Optimising A Compact Dual-Particle Imager with A Novel Combination of Organic and Inorganic Scintillators.

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Abstract

This work discusses the process of optimising the performance of a compact dual-particle imager with a fast response time of 60 s and a signal processing time of 60 s. The imaging concept relies on a radiation scattering technique with a neutron-scattering sub-system, a Compton-scattering sub-system and a thermal neutron absorption layer. The enhanced design proposed here reduces the signal processing time compared to earlier work. The time lagging occurs mainly during neutron-gamma discrimination within the neutron scattering sub-system. Hence, the optimisation here which mainly targets investigating two promising dual particle detectors EJ-212 and EJ-276D as possible replacement for the EJ-204 in the original device. The results indicated that EJ-212 and EJ-276D offer similar elastic scattering and escape probabilities of neutrons at energies less than 100 keV. At energies higher than 500 keV, the elastic scattering probabilities increase with thickness, reaching a maximum around 24% in both detectors. As for gamma-ray photons, the results showed that the two detectors have similar total mass attenuation coefficients. Further investigation showed that EJ-212 exhibits a higher Compton scattering cross-section with respect to EJ-276D. Additionally, results show that EJ-276D maintains the imager intrinsic efficiency while offering build-in neutron-gamma discrimination abilities.

Full Text

Preamble

Optimising A Compact Dual-Particle Imager with A Novel Combination of Organic and Inorganic Scintillators

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Abstract: This work discusses the optimisation of a compact dual-particle imager featuring a 60-second response time and 60-second signal processing time. The imaging concept relies on radiation scattering techniques comprising a neutron-scattering sub-system, a Compton-scattering sub-system, and a thermal neutron absorption layer. The enhanced design proposed here reduces signal processing time compared to earlier work, with the primary bottleneck occurring during neutron-gamma discrimination within the neutron scattering sub-system. The optimisation therefore focuses on investigating two promising dual-particle detectors, EJ-212 and EJ-276D, as potential replacements for the EJ-204 scintillator in the original device. Results indicate that EJ-212 and EJ-276D offer similar elastic scattering and escape probabilities for neutrons at energies below 100 keV. At energies above 500 keV, elastic scattering probabilities increase with thickness, reaching a maximum of approximately 24% in both detectors. For gamma-ray photons, both detectors exhibit similar total mass attenuation coefficients. Further investigation reveals that EJ-212 shows a higher Compton scattering cross-section compared to EJ-276D. Additionally, EJ-276D maintains the imager's intrinsic efficiency while offering built-in neutron-gamma discrimination capabilities.

Keywords: Neutrons; gamma photons; dual particle imagers; EJ-212 plastic scintillator; EJ-276D plastic scintillator.

1. Introduction

Localisation and characterisation of radiation sources and nuclear material is indispensable in many fields including counterterrorism, border security, nuclear industry, nuclear medicine, medical imaging, and molecular imaging [1]. With the reported increase in nuclear applications worldwide, particularly in the nuclear power industry, the need for fast, accurate, and portable imaging systems capable of localising radiation sources has become vital.

Several imaging systems offer accurate localisation and characterisation capabilities for single-mode radiation field emitters [1]. However, since the type of radiation emitted varies across sources and nuclear materials, mixed-field radiation detection has gained significant interest in recent years [1]. Sensitivity to both neutrons and gamma photons enables monitoring and identification of a wider range of radioactive sources and nuclear materials, such as Special Nuclear Materials (SNM) for radiation protection applications [2][3][4]. Yet, a key challenge in radiation imaging is developing a fast, accurate, compact, and portable system that can efficiently detect and accurately identify the origin of highly penetrating neutrons and energetic gamma photons emitted by SNM [1].

The main types of dual-particle imagers described in literature are pixelated detectors, coded aperture imaging systems, and multilayer scattering imaging systems [1]. Among these techniques, scatter imaging systems simultaneously offer the optimum combination of detection efficiency and spatial resolution, thus providing a wider application scope. While large imaging systems offer higher sensitivity and spatial resolution, their applications are limited by size [3][4]. Other portable systems are restricted to passive fast neutron-gamma imaging systems where a collimated radiation beam from a well-defined source is targeted [5], limiting both the imager’ s applications and sensitivity since only radiation from a selected direction reaches the detection medium. Several dual-particle imagers offer portability and a wider angular view, such as the CdZnTe-based imager by M. Streicher et al. [6], the stilbene organic scintillator system by Steinberger W. et al. [7], and the CLYC-6 imager by J. Lerendegui-Marco et al. [8]. However, some of these systems have confined energy ranges.

The portable dual-particle imager proposed in earlier work by the same authors consisted of three detector layers capable of simultaneously imaging thermal neutrons, fast neutrons, and gamma photons [9]. With a 60-second scan time, the imager could locate radiation sources with 15° angular resolution. While the system could analyse mixed radiation fields, longer processing times were required for pulse shape discrimination (PSD) analysis of neutron-gamma events in the chosen plastic scintillator, EJ-204 [9]. This limitation arises because pulses from EJ-204 exhibit a very fast decay time of 1.8 ns and very short pulse width of 2.2 ns [9][10]. This can be mitigated by selecting a material featuring a longer decay time or inherently better neutron-gamma discrimination abilities.

Unlike many other detector types, plastic scintillators offer flexibility in tailoring to required shapes or sizes, along with non-toxicity and non-flammability [11]. These features are highly desirable in a portable neutron-gamma imager. EJ-204 plastic scintillators have already been investigated for fast neutron scattering in dual-particle imagers [9]. According to literature, EJ-212 and EJ-276D can overcome the drawbacks of EJ-204 in the fast neutron scattering sub-system [12][13][14][15]. EJ-212 offers similar features to EJ-204, including a long optical attenuation length and an emission spectrum matching most common photomultipliers, but with a longer decay time of 2.4 ns compared to EJ-204 [16]. EJ-276D offers inherently superior neutron-gamma discrimination abilities due to its long slow decay time, reportedly hundreds of nanoseconds [14][15]. These features make both scintillators suitable replacements for EJ-204 in the neutron scattering sub-system of the novel compact dual-particle imager proposed in earlier work by the authors [9].

The objective of this study is to evaluate EJ-212 and EJ-276D plastic scintillators for their abilities to attenuate fast neutrons and gamma photons at different energies. These results will enhance the performance of the aforementioned dual-particle imager by replacing the plastic scintillator in the system. Additionally, the study aims to test the imager’ s performance by calculating the system’ s intrinsic efficiency using these two scintillators.

2.1 Imaging Concept

The imaging concept relies on radiation scattering techniques for both fast neutrons and gamma-ray photons using three detector layers separated by specific distances, as shown in Fig. 1 [Figure 1: see original paper].

In the original study by H. Al Hamrashdi et al. [9], the radiation imaging system consisted of a 10-mm Li-based glass detector (GS10) [17] optically coupled with a 20-mm plastic scintillator (EJ-204) [12] in the first layer. The GS10 captures thermal neutrons (neutrons with most probable energy of 0.025 eV) via the ^{6}Li(n,α)t thermal neutron capture reaction, while the plastic scintillator scatters fast neutrons (neutrons with energies higher than 1 keV). Scattered neutrons then interact with the GS10 glass detector in the system' s second layer. Both layers are backed with high fill-factor J-series SiPM sensor arrays (ArrayJ-30035-64P-PCB 8$×$8 SiPM, SensL, Cork, Ireland [8]) serving as photodetectors. Neutron interactions in the second layer are primarily attributed to capture reactions.

In this imaging system, a fast neutron undergoes elastic scattering with protons in the plastic scintillator of the first layer, followed by capture (or inelastic scattering) in the glass scintillator of the second layer. The scattering angles and incident trajectories can be calculated from the relative positions of detected pulses via the activated pixels in the SiPM array. The energy of an incident neutron equals the sum of the scattered proton energy in the plastic scintillator and the scattered neutron energy detected in the second GS10 glass scintillator [30,31]. These energies relate to the scattering angle θ through equation (1). The energy of the scattered neutron can be calculated using time-of-flight (TOF) measurements between the first and second layers, as shown in equation (2), where m_n is the neutron mass in kilograms and d is the distance in meters between the centers of the plastic scintillator in the first layer and the GS10 detector in the second layer.

For each neutron scattering event, the scattering position is determined from the pixelated SiPM with precision equal to the pixel size (3.07×3.07 mm^2). The scattered proton energy, scattered neutron energy, and scattering angle are then used to create a probability cone. The compound image formed by the probability cones (specifically their circular bases) from all successful scattering events reveals the fast neutron source location. A schematic of the neutron imaging sub-system is shown in Fig. 2 [Figure 2: see original paper].

Gamma-ray sources are imaged using Compton scattering techniques in the second and third layers of the imaging system [18]. The system design, particularly the first layer, ensures that gamma photons interact only in the second and third layers. Incident gamma photons in the Compton energy range (10 keV–10 MeV) undergo Compton scattering in the GS10 detector of the second layer. The interaction position and Compton electron energy are registered via the pixelated SiPM array in this layer. Scattered gamma photons then undergo the photoelectric effect in the CsI(Tl) detector of the third layer, with the scattered photon energy registered via the pixelated SiPM array as shown in Fig. 3 [Figure 3: see original paper].

Using the registered information from layers two and three, the scattering angle of the incident photon is calculated using the following equation:

$$\cos\theta = 1 - \frac{m_{ec}^2}{E_\gamma}\left(\frac{1}{E'} - \frac{1}{E_\gamma}\right)$$

where m_{ec}^2 is the electron rest mass in energy units. For each Compton scattering event, a probability cone is generated using the pixel location where the event was registered (cone apex) and the scattering angle (cone base). The intersection of all cones from successful Compton scattering events determines the gamma-ray source location. The incident gamma photon energy equals the sum of the Compton electron energy deposited in layer two and the scattered photon energy deposited in layer three.

2.2 EJ-212 and EJ-276D Plastic Scintillators

EJ-212 and EJ-276D scintillators share the same base composition of a polyvinyl toluene plastic matrix with fluors, with variations in this combination giving each scintillator its unique properties. Both scintillators investigated in this study are from Eljen Technology, where EJ-212 is equivalent to NE-102A and BC-400 commercial scintillators, and EJ-276D is equivalent to NE-142 and BC-452 commercial scintillators [12][13]. The scintillation output of EJ-212 is 10,000 photons/MeV e^-, slightly higher than EJ-276D at 8,000 photons/MeV e^-. The maximum emission wavelength is approximately 423 nm for EJ-212 and 425 nm for EJ-276D, both coinciding with the photon detection efficiency range of the Onsemi SiPM J-series array [19] used in this imager. In terms of material density, EJ-212 has a slightly lower density of 1.023 g/cm^3 compared to 1.099 g/cm^3 for EJ-276D. For neutron interactions with detector materials, light nuclei content greatly affects the interaction cross-section. EJ-212 is composed of 8.5% hydrogen and 91.5% carbon, while EJ-276D comprises 7.3% hydrogen and 92.7% carbon.

2.3 Means of Comparison and Calculations of Interest

Optimising this instrument involves maximising neutron elastic scattering probability while minimising neutron absorption. Each detector' s response was investigated at ten thicknesses (10, 20, 30, 40, 50, 60, 80, 100, 150, and 250 mm) and six neutron energies (1 keV, 10 keV, 100 keV, 0.5 MeV, 1 MeV, and 5 MeV). Gamma photon attenuation was investigated at eight energies (0.01, 0.025, 0.05, 0.1, 0.7, 1.0, 5.0, and 10 MeV), covering the typical range in radiation detection applications [1]. The total mass attenuation coefficient can be calculated using equation (4):

$$\mu_m = \frac{\mu}{\rho} = \frac{\ln(I/I_0)}{x}$$

where μ is the linear attenuation coefficient, ρ is the detector material density, I is the radiation intensity after passing through thickness x, and I_0 is the original incident radiation intensity.

To further investigate the detectors for SNM non-proliferation applications, Compton scattering cross-sections for both detectors at 25 mm thickness were determined at eight different energies. Lower Compton scattering probabilities verify the detector' s suitability to replace EJ-204 in the neutron scattering subsystem. The imager' s overall performance was examined with both candidate detectors, and intrinsic efficiency was calculated using a Cf-252 source.

The testing environment was simulated using the Geant4.11.1 simulation toolkit at room temperature (293 K) [20]. Cross-section data for fast neutron simulations are based on G4NDL libraries derived from multiple sources including ENDF/B-VII.0 and JENDL-4.0 [20]. Gamma simulations in Geant4 use Electromagnetic (EM) physics modeling based on the Livermore evaluated library [20]. Detector geometry follows the same configuration as the EJ-204 detector described in section 2.1.

3.1 EJ-212 and EJ-276D Neutron Attenuation Abilities

Simulation results for single elastic scattering efficiency and escape probability versus thickness for EJ-212 are illustrated in Fig. 4 [Figure 4: see original paper]. The elastic scattering probability trend varies across energies. At 5 MeV, elastic scattering probability peaks at 22% of total events around 60 mm thickness before declining. The peak shifts to smaller thicknesses at 1 MeV and 0.5 MeV. At 100 keV, 10 keV, and 1 keV, elastic scattering probabilities decrease with increasing EJ-212 thickness. A common trend across all neutron energies is the exponential decay of escape probabilities with thickness. However, the decrease is less rapid at 5 MeV and 1 MeV compared to lower energies (1 keV and 10 keV). For all energies, elastic scattering probability exceeds escape probability at thicknesses greater than 25 mm.

Similarly, single elastic scattering probability and escape probability for neutrons in EJ-276D were investigated, with results shown in Fig. 5 [Figure 5: see original paper]. The elastic scattering probability trend varies across energies, with both probabilities generally decreasing as thickness increases. At 5 MeV, elastic scattering probability peaks around 50 mm thickness before declining. The peak shifts to smaller thicknesses at 1 MeV and 0.5 MeV. As with EJ-212, elastic scattering probabilities decrease with increasing EJ-276D thickness at lower energies (Fig. 5a, b, c). All incident neutron energies show exponential decay of escape probabilities with thickness in EJ-276D. Like EJ-212, the decrease is less rapid at 5 MeV, 1 MeV, and 0.5 MeV compared to lower energies. Overall, at thicknesses greater than 25 mm, elastic scattering probability exceeds escape probability for all energies. Both detectors exhibit similar fast neutron attenuation capabilities.

3.2 EJ-212 and EJ-276D Gamma Photon Attenuation Abilities

Total mass attenuation coefficients between 0.01 MeV and 10 MeV were calculated using equation (4) for both EJ-212 and EJ-276D. Results were compared to NIST values (extracted using XCOM database 3.1 [9]) across this energy range, as shown in Fig. 6 [Figure 6: see original paper]. The results show good agreement with NIST mass attenuation coefficient values, which decrease with increasing gamma energy. Compared to values reported by H. Al Hamrashdi et al. [11], both detectors have similar mass attenuation coefficients to the widely used EJ-309 gamma-neutron detector, reflecting their suitability for gamma-ray imaging.

To further investigate the detectors' suitability for Compton scattering imaging systems, Compton scattering probabilities were studied as functions of incident energy, as shown in Fig. 7 [Figure 7: see original paper] (with both plastic scintillators fixed at 25 mm thickness). For both detectors, Compton scattering probability increases between 0.01 MeV and 0.05 MeV before gradually declining beyond this energy. EJ-212 generally shows higher Compton scattering ability than EJ-276D, with the maximum percentage difference of 11.4% recorded at 0.05 MeV, where both detectors exhibit their highest Compton scattering probability. This is attributed to the fact that Compton scattering probability decreases with increasing energy beyond 0.05 MeV [21]. Another relevant conclusion is that at any given thickness, EJ-276D produces fewer Compton scattering events than EJ-212, resulting in fewer gamma scattering events within this detector in the neutron scattering sub-system of the dual-particle imager.

3.3 Special Case Study: Testing New Configuration of a Dual-Particle Imaging System with EJ-212 and EJ-276D

EJ-212 and EJ-276D scintillators were investigated as potential replacements for EJ-204 in the dual portable particle neutron-gamma scattering system proposed by H. Al Hamrashdi et al. [9]. The imaging concept discussed in section 2.1 explains the neutron scattering approach and detection mechanism. Using Cf-252 with an average energy of 2.1 MeV as a neutron source, the intrinsic efficiency in the original system was found to be 6.1×10^{-3}. In this work, simulations were repeated using the same neutron source but with different scattering layers.

The intrinsic efficiency using EJ-212 was 5.9×10^{-3}, whereas with EJ-276D it was 6.1×10^{-3}. Compared to the reported value by H. Al Hamrashdi et al. [9], EJ-276D matched the fast neutron intrinsic efficiency of EJ-204, while EJ-212 showed slightly lower efficiency. Based on these results, EJ-276D offers advantageous features and is currently the most appropriate candidate to replace EJ-204 in the dual-particle imaging system.

4. Conclusions

This study enhanced the performance of a hybrid portable dual-particle imager by investigating EJ-212 and EJ-276D plastic scintillators as neutron scattering layers within its neutron scattering sub-system. Both candidates were tested for neutron and gamma attenuation abilities across wide energy ranges. The system' s overall intrinsic efficiency with both scintillators was investigated using Monte Carlo simulations with a Cf-252 fast neutron source. Results indicate both detectors share similar fast neutron scattering efficiencies, consistent with measured fast neutron intrinsic efficiencies. EJ-276D achieved an intrinsic efficiency of 6.1×10^{-3}, while EJ-212 achieved 5.9×10^{-3}. Compared to EJ-204, EJ-276D maintains the imager' s fast neutron detection efficiency while EJ-212 exhibits lower efficiency.

These results, combined with the reported built-in PSD abilities of EJ-276D, demonstrate that this detector is the best replacement for EJ-204 and will enhance the original processing time of the imager while maintaining its computationally and experimentally reported efficiencies.

Author Contributions: H. Al Hamrashdi designed this work, contributed to simulations, performed analysis, and wrote the initial draft. S. D. Monk and D. Cheneler participated in originating ideas and reviewing the draft. S. Al Ma' Amari worked on simulations.

Conflicts of Interest: The authors declare no competing interests.

Data Availability: All datasets generated or analysed during this study are available from the corresponding author upon reasonable request.

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References

[1] H. Al Hamrashdi, S. D. Monk, and D. Cheneler, "Passive gamma-ray and neutron imaging systems for national security and nuclear non-proliferation in controlled and uncontrolled detection areas: Review of past and current status," Jun. 01, 2019, MDPI AG. doi: 10.3390/s19112638.
[2] IAEA, "IAEA Safeguards," 2011.
[3] P. B. Rose, A. S. Erickson, M. Mayer, J. Nattress, and I. Jovanovic, "Uncovering Special Nuclear Materials by Low-energy Nuclear Reaction Imaging," Sci Rep, vol. 6, Apr. 2016, doi: 10.1038/srep24388.
[4] A. Poitrasson-Rivière et al., "Angular-resolution and material-characterization measurements for a dual-particle imaging system with mixed-oxide fuel," Nucl Instrum Methods Phys Res A, vol. 797, pp. 278–284, Oct. 2015, doi: 10.1016/j.nima.2015.06.045.
[5] J. Shuai et al., "Experimental study of plastic scintillators array for compact fast neutron-gamma dual-modality imaging system," Nucl Instrum Methods Phys Res A, vol. 1064, Jul. 2024, doi: 10.1016/j.nima.2024.169485.

[6] M. Streicher, S. Brown, Y. Zhu, D. Goodman, and Z. He, "Special Nuclear Material Characterization Using Digital 3-D Position Sensitive CdZnTe Detectors and High Purity Germanium Spectrometers," IEEE Trans Nucl Sci, vol. 63, no. 5, pp. 2649–2656, 2016, doi: 10.1109/TNS.2016.2593631.
[7] R. Lopez, W. M. Steinberger, N. Giha, P. Marleau, S. D. Clarke, and S. A. Pozzi, "Neutron and gamma imaging using an organic glass scintillator handheld dual particle imager," Nucl Instrum Methods Phys Res A, vol. 1042, Nov. 2022, doi: 10.1016/j.nima.2022.167407.
[8] J. Lerendegui-Marco et al., "Simultaneous Gamma-Neutron Vision device: a portable and versatile tool for nuclear inspections," EPJ Tech Instrum, vol. 11, no. 1, Feb. 2024, doi: 10.1140/epjti/s40485-024-00108-w.
[9] H. Al Hamrashdi, D. Cheneler, and S. D. Monk, "A fast and portable imager for neutron and gamma emitting radionuclides," Nucl Instrum Methods Phys Res A, vol. 953, Feb. 2020, doi: 10.1016/j.nima.2019.163253.
[10] D. P. Broughton et al., "Commissioning a time-gated camera for fast neutron beamline spatial-energy characterization at LANSCE-WNR spallation source," Nucl Instrum Methods Phys Res A, vol. 1071, Feb. 2025, doi: 10.1016/j.nima.2024.170088.
[11] H. Al Hamrashdi, D. Cheneler, and S. D. Monk, "Material optimization in dual particle detectors by comparing advanced scintillating materials using two Monte Carlo codes," Nucl Instrum Methods Phys Res A, vol. 869, pp. 163–171, Oct. 2017, doi: 10.1016/j.nima.2017.06.043.
[12] "GENERAL PURPOSE EJ-200, EJ-204, EJ-208, EJ-212."
[13] "PULSE SHAPE DISCRIMINATION EJ-276D & EJ-276G."
[14] F. Pino et al., "Novel Detector Assembly for Neutron/Gamma-Ray Discrimination Applications Based on Large-Sized Scintillators Coupled to Large Area SiPM Arrays," IEEE Trans Nucl Sci, vol. 69, no. 4, pp. 668–676, Apr. 2022, doi: 10.1109/TNS.2022.3154015.
[15] M. Grodzicka-Kobylka et al., "Fast neutron and gamma ray pulse shape discrimination in EJ-276 and EJ-276G plastic scintillators," Journal of Instrumentation, vol. 15, no. 3, Mar. 2020, doi: 10.1088/1748-0221/15/03/P03030.
[16] I. Holl, E. Lorenz, and G. Mageras, "A measurement of the light yield of common inorganic scintillators," IEEE Trans Nucl Sci, vol. 35, no. 1, pp. 105–109, 1988, doi: 10.1109/23.12684.
[17] "Lithium-6 glass scintillators for neutron detection."
[18] D. B. Everett, J. S. Fleming, R. W. Todd, and J. M. Nightingale, "Gamma-radiation imaging system based on the Compton effect," Proceedings of the Institution of Electrical Engineers, vol. 124, no. 11, p. 995, 1977, doi: 10.1049/piee.1977.0203.
[19] "Silicon Photomultipliers (SiPM) | ARRAYJ."Accessed: [Online]. Available: https://www.onsemi.com/products/sensors/photodetectors-sipm-spad/silicon-photomultipliers-sipm/arrayj
[20] J. Allison et al., "Geant4 developments and applications," IEEE Trans Nucl Sci, vol. 53, no. 1, pp. 270–278, 2006, doi: 10.1109/TNS.2006.869826.
[21] M. J. Berger et al., "XCOM: Photon Cross Sections Database."