Modeling of Time-Correlated Detection of Fast Neutrons Emitted in Induced SNM Fission

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Abstract

Neutron multiplicity methods are widely used in the assay of fissile materials. Fission reactions release multiple neutrons simultaneously. Time-correlated detection of neutrons provides a coincidence signature that is unique to fission, which enables distinguishing it from other events. In general, fission neutrons are fast. Thermal neutron sensors require the moderation of neutrons prior to a detection event; therefore, the neutron’s energy and the event’s timing information may be distorted, resulting in the wide time windows in the correlation analysis. Fast neutron sensing using scintillators allows shortening the time correlation window. In this study, four EJ-299-33A plastic scintillator detectors with neutron/photon pulse shape discrimination properties were modeled using the MCNP6 code. This sensor array was studied for time-correlated detection of fast neutrons emitted in the induced fission of $^{239}$Pu and ($\alpha$,n) neutron sources. This paper presents the results of computational modeling of arrays of these plastic scintillator sensors as well as $^3$He detectors equipped with a moderator.

Keywords: fast neutrons; multiplicity; fission; computational modeling

1. Introduction

The advancement of radiation detection technologies is essential to ensure nuclear nonproliferation and homeland security. Radiation sensors capable of time-correlated detection of neutrons emitted from fission of special nuclear materials (SNM) are a highly regarded means of detection for these applications. A detector with a faster time response could improve the ratio of actual coincidences to accidental coincidences produced by fission events in
SNM. \(^3\text{He}\) proportional counters are widely used to measure fission neutron multiplicity. With the addition of a moderating material (i.e., polyethylene), a \(^3\text{He}\) counter is capable of detecting fast neutrons. However, the recent problem of a \(^3\text{He}\) shortage poses a significant problem in supporting existing systems and developing future detection technologies. The natural abundance of \(^3\text{He}\) gas on Earth is about 0.00014\%. Thus, the majority of \(^3\text{He}\) isotope production comes from either the decay of tritium or as a byproduct of lithium generated in nuclear reactors. The cost of \(^3\text{He}\) gas is increasing continually with the decrease in resources. Moreover, gaseous sensors have count rate limitations. Furthermore, they are not rigid enough for field applications.

To address these issues, an alternative for neutron detection technology is necessary that is reliable, easily manufactured, readily available, and low cost. One of the alternatives is the use of solid-state scintillators that are sensitive to fast neutrons. This allows for neutron measurements without the necessity of moderator materials. Because fission-spectrum neutrons are fast, generally, then methods employing fast-neutron detection are applicable for the assay of fissile materials.

This research consists of a computational study of an array of EJ-299-33A plastic scintillator detectors for use in assays of nuclear material; this study was carried out using the MCNP6 code. The array was compared to an array of moderated \(^3\text{He}\) proportional counters by means of time-correlated detection of fast neutrons emitted in the induced fission of \(^{239}\text{Pu}\) and \((\alpha,n)\) neutron sources.

### Nomenclature

<table>
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>PHL</td>
<td>pulse-height light tally</td>
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<tr>
<td>PMT</td>
<td>photomultiplier tube</td>
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<td>PSD</td>
<td>pulse shape discrimination</td>
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<td>SNM</td>
<td>special nuclear material</td>
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### 2. Array of \(^3\text{He}\) proportional counters

The array of the polyethylene-moderated \(^3\text{He}\) detectors modeled in this study was based on the Neutron Multiplicity Detector System (NMDS) at the University of Nevada, Las Vegas (UNLV). As shown in Fig. 1(a), the single-detector assembly consisted of a 40-cm-long polyethylene box of a cross-section (5 cm \(\times\) 5 cm), which encapsulated a thin-wall steel tube that was 28.5-cm long, 1.55-cm in diameter, and filled with \(^3\text{He}\) gas at a pressure of 4 atm. The NMDS design was discussed by Beller et al. (2004).

When a low-energy neutron interacts inside the gas volume by means of the reaction \(n + ^3\text{He} \rightarrow p + ^3\text{H} + 765\) keV, which has a capture cross-section between 5330 b and 824 b for thermal neutrons (0.0253 to 1 eV), an ionization cloud is created by the motion of a proton and a triton in the gas medium. An electric current signal develops in the anode wire due to charge multiplication and ion motion in the electric field of the detector. Then, the current signal is converted into a voltage waveform with subsequent amplification. In this study, these analog waveforms from multiple counters were digitized with the event’s capture time. The output of the detector array was used for neutron multiplicity studies.
3. Array of EJ-299-33A scintillator detectors

Plastic scintillator detectors are a feasible alternative to $^3$He proportional counters for neutron measurements. The EJ-299-33A plastic scintillator, produced by Eljen Technology, was used in this study. The composition of this material is based on a combination of a polyvinyltoluene matrix loaded with fluorescent compounds 2,5-diphenyloxazole and 9,10-diphenylanthracene, which are used as a primary and a secondary dye, respectively (Zaitseva et al., 2012). This plastic can be fabricated effectively into various shapes and sizes. The EJ-299-33A scintillator possesses pulse-shape discrimination (PSD) capabilities that can be used to separate the neutrons from gamma ray photons.

The EJ-299-33A scintillation detectors used in this study, shown in Fig. 1 (b), were modeled after the 5-cm by 5-cm cylindrical detectors designed at UNLV. Incident radiation excites the atomic electrons of the scintillator material, releasing photons of a characteristic spectrum during the de-excitation process. Subsequently, this light is amplified and converted to a current signal by using an optically coupled photomultiplier tube (PMT). In this study, this current signal was transformed to a voltage signal and then digitized. The digitized waveform was sent to a computer for ‘on-the-fly’ PSD analysis.

4. Computational models

An array of four moderated $^3$He proportional counters and four EJ-299-33A plastic scintillator detectors were modeled using the Monte Carlo particle transport code, MCNP6 (MCNP6 Team, 2013) as fast-neutron sensors. The geometry of computational models of the $^3$He counters and scintillation detectors are shown in Fig. 2 (a) and (b), respectively. Fast-neutron detection using these sensor arrays was studied for the induced fission of $^{239}$Pu as well as for ($^{6}$Li,n) neutron sources. The detector responses of the two arrays were analyzed using MCNP6 tallies. An F8 tally with the pulse-height light (PHL) treatment converted an F6 energy deposition tally to a tally of detected pulses for each detector in the array. Single pulses, double coincidence, triple coincidence, and zero coincidence were evaluated with this tally. An F1 surface-current tally provided the time delay in neutron detection due to the moderation of the neutrons in the $^3$He detector assembly.
5. Results and discussion

Fission reactions release multiple neutrons simultaneously from a source material, thus enabling time-coincidence events in an array of detectors surrounding this source. In contrast, $(\alpha,n)$ reactions release a single neutron at a time resulting in zero coincidences in the surrounding detectors. When both of the detector arrays were simulated in MCNP6 with a $^{239}$Pu fission neutron source, double and triple coincidences were observed. In calculations using an $(\alpha,n)$ neutron source, no coincidences were observed in both of the detector arrays. These computational results from the MCNP6 F8 PHL tally agree with what is expected. From these results, it is obvious that the two detectors have vastly different responses. The EJ-299-33A detector response has a faster decay rate than the response of the $^3$He detector. A faster decay rate allows for more subsequent pulses to be detected and thus, less accidental coincidences. This difference can be observed from the responses of the two detector arrays to the detection of single neutrons in Figs. 3 (a), 3 (b), and 4 (a).
The coincidence study produced similar results, shown in Fig. 4 (b), representing the difference in response for double coincidences from the $^{239}$Pu neutron source. The ($\alpha, n$) source study produced results confirming that no coincident neutrons were detected. Fig. 5 shows the difference in response of the two detector arrays when exposed to an ($\alpha, n$) source. No double or triple coincidences were detected from the ($\alpha, n$) source. The number of detected pulses per shake normalized per one source neutron (where one shake is equal to $10^{-8}$ seconds) with both SNM and ($\alpha, n$) neutron sources is considerably larger for the EJ-299-33A detectors than for the $^3$He detectors.

There is a noticeable difference between the two detector arrays in the timing behavior of the detected pulse. The EJ-299-33A scintillator detector has a decay time of less than two shakes, whereas the $^3$He proportional counters possess a decay time of larger than 10 shakes. The shorter the decay time of a pulse, the faster another pulse can be processed by a detector. Thus, the EJ-299-33A scintillator will be able to process many more pulses than the $^3$He proportional counter.
Fig. 4. (a) Representative response of $^3$He and EJ-299-33A detectors for single pulses from a $^{239}$Pu source; (b) double coincidences from $^{239}$Pu source.

Moreover, it is apparent that the $^3$He proportional counters possess a time delay in the detection of the neutron. It requires several collisions for a fission spectrum neutron to lose its energy and be detected by means of a neutron-
capture reaction, thus affecting temporal and spatial characteristics of the neutron flux. The moderator presence around the detector affects the timing properties of neutron detection, thus increasing the neutron lifetime. This is confirmed by the results of the F1 surface current tally, which showed that the $^3$He detector had a delay in detection time of approximately 1.3 ns.

6. Conclusion

This study compared the performance of two neutron sensor arrays, $^3$He proportional counters to EJ-299-33A plastic scintillator detectors, by utilizing the MCNP6 code. The study of the detector array responses to the induced fission of SNM and ($\alpha$,n) reactions showed that the EJ-299-33A detector properties are more suitable to coincidence counting. The EJ-299-33A scintillator detector was able to detect more single pulses and coincidences created by incident neutrons. Additionally, this detector had a shorter time-coincidence gate for neutron multiplicity measurements. This allowed for decreasing the level of the accidental coincidence events. Moreover, direct measurement of fast neutrons without moderation preserved the spatial signatures of the neutron flux and decreased the neutron lifetime in the detection system.

The utilization of EJ-299-33A scintillator sensors for SNM detection could improve overall results during the assay of fissile materials. It is of great interest to continue the study of the performance of EJ-299-33A scintillator detectors for this purpose. Experiments comparing the response of $^3$He proportional counters to plastic scintillator detectors to induced SNM fission could be utilized to validate the computational results.

References

