Characterisation of a pixelated plastic scintillator for a coded aperture neutron/gamma imaging system

Michal J. Cieslak*[1] and Kelum A.A. Gamage[2]

[1]Department of Engineering, Lancaster University, Lancaster LA1 4YW, UK
[2]School of Engineering, University of Glasgow, Glasgow, G12 8QQ, UK

21st November 2018

Abstract

This paper experimentally investigates, the suitability of an organic pixelated plastic scintillator for a coded aperture neutron/gamma imaging system. The scintillator used in this study has been designed as a small scaled detector with an individual pixel size of 2.8 mm x 2.8 mm x 15 mm. Individual blocks of the scintillator have been separated from one another with ESR^{TM} reflector foil to provide over 70% of optical isolation between pixels. Individual scintillator cells are arranged into 13x13 array with overall dimension of 39.52 mm x 39.52 mm. In this study the scintillator was attached to a single channel photomultiplier tube to assess its pulse shape discrimination capabilities. Initially the scintillator was irradiated with ^{137}Cs gamma-ray source, and gamma-ray pulses were benchmarked with respect to a mathematical model. The detector was then irradiated with a spontaneous fission source, ^{252}Cf, and preliminary results suggested good pulse shape discrimination potential of the scintillator. It is believed, that it is the first time a small scale pixelated organic plastic scintillator has been tested in context of PSD capabilities for a coded aperture neutron/gamma imaging system.

1 Introduction

For decades organic liquid scintillators have been established as the preferred choice in the field of fast neutron detectors, based on Pulse Shape Discrimination (PSD) methods for mixed-filed characterisation applications [1, 2]. Fluorescence emitted as a result of particle (neutron or gamma-ray photon) interaction within the organic medium scintillator is proportional to the rate of energy decay of the interacting particle. The fluorescence can be detected by a dedicated photodetector, such as photomultiplier tube (PMT). Interactions detected on the PMT cathode can be further processed to perform particle separation based on the shape of the generated pulses [3].

Numerous characterisation studies of organic liquid scintillators have been performed in the past [4–6]. Despite their proven PSD capabilities, organic liquid scintillators have been reported to be flammable and prone to leaks [7]. Such characteristics make them not suitable for harsh decommissioning or security environments.

In recent years significance of the organic solid scintillators has been steadily growing, owing to their continuously improving PSD performance and less hazardous characteristics. Even though PSD performance of plastic scintillators was deemed inferior to liquid counterparts in the past [8], recent findings present a comparable performance of the latest organic plastic scintillator (EJ-276) and one of the most widely used liquid detectors – EJ-309 [9].

Up to now, coded aperture neutron imaging systems utilising organic scintillators (liquid and plastic) comprise scintillator blocks of relatively large dimensions [10], [11]. Further information related to coded aperture imaging can be found in authors' preceding work [12].

In this study a small scale pixelated plastic scintillator (pixel size: 2.8 mm x 2.8 mm x 15 mm) has been characterised with regards to its neutron/gamma separation performance. The scintillator was irradiated with gamma-ray photons from a ^{137}Cs source, and the recorded pulses compared with a mathematical model of a gamma-ray pulse. Further, the scintillator was exposed to ^{252}Cf spontaneous fission source and results obtained were compared with the characterisation results of a single block (25.4 mm x 25.4 mm) cylindrical PSD

---

*m.cieslak@lancaster.ac.uk

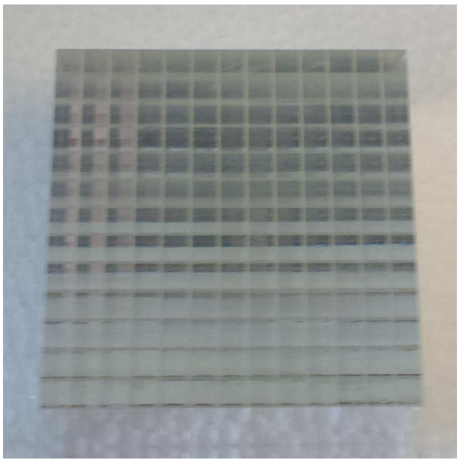

Figure 1: Solid organic plastic scintillator (EJ-299-34).

plastic scintillator.

2 Methodology

Pixelated plastic scintillator (Fig. 1) was coupled to a single channel ET Enterprises 9107B bialkali type PMT and placed in a cylindrical light-proof box made of Al. The complete assembly was then exposed for 10 minutes to ^{137}Cs gamma-ray source and a number of pulses recorded using 4 GS/s high accuracy oscilloscope. Following that the assembly was exposed for 30 minutes to ^{252}Cf source located at Lancaster University, Lancaster, UK. The oscilloscope was replaced with a customised FPGA based 12-bit 150 MS/s digitising system to allow for real-time neutron/gamma discrimination.

The spontaneous fission source ^{252}Cf is stored in a centre of a steel tank filled with water in order to modulate the neutron field around. When required, the source is pneumatically release to the edge of the water tank. The source however, is still approximately 20 cm away from the edge of the water tank. Therefore, the actual distance between the detector front and the source is approximately 35 cm. Furthermore, because of the water and steel interactions before reaching the detector, the neutron energy spectrum measured at the detector approximates the average energy to 0.7 - 0.8 MeV [12].

3 Results

One of the pulses recorded with the oscilloscope, as shown in Fig. 2b, has been compared to the mathematical model shown in Fig. 2a. Since the recorded pulse resembles the expected shape closely, particularly for the region where neutron/gamma separation sensitive, it suggests the pixelated scintillator is capable of producing a pulse that is proportional to the rate of the energy loss of the interacting particle; despite the small size of the individual blocks and the separation between adjoining blocks of 0.24 mm.

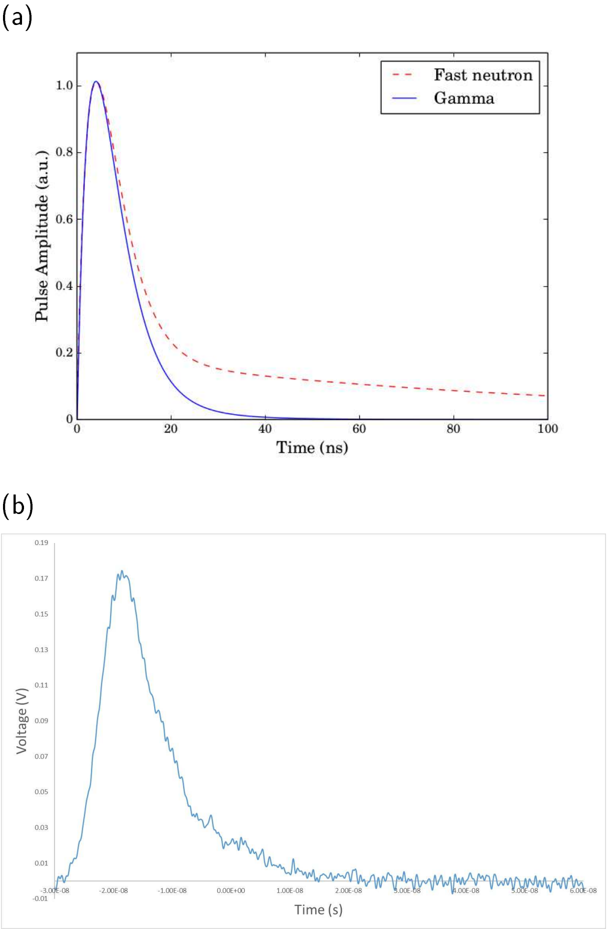

Figure 2: A comparison of a) A mathematical model of gamma-ray photon and neutron induced pulses from organic scintillator, b) A recoded gamma-ray pulse from ^{137}Cs.

Following that, oscilloscope was replaced with the customised digitiser system, which was previously used to compare the performance of three solid organic scintillators [14]. Charge comparison method (CCM) was used to discriminate between neutron and gamma-ray events [3]. As shown in Fig. 2, the difference between the two particle types can be observed through the different rate of the tail of the pulse. Therefore, the area between the peak sample and the last detected sample have been investigated. Long integral corresponds to integral calculated over the entire pule tail (the peak sample is used as the first sample), whereas the short integral was calculated between a specific point after the peak sample and the last sample of the signal.

The same experimental set-up and method were used to collect the data for both experiments. The scintillator and PMT assembly was placed 15 cm away from a water-filled steel tank where ^{252}Cf source is normally stored. During the experiments the source is pneumatically released to the edge of the tank. In order to reduce the number of gamma-ray photons a Pb block of 5 cm thickness was placed adjacent to the water tank. PSD scatter plots produced during both experiments are presented in Fig. 3a and Fig. 3b.

The figure-of-merit (FOM), as defined in Eq. (1), was calculated for the pixelated scintillator and compared with the FOM figure previously obtained for the cylindrical plastic scintillator sample (Table 1). In line with the visual analysis of the respective figures, it can be noticed that the cylindrical scintillator sample provides slightly better neutron/gamma discrimination performance at the cost of neutron detection efficiency. The results presented suggest that the small scale pixelated plastic scintillator should be capable of performing neutron/gamma separation based on pulse shape analysis.

$$FOM = \frac{Peak\ separation}{FWHM_g + FWHM_n} \tag{1}$$

Table 1: FOM calculations for each scintillator

Scintillator	Exposure time	FOM
Cylindrical Sample	30 min	0.551
Pixelated (EJ-299-34)	30 min	0.337

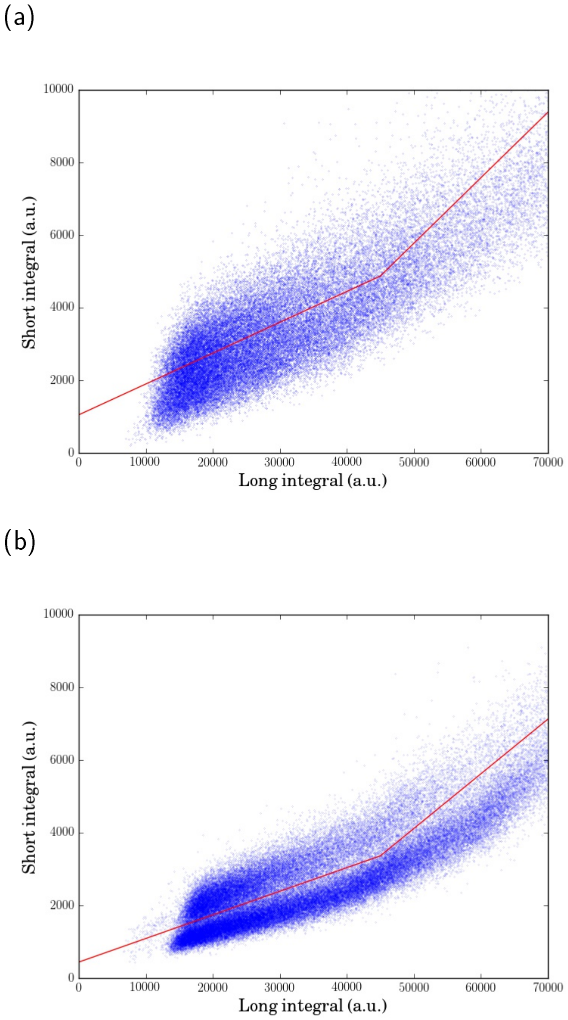

Figure 3: PSD scatter plots using CCM for: a) Pixelated EJ-299-34 plastic scintillator, b) Cylindrical PSD plastic sample.

4 Conclusions

Small size of an individual scintillator blocks could be perceived as a concern, when used as a sensitive detector neutron/gamma identification application. Small volume of the blocks could affect the interaction probability of the incoming particles. However, the shape of the pulses obtained (Fig. 3) and lack of pulse pile-up suggest that not only the correct signal from individual pixels can be extracted, but also the pixel separation is sufficient for cross-talk reduction.

Experiment performed with ^{252}Cf supports the claim that despite the small pixel size, the proposed sensitive detector is capable of performing PSD. It should be noted that the pixelated array was manufactured in August 2017, before the latest plastic scintillator EJ-276 was released by Eljen Technology. Based on the recently published work of characterising EJ-276 (replacement for EJ-299-33/34), it is expected that similar array built with this new material would significantly improve PSD performance of the system tested in this paper [9].

Moreover, the presented scintillator could be matched to a position sensitive PMT (PSPMT), such as Hamamatsu H9500, to perform localisation of the particle interactions. Based on previously performed simulation work, it is believed that such system be capable of simultaneous neutron/gamma 2D imaging [15]. Moreover, because of the identical pixel size of the scintillator and cells of the PSPMT, the optical bond should be improved, and as a result the quality of neutron/gamma-ray separation.

Further, as shown in Fig. 3a it is very difficult to distinguish between the neutron and gamma-ray plumes. It is expected that low sampling rate of the FPGA based digitiser can be insufficient for good neutron/gamma-ray separation. Previous study performed with 250 MS/s digitiser suggests the PSD quality improvement when the sampling rate is increased to 500 MS/s [16]. Therefore, it would be advisable for any readout electronics or further testing equipment to operate at 500 MS/s.

Water and steel modulation, experienced by many produced particles, will also contribute to the lack of clarity in regard to plumes' separation in Fig. 2a. The quoted 0.7-0.8 MeV average neutron energy is considerably lower than that of the expected 2.1 MeV. The plastic scintillator EJ-299-34, which was used in the study, is more suitable for block machining than EJ-299-33 at the cost of poorer PSD performance. Previous study has shown that EJ-299-34 is capable of performing good PSD with higher average neutron energy sources (>1 MeV), such as AmBe [17].

Acknowledgment

The authors would like to acknowledge the funding support from EPSRC via Faculty of Science and Technology, Lancaster University, U.K. and Sellafield Ltd.

References

[1] Anthony Lavietes, Romano Plenteda, Nicholas Mascarenhas, L. Marie Cronholm, Michael Aspinall, Malcolm Joyce, Alice Tomanin, and Paolo Peerani. Development of a liquid scintillator-based active interrogation system for LEU fuel assemblies. *2013 3rd International Conference on Advancements in Nuclear Instrumentation, Measurement Methods and Their Applications, ANIMMA 2013*, pages 6–9, 2013.

[2] Jonathan S. Beaumont, Tae Hoon Lee, Mikhail Mayorov, Carlo Tintori, Francesco Rogo, Bruno Angelucci, and Matteo Corbo. A fast-neutron coincidence collar using liquid scintillators for fresh fuel verification. *Journal of Radioanalytical and Nuclear Chemistry*, 314(2):803–812, 2017.

[3] F.D. Brooks. A scintillation counter with neutron and gamma-ray discriminators. *Nuclear Instruments and Methods*, 4(3):151–163, April 1959.

[4] M. D. Aspinall, B. D'Mellow, R. O. Mackin, M. J. Joyce, Z. Jarrah, and A. J. Peyton. The empirical characterization of organic liquid scintillation detectors by the normalized average of digitized pulse shapes. *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 578(1):261–266, 2007.

[5] K A A Gamage, M J Joyce, and N P Hawkes. A comparison of four different digital algorithms for pulse-shape discrimination in fast scintillators. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 642(1):78–83, 2011.

[6] Tomasz Szczęśniak, Marek Moszyński, Agnieszka Syntfeld-Kazuch, Świderski, Dariusz Wolski, Martyna Grodzicka, Guntram Pausch, Juergen Robert Stein, Frans Kniest, Michael R. Kusner, Paul Schotanus, and Chuckn Hurlbut. Light pulse shapes in liquid scintillators originating from gamma-rays and neutrons. *IEEE Transactions on Nuclear Science*, 57(6 PART 2):3846–3852, 2010.

[7] F. Pino, L. Stevanato, D. Cester, G. Nebbia, L. Sajo-Bohus, and G. Viesti. The light output and the detection efficiency of the liquid scintillator EJ-309. *Applied Radiation and Isotopes*, 89:79–84, 2014.

[8] S. A. Pozzi, M. M. Bourne, and S. D. Clarke. Pulse shape discrimination in the plastic scintillator EJ-299-33. *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 723:19–23, 2013.

[9] N. P. Zaitseva, A. M. Glenn, A. N. Mabe, M. L. Carman, C. R. Hurlbut, J. W. Inman, and S. A. Payne. Recent developments in plastic scintillators with pulse shape discrimination. *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 889(February):97–104, 2018.

[10] Christopher V Griffith, Richard S Woolf, and Bernard F Phlips. 64-Element Fast-Neutron, Coded-Aperture Imager. *IEEE International Symposium on Technologies for Homeland Security (HST)*, pages 1–5, 2017.

[11] Paul Hausladen. The Deployable Fast-Neutron Coded- Aperture Imager : Demonstration of Locating One or More Sources in Three Dimensions. 2013.

[12] Michał J. Cieślak, Kelum A.A. Gamage, and Robert Glover. Coded-aperture imaging systems: Past, present and future development – A review. *Radiation Measurements*, 92:59–71, 2016.

[13] Malcolm J. Joyce, Kelum A.A. Gamage, M. D. Aspinall, F. D. Cave, and A. Lavietes. A 4-channel multiplex analyzer for real-time, parallel processing of fast scintillators. *IEEE Nuclear Science Symposium Conference Record*, pages 134–138, 2012.

[14] Michal J. Cieslak and Kelum A.A Gamage. Comparison of Pulse Shape Discrimination Characteristics in Three Organic Scintillators for a High Resolution Coded-Aperture Neutron Imager. In *2016 European Nuclear Conference (ENC-2016)*, pages 306–309. European Nuclear Society, 2016.

[15] M. J. Cieślak, K. A.A. Gamage, and R. Glover. Investigation into a suitable scintillator and coded-aperture material for a mixed-field radiation imaging system. *Journal of Instrumentation*, 12(12), 2017.

[16] C. S. Sosa, M. Flaska, S. A. Pozzi. Comparison of analog and digital pulse-shape-discrimination systems. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 826(72-97), 2016.

[17] C. Payne, P. J. Sellin, M. Ellis, K. Duroe, A. Jones, M. Joyce, G. Randall, R. Speller Neutron / gamma pulse shape discrimination in EJ-299-34 at high flux.