MONTE CARLO MODELS OF NEUTRON DETECTION WITH ORGANIC SCINTILLATORS

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ABSTRACT

We describe the use of the MCNP-PoliMi code to simulate, on an event-by-event basis, the detection of neutrons by organic scintillators. This code keeps track of single neutron interactions, including the collision nucleus, the energy deposited, and the time distribution of collision events. We show that the total pulse-height response is given by the sum of many possible neutron histories, each composed of a certain number of neutron scatterings on hydrogen and/or on carbon. The simulated pulse-height distributions are compared to experimental data acquired using various neutron sources. Simulations and measurements of neutron pulse-height distributions are essential for neutron spectrum unfolding procedures. This work has applications in the areas of nuclear nonproliferation and homeland security.

Key Words: MCNP, MCNP-PoliMi, pulse-height distribution, neutron detection, organic scintillator, neutron spectrum unfolding

1. INTRODUCTION

Organic scintillators, in both liquid and plastic form, are commonly used in systems for the detection of nuclear materials in nonproliferation and homeland security applications. Neutron detection in this type of detector occurs by multiple scatterings on hydrogen (H) and carbon (C), the main constituents of the scintillator. The analysis of the statistics of neutron collisions is important for understanding the mechanism of neutron detection, and for performing subsequent unfolding procedures aimed at determining accurately the incident neutron spectrum.

We describe the Monte Carlo simulations of neutron interactions within the detector material for various detector sizes and incident neutron energies. The simulations are performed using the code MCNP-PoliMi [1], which allows event-resolved predictions of the interactions of neutrons within the detector. A subsequent postprocessing of the simulation results allows us to determine the number of elastic collisions that the
neutrons undergo with the H and C nuclei. In addition, the codes allow us to calculate the amount of energy that is deposited as a function of the number of collisions. We also show how much of the light is generated by proton recoils on H and C nuclei as a result of collisions with energetic neutrons from monoenergetic and continuous sources. The total detector efficiency is determined as a function of the incident neutron energy. Finally, simulation results are compared to experimental data acquired using neutron sources, such as Cf-252 and Am/Be.

2. MONTE CARLO SIMULATIONS

The Monte Carlo analysis allows us to calculate not only the average pulse height generated in the detector as a function of the \( n \) and \( m \) scatterings on H and C, respectively, but also the entire pulse-height distribution.

The simulations were performed using the MCNP-PoliMi code. The detector modeled consists of a cube having the dimensions of \( 10 \times 10 \times 10 \text{ cm}^3 \) and a H:C composition of 0.548:0.452. This composition corresponds to that of the liquid scintillator BC-501A manufactured by Saint-Gobain. Separate simulations were performed for each incident neutron energy interval, in the energy range 0 to 5 MeV in 0.1-MeV intervals, with neutron energies distributed uniformly in each energy interval. The neutrons were incident perpendicularly on one of the faces of the detector cube, and uniformly distributed over the face.

The MCNP-PoliMi output files record every neutron interaction that occurs in the detector volume, including interaction type, energy deposited, and collision nucleus (H or C). The energy deposited is then converted into the light output, taking into account the type of collision nucleus. In the case of scattering on H, the relationship between energy deposited \( (T, \text{ in MeV}) \) and light output \( (L, \text{ in MeVee}) \) is

\[ L = aT^2 + bT \equiv L(T), \]

where \( a = 0.035 \text{ MeVee/MeV}^2 \) and \( b = 0.141 \text{ MeVee/MeV} \) for liquid scintillators. In the case of scattering on C, the light output is very small. For this study we used the following relationship:

\[ L(T) = cT, \]

where \( c = 0.02 \text{ MeVee/MeV} \).

3. MONTE CARLO RESULTS

The pulse-height distributions were collected separately for neutron histories with \( n \) and \( m \) scatterings on H and C. Figure 1 shows one such distribution for 1- to 1.1-MeV incident neutrons. Figure 1(a) shows the total pulse-height distribution, and Figure 1 (b) shows the contributions to the total distribution from histories comprising \( n \) and \( m \).
scatterings on H and C, respectively, with $n = 1, 2, \text{ and } 3 \text{ and } m = 0 \text{ and } 1$. Figure 1(b) also shows that multiple scatterings on H contribute to increasing the detector response at higher pulse heights, whereas scatterings on C contribute to an increase in the detector response at lower pulse heights. The distribution labeled “Others” represents the cumulative contribution of all other combinations of $n$ and $m$ scatterings not shown separately.

Figure 1 Pulse-height distributions for 1- to 1.1-MeV incident neutrons. (a) Total pulse-height distribution is shown with error bars that represent statistical error ($\pm 1\sigma$). (b) Total pulse-height distribution is subdivided according to the total number of scatterings on H ($n = 1, 2, \text{ and } 3$) and C ($m = 0 \text{ and } 1$) in the neutron history. Error bars are not shown for clarity.

Figure 2 shows the pulse-height distributions for 2.5- to 2.6-MeV incident neutrons. As can be seen, the maximum light output produced by neutron interactions now extends up to a value of approximately 0.6 MeVee. This is consistent with the evaluation of Eq. (1) for $T = 2.5 \text{ MeV}$, corresponding to the maximum energy deposition on H from neutrons with energy 2.5 MeV. The result shown in Figure 2 agrees well with the experimental and simulation data reported by Klein and Neumann [2].

Figure 3(a) shows the number of neutron histories as a function of the number of scatterings on H and C for 2.5- to 2.6-MeV incident neutrons. As can be seen, the most probable type of interaction is single scattering on H, followed by single scattering on C. Histories with single scatterings on both H and C are the third most probable events, followed by histories with double scatterings on H.

Figure 3(b) shows the average pulse height generated per history as a function of the number of scatterings on H ($n$) and on C ($m$). These results show that histories comprised only of scatterings on C have small light outputs compared to histories that include scatterings on H.
Figure 2 Pulse-height distributions for 2.5- to 2.6-MeV incident neutrons. (a) Total pulse-height distribution is shown with error bars that represent statistical error (± 1σ). (b) Total pulse-height distribution is subdivided according to the total number of scatterings on H (n = 1, 2, 3) and C (m = 0, 1, 2) in the neutron history. Error bars are not shown for clarity.

Figure 3 (a) Number of neutron histories as a function of the number of scatterings on H (n) and on C (m) (2.5- to 2.6-MeV incident neutrons). (b) Average pulse heights as a function of the number of scatterings on H (n) and on C (m) (2.5- to 2.6-MeV incident neutrons).
4. EXPERIMENTAL VERIFICATION

The results from the simulations were verified by performing experiments with a cylindrical liquid scintillator, a fast waveform digitizer, and several neutron sources. A previously developed pulse-shape discrimination technique allowed an accurate separation of neutron pulses from gamma-ray pulses [3]. A 2.5-cm lead shield was used to reduce the number of gamma rays registered at the detector. The experimental setup is shown in Figure 4.

![Experimental setup](image)

Figure 4 The experimental setup for the collection of neutron pulse-height distributions for various neutron sources. The Am-Be source is shown.

Figure 5 shows the neutron energy spectra for two neutron sources that were used in the experiments: Cf-252 and Am-Be. Neutrons from the former have a spontaneous fission spectrum that peaks around 800 keV, with average energy of approximately 2.1 MeV. Neutrons from the latter have a harder energy spectrum, with an average energy of approximately 4.2 MeV.
Figure 5 Neutron energy spectra as simulated in MCNP-PoliMi for Cf-252 and Am-Be neutron sources.

Figure 6 shows the simulated and measured neutron pulse-height distributions obtained using the Am-Be source. The experimental data are shown with error bars at the one-sigma level. The error bars on the simulations results are not shown as they would have been smaller than the symbol. As can be seen, there is very good agreement between the simulation and measurement.

Figure 6. Simulated and measured pulse-height distributions for Am-Be neutrons. Experimental data are shown with error bars.
Figure 7. Simulated and measured pulse-height distributions for Cf-252 neutrons. Experimental data are shown with error bars.

Figure 7 shows the simulated and measured pulse-height distributions for the Cf-252 source. Again, there is very good agreement between the simulation and the measurement. It can be observed that the pulse-height distribution for the Cf-252 source has more contributions at low pulse heights when compared to the pulse-height distribution for the Am-Be source. This result is expected on the basis of the neutron spectrum distributions shown in Figure 5.

Figure 8 shows the pulse-height distribution for the Am-Be source subdivided into its components on the basis of the number of collisions on H and C that the neutrons underwent in their history. It can be seen that single scatterings on H are the predominant mechanism of detection, followed by double scatterings on H and histories with single scatterings on both H and C.
Figure 8. Simulated pulse-height distributions for Am-Be neutrons. (a) Total pulse-height distribution is shown with error bars that represent statistical error (± 1σ). (b) Total pulse-height distribution is subdivided according to the total number of scatterings on H (n = 1, 2, and 3) and C (m = 0, 1, and 2) in the neutron history. Error bars are not shown for clarity.

5. CONCLUSIONS

This paper described how a Monte Carlo approach based on the use of the MCNP-PoliMi code can be used to analyze the statistics of neutron interactions with organic scintillation detectors. The simulation results were used to discuss the response of organic scintillators to neutron sources from a monoenergetic source and from two continuous energy sources: Cf-252 and Am-Be. The simulated results were compared with experimental data, and very good agreement was obtained.

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