optimization of the organic scintillator media and the search for materials with more optimal PSD properties [4], [5].

One area that is largely overlooked is the geometry of the detection medium. The size and geometry of the detection volume impact both the chance of incident radiation being detected and the time it takes for the produced optical photons to reach the photocathode. Given the different mechanisms of interaction between neutrons and γ-rays, and the difference in associated decay times, it seems prudent to investigate the detection volume geometry and how it could affect the discrimination in the recorded pulses produced by the two radiation types. Furthermore, compared to the cost of developing and purchasing new electronics, which may include new components, manufacturing processes, and development of firmware, changing the shape of the scintillator volume would be simple and relatively low-cost.

There are a small number of works that show the effect of detector geometry on the PSD performance. It has been shown that despite an overall drop in detection efficiency, a conical volume, or a truncated conical volume, has an increased separation and resolution between the neutron and γ-ray peaks, characterized by the *Figure of Merit* (FoM) value [6], making discrimination of γ-rays events more readily. Further, work on the light collection efficiency of simulated EJ200 scintillators also reached a similar conclusion, that conical detectors offer improved in energy resolution over cylindrical volumes, particularly at lower particle energies (<500 keVee) [7]. Experimental results of trans-stilbene scintillators have shown that conical volumes can have a 22.6 % increase in the FoM value in the 25-100 keVee range, and over 10% improvement in FoM values up to 500 keVee, which is the energy range where discrimination between neutron and gamma events is most difficult [8]. The authors again note, the loss in overall detector efficiency of conical volumes over cylinders (upwards of 65 % loss), primarily due to the lower volume for cones when the base-radii are the same.

Despite these encouraging results there has been little apparent adoption in the use of conical detector volumes commercially. As such, there is scope to further investigate the area of research and to promote a relatively simple, cost-effective means of improving neutron-γ-ray pulse shape discrimination This could have significant impact on the activities in in the nuclear sciences where rapid and accurate measurement of neutrons is critical.

II. METHODS

To evaluate the influence of the geometry on detection characteristics of a scintillator for neutron and gamma-rays, two basic shapes where chosen: cylinder and cone. These were chosen based on the results of previous studies on detector geometry referred to above. Within those two geometries the respective radii and height were varied to create a total of 52 detectors, with radii varying between 2 – 3.5 cm and the height varying between 1 – 7 cm. Fig 1 shows a simplified 3d representation of the geometries studied for comparative purposes.

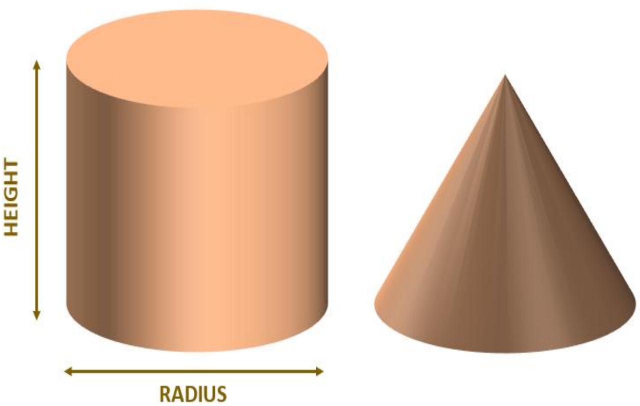

Fig 1. 3-dimensional representation of the main two geometries studied. The dimensions range for the height and radius was 7 cm – 1 cm, for each main geometry types.

The Monte Carlo code GEANT4 was used to simulate the detector and source environment. The scintillation volume was assigned material and optical properties consistent with the EJ276 plastic scintillator, one of the more newest plastic scintillators [9]. Each detector had a simulated 200 nm thick KCsSb bialkali photocathode, with 2 mm thick aluminium housing surrounding the scintillator, photocathode, and photomultiplier (PMT). The size of the photocathode was varied to be the same as the radius of the scintillator being used. A cross-section schematic of the setup is shown in Fig 2.

For the source, mixed n/γ fields were simulated as planar sources, located 20 cm from the detector surface, with measurements taken at varying angles along the XZ plane, from 0° to 90°, where 90° is perpendicular to the height axis (Z axis). Fig 3 shows the visual representation of the simulated source interacting with the detection volume along the three source angles. The energy of the source was varied between 0.1 to 10 MeV, to simulate the board energy spectrum found in complex decommissioning environments, such as those found at Sellafield and Fukushima.

For this study, the measurement of interest was the energy deposited in the KCsSb photocathode by optical photons produced in the scintillation volume. The energy deposited for both neutron and gamma-rays was recorded and the ratio of the two used as the metric to compare the different geometry types (taken as the percentage neutron to γ-ray).

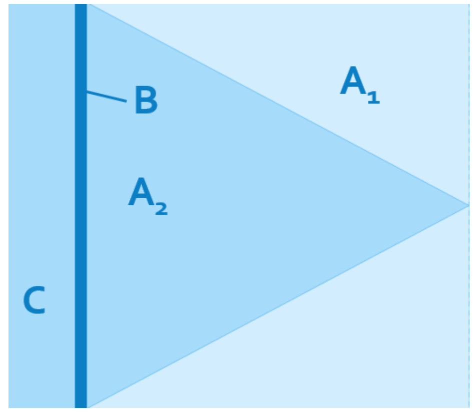

Fig 2. Cross section schematic of the detector (A1/A2 cylinder/cone) EJ276 scintillation volume, B K2CsSb Photocathode, C Photomultiplier Tube. (NOT TO SCALE). 5 mm Al casing not shown.

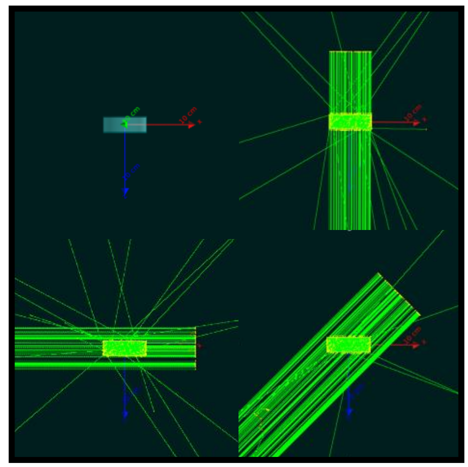

Fig 3. GEANT4 GUI of 7 cm radius, 2 cm height EJ276 detector with sources placed at 0° (top right), 45 ° (bottom right), 90 ° (bottom left) in the XZ plane. Run with and example 100 particles for illustration.

III. RESULTS AND DISCUSSION

Figure 4 shows data taken for the absolute energy deposited in the photocathode of the 7 cm diameter EJ276 volume from optical photons arising from the 10 MeV neutrons and γ-rays. Firstly, it is apparent from the data the absolute optical photon energy deposited by neutrons and γ-rays in the photocathode is higher for the cylindrical geometry. This is because the volume is 3x larger than the comparable cone volume. Secondly, as the detector height decreases the energy deposited in the photocathode reduces, for both geometries and particle types. This is expected as there is less volume for interactions between particle and scintillator to occur. This is consistent with previous works investigating the detector geometry [6]–[8].

However, the rate at which the reduction in energy deposited occurs is not the same for all particle types. Given that the rate of change between the volume and surface area of the different height detectors is the same for the particles, the reason for the disparity in rate change is most likely due to the inherent physical interactions between the particle types have with the varying sized detectors. Specifically, that the chances of interaction of γ-rays reduces more rapidly than the possibility of the neutrons interacting, therefore a higher proportion of energy in the photocathode will come from the neutron interactions. This could result in better rates of light collection efficiency and improve PSD performance.

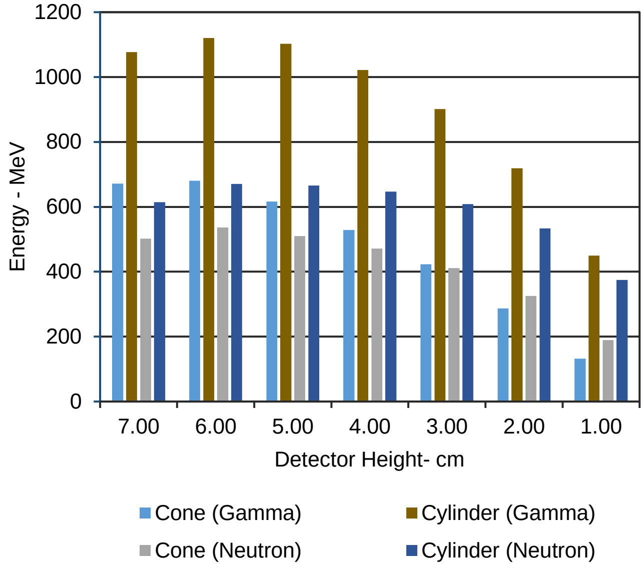

Fig 4. Comparison of the absolute optical photon energy being deposited in the photocathode for the different particle types in the different geometries (10 MeV particle energy, 2 x 10^5 particles, in 7 cm base diameter detection volumes).

As such, the greatest disparity in the n/γ energy deposited is seen at the extreme ends of the geometries, either large radius-small height volumes or *vice versa*. Specifically, in **Error! Reference source not found.**, the amount of energy deposited from optical photons produced by neutron interactions in the 2 cm and 1 cm radii conical detectors is greater than that for the γ-rays, which is not the case for the larger heights. This could be that as the cross-sectional area of the detector decreases relative to the angle of incidence, the 10 MeV γ-rays are more likely to pass through the low Z-number EJ276, rather than interact, with the detection medium. Whereas neutrons of the same energy have more favourable interactions with low Z-number materials, even at higher energies [10].

Figure 5 provides further evidence of this, showing a comparison of the average n/γ ratio for conical and cylindrical volumes, with each data point representing the average n/γ ratio recorded for the volumes with 7 cm base diameters for a given source energy and source angle. The black dashed line denotes the 1:1 ratio, which would imply both geometry types produced and absorbed the same ratio of optical photons for the particle types. However, all the values presented fall below this 1:1 ratio, with higher ratios produced in the conical volumes relative to that of the cylindrical geometries. As such, it is apparent that, over the energy range (100 keV – 10 MeV), particle angle, and the range of volumes simulated, conical volumes displayed a higher proportion of optical photon energy being absorbed in the photocathode from neutrons than γ-rays, when compared to the cylindrical volumes.

The highest discrimination rates occur for each of the simulated particle energies occurs when the angle of incidence is 0 degrees, i.e. with the particles hitting the face of the detector along the Z axis (see the top right image in Figure 3). This data supports the hypothesis above,

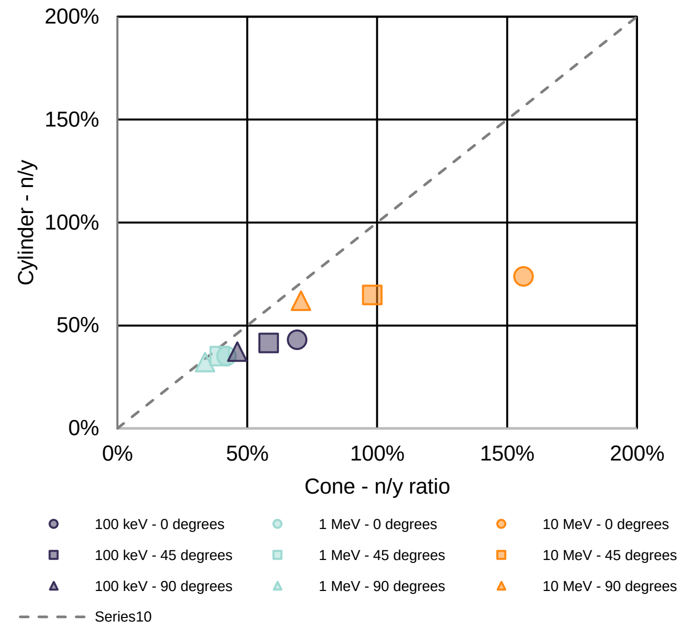

Fig 5. Average ratio of the optical photon energy reaching the photocathode from neutrons vs. γ-rays across volumes with a 7 cm base diameter (varying detector height).

In contrast, when the particles enter the detector along the X plane, i.e. at 90 degrees, they still have to pass through a significant distance within the detector volume. In the case of Fig 5, this could be up to 7 cm, for both conical and cylindrical geometries. As such, the chances of interaction are similar between the two, hence the data point for this being closer to 1:1, though still marginally in favour of the comical geometry.

Figure 6 shows this relationship more clearly. The figure represents the data points from Figure 5 taken as the cone-to-cylinder ratio values. These have then been plotted against the respective source angle at which they were generated. The highest value recorded is for the 10 MeV energy particles entering the detector at 0° degrees. For this simulation the conical detector had over 2.11 times the discrimination of neutrons over γ-rays. At 100 keV and 1 MeV there was 1.51 and 1.15 the discrimination, respectively.

This is an interesting point; that at lower particle energies the conical detectors show improved discrimination relative to cylindrical volumes, but as the particle energy increases the ratio trends toward unity. Beyond a certain energy, this trend reverses and conical detectors demonstrate a higher proportion of γ-ray discrimination, particularly as particle energy approaches 10 MeV. This is of potential relevance to cosmological detector design, given the higher particle energies typically observed in the field.

These findings are consistent with the previous work in this area. As discussed above, Sosa et al. (2019) noted the improved energy resolution and FoM values for 500 keVee particles in trans-stilbene conical detector volumes, and the values presented in **Error! Reference source not found.** and 6 are consistent with this finding [8]. The authors also showed how the improvement reduces as the incident particle energy increases toward 1 MeV, again consistent with the finds here.

However, though Begin et al (2006) reported an overall increase in the FoM values for a conical BC501A scintillator volume over a similar dimension cylinder, they reported that the neutron efficiency to γ efficiency ratio was worse [6]. The authors only simulated a single source angle and one single geometry volume for the cylinder and cone respectively. Also, the neutron-γ-ray efficiency over different energies was not presented. As such, direct comparison must be understood with these factors in mind.

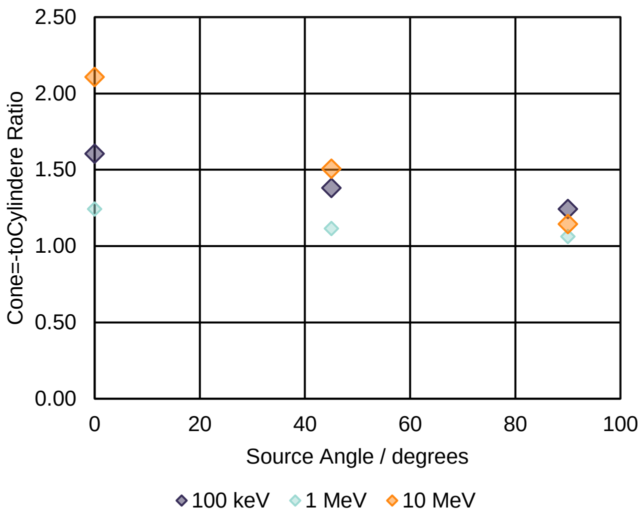

Figure 6. The data points from Figure 5 taken as the cone-to-cylinder ratio of the n/γ proportions at the different source angles.

Whilst the results presented here appear consistent with similar, prior studies, there remains a significant amount of work to fully validate the hypothesis that conical geometries offer improve PSD performance. Firstly, to study a wider range of geometries such that more representative comparisons to previous work can be made. Most important will be to study the timing characteristics of the optical photons as this is the fundamental basis for neutron-γ-ray pulse shape discrimination. Principally, what effects the internal geometries of the conical volume will have on temporal aspects, relative to cylindrical volumes. Additionally, the radioactive sources modelled here are not fully representative of real-world decommissioning environments. As such, it would be prudent to conduct these simulations with more complex radiation fields.

IV. Conclusions and Further Work

The results of the simulations presented here show that a higher proportion of energy reaching the photocathode from optical photons arises from neutrons rather than γ-rays of the same energy in conical over cylindrical geometries. This is seen when the detection volumes have the same height and radius; this observed over all simulated particle energies and source angles simulated.

The highest rates of discrimination seen in the extreme ends of the energy ranges studied, e.g. 10 MeV and 100 keV particles, with the 7 cm radii conical volume having 2.11 better neutron-γ-ray efficiency that the same radii cylindrical detector. The least difference between the two geometry types was for the 1 MeV particles. These findings are consisted with prior studies on detection volume geometry.

To make these conclusions more robust, follow-on work will include: a study of the timing of the optical photon pulse produced in the different detector geometries; simulating more complex radioactive source environments; and validating the simulated results with experimental measurements.

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