MONTE CARLO ANALYSIS OF THE STATISTICS OF NEUTRON DETECTION BY ORGANIC SCINTILLATORS

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Abstract. In this paper, we describe an event-by-event analysis of neutron detection in organic scintillators (plastics and liquids). Monte Carlo simulations and analytical descriptions are discussed. The analysis of the statistics of neutron collisions is important to understanding the mechanism of neutron detection and to performing subsequent unfolding procedures aimed at determining the incident neutron spectrum.

INTRODUCTION

Several measurement systems used in the area of nuclear nonproliferation employ liquid and plastic scintillators to detect neutrons and gamma rays from assemblies of fissile materials. Analysis of the neutron response functions of these detectors is essential for the development of unfolding techniques that can be used in neutron spectroscopy and neutron source identification methods [1]. The neutron response in these types of detectors is dominated by scattering on hydrogen, which is the mechanism that generates most of the scintillation light. Neutron scattering on carbon, the other main constituent of these scintillators, produces significantly less light. However, scattering on carbon affects the detector response because the neutron can lose energy in the scattering collision and, therefore, deposit less energy in subsequent interactions with hydrogen nuclei.

We conducted a detector response investigation based on an event-by-event statistical analysis of neutron histories in the detector. Quantities such as the number of collisions occurring in a scintillator are not measurable: what is measured is the combined effect of all collisions that contribute to a detector pulse. However, the statistics of the number of collisions is important when we consider neutron spectrum unfolding procedures. In fact, two effects, (1) nonlinearity in the light production from hydrogen scattering and (2) small light output from carbon scattering, make the light output dependent not only on the total neutron energy deposited in the detector, but also on the history of the neutron energy deposition.

In this paper, we describe the Monte Carlo simulation of neutron interactions with detector materials for varying incident neutron energies and varying detector sizes. The simulations were performed with the code MCNP-PoliMi, which allows event-resolved predictions of the interactions of neutrons with detector materials. A subsequent post-processing of the simulation results allowed us to determine the number of elastic collisions the neutrons undergo with hydrogen and carbon and the amount of energy that is deposited as a function of the number of collisions. We also modeled the light output generated by the hydrogen and carbon recoils and determined the total detector efficiency as a function of the incident neutron energy.

MONTE CARLO SIMULATIONS

The simulations were performed using the code MCNP-PoliMi [2]. The detector modeled consists of a cube having the dimensions 10 × 10 × 10 cm and a 0.548 : 0.452 hydrogen to carbon ratio. This composition corresponds to that of the liquid scintillator BC-501 manufactured by Saint-Gobain.

Separate simulations were performed for each incident neutron energy interval in the range 0 to 5 MeV, in 0.1 MeV intervals with neutron energies distributed uniformly in the 0.1 MeV intervals. The neutrons were incident perpendicularly on one of the faces of the detector cube and uniformly distributed within the face.

The Monte Carlo output files record every neutron interaction that occurs in the detector volume, including interaction type, energy deposited, and collision nucleus (hydrogen or carbon). The energy deposited is then converted into light output, taking into account the identity of the collision nucleus (hydrogen or carbon). In the case of hydrogen, the relationship between energy deposited (T in MeV) and light output (L in MeVee) is

$$L = aT^2 + bT \equiv L(T) \quad , \tag{1}$$

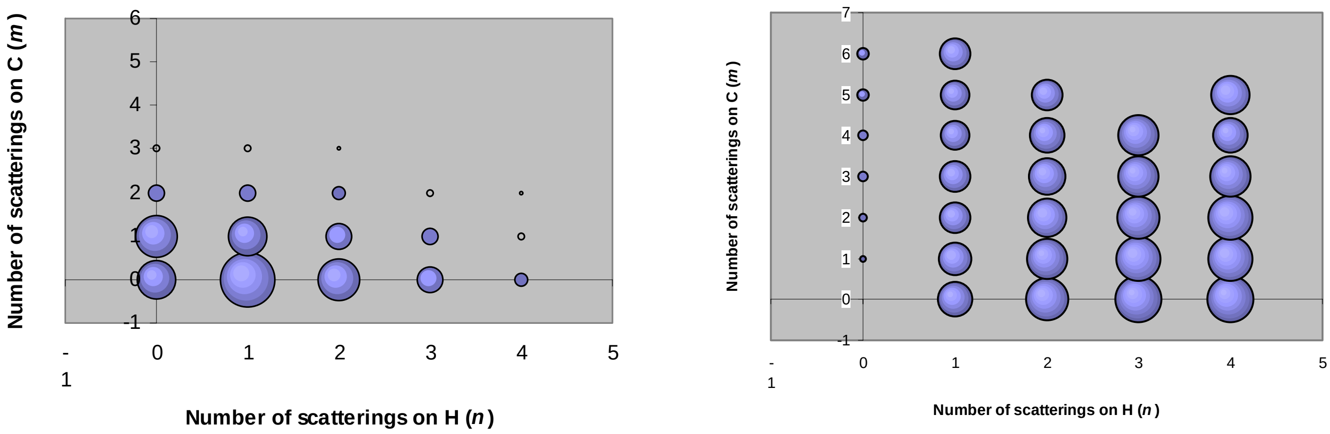
with a = 0.035 MeVee/MeV^2 and b = 0.141 MeVee/MeV for liquid scintillators. In the case of scattering on carbon, the light output is very small. For this study we used the following relationship:

$$L(T) = cT \quad , \tag{2}$$

with c = 0.02 MeVee/MeV.

MONTE CARLO RESULTS: PROBABILITY DISTRIBUTIONS AND AVERAGE PULSE HEIGHTS

Figure 1 shows probability distributions and average pulse heights. Figure 1a shows the relative probability that neutron histories will include n scatterings on hydrogen and m scatterings on carbon for incident neutrons having energy uniformly distributed in the interval 1 to 1.1 MeV on a detector having dimensions 10 × 10 × 10 cm. In the figure, the radii of the spheres are proportional to this relative probability. Figure 1a shows that the most probable event at this neutron energy and detector size is single scattering on hydrogen. Histories with only two scatterings on hydrogen (*n* = 2 and *m* = 0) and only one scattering on carbon (*n* = 0 and *m* = 1) are about equally probable. Slightly less probable are histories with no interactions (*n* = 0 and *m* = 0) and histories with one scattering on carbon and one on hydrogen (*n* = 1 and *m* = 1).



(a) (b)

Fig. 1. Probability distributions and average pulse heights. (a) Relative probability of neutron histories as a function of the number of scatterings on hydrogen (n) and on carbon (m) (1- to 1.1-MeV incident neutrons). (b) Average pulse heights as a function of the number of scatterings on hydrogen (n) and on carbon (m) (1- to 1.1-MeV incident neutrons).

Figure 1b shows the average pulse height generated by neutron histories with *n* scatterings on hydrogen and *m* scatterings on carbon. In the figure, the radii of the spheres are proportional to an average pulse height for *n* and *m* scatterings on hydrogen and carbon, respectively. As expected, the histories consisting solely of scatterings on carbon do not generate much light in the detector (*n* = 0).

Single scatterings on hydrogen (*n* = 1, *m* = 0) generate less light than multiple scatterings on hydrogen (*n* = 2 to 4, *m* = 0).

MONTE CARLO RESULTS: PULSE-HEIGHT DISTRIBUTIONS

The Monte Carlo analysis allowed us to calculate not only the average pulse height generated in the detector as a function of the *n* and *m* scatterings on hydrogen and carbon, but also the entire pulse-height distribution. One such distribution is shown in Fig. 2 for 1-MeV incident neutrons. Figure 2a shows the total pulse-height distribution, and Fig. 2b shows the contributions to the total distribution from histories comprising *n* and *m* scatterings on hydrogen and carbon, respectively, with *n* = 1, 2, and 3 and *m* = 0 and 1. Figure 2b shows that multiple scatterings on hydrogen contribute to increasing the detector response at higher pulse heights, whereas scatterings on carbon 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.

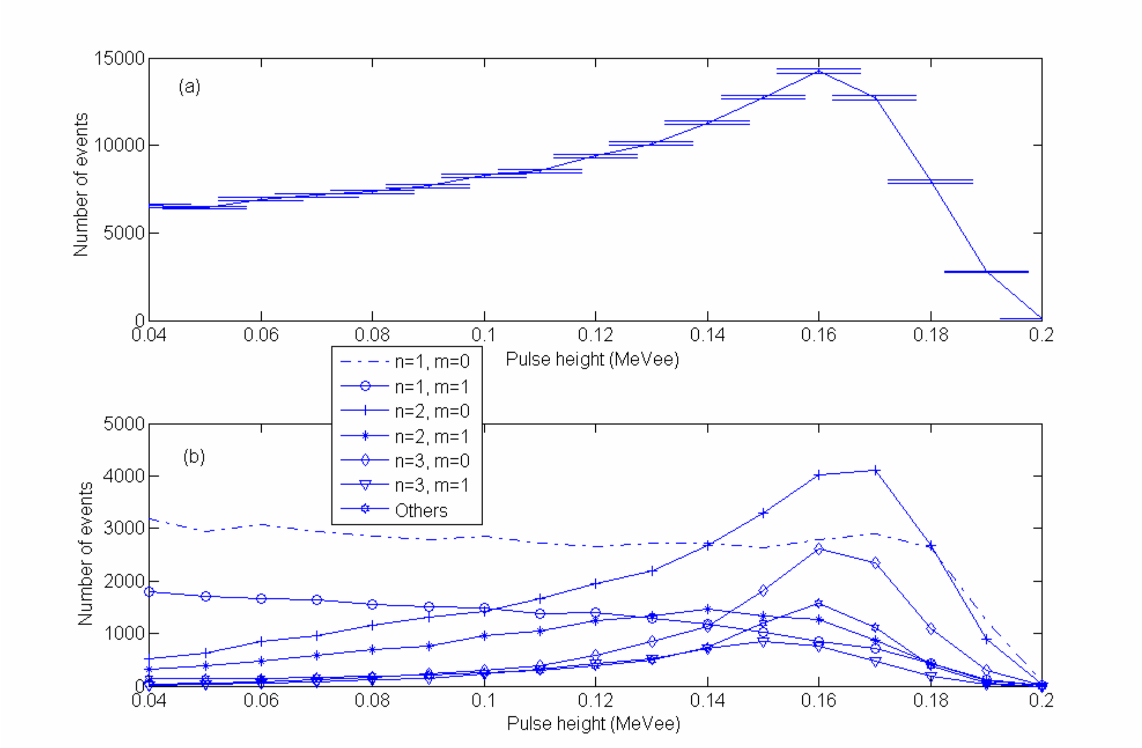


Fig. 2 Pulse-height distributions for 1- to 1.1-MeV incident neutrons. (a) Total pulse-height distribution is shown with error bars that represent statistical error. (b) Total is subdivided according to the total number of scatterings on hydrogen (n = 1, 2, and 3) and carbon (m = 0 and 1) in the neutron history. Error bars are not shown for clarity.

DETECTOR SIZE

Figure 3 shows pulse-height distributions for 1- to 1.1-MeV incident neutrons generated in two different detector sizes: a 10 × 10 × 10 cm detector (as in Fig. 2) and a 20 × 20 × 20 cm detector. In the larger detector the peak at high pulse heights is more pronounced because of the increased probability of multiple scatterings of neutrons in collisions with hydrogen nuclei.

CONTINUOUS SPECTRUM: CF-252

In the case of a continuous neutron energy spectrum (e.g., Cf-252), the resulting pulse-height distribution will be the sum of many distributions, such as those shown in Fig. 2b. As a result, the cumulative distribution will typically include a broad continuum that extends up to the maximum light output generated by the neutrons having the highest energy and an accumulation of many pulses at low pulse heights. In an experiment, the detector threshold setting in the data acquisition system would eliminate the contributions at the low pulse heights.

Figure 4 shows pulse-height distributions for Cf-252 neutrons impinging on a liquid scintillator. Figure 4a shows the total pulse-height distribution. Note that the scale in the figure is now log-log. Figure 4b shows the contributions to the total distribution from histories comprising *n* and *m* scatterings on hydrogen and carbon, respectively, with *n* = 0 to 3 and *m* = 0 to 3. Note that the histories comprising only scatterings on carbon (*n* = 0) contribute mainly to the low pulse heights.

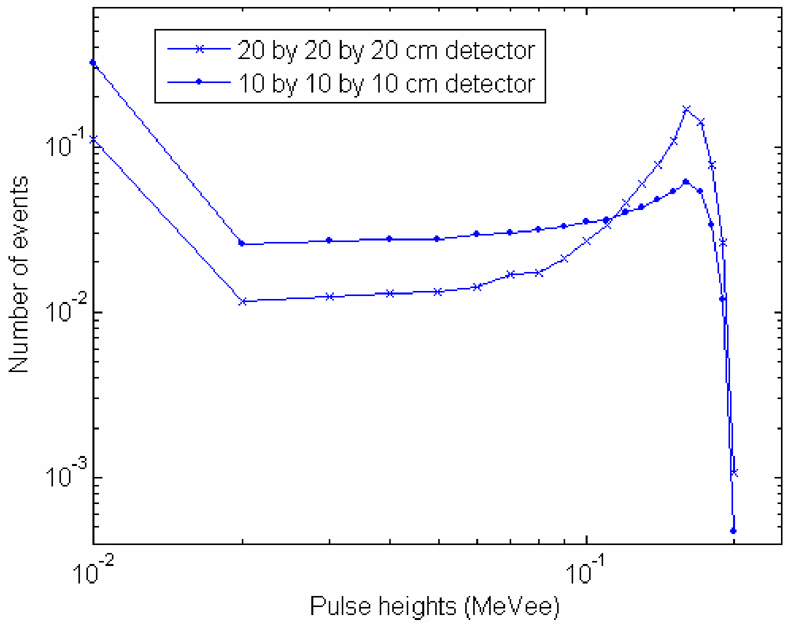


Fig. 3 Pulse-height distributions for 1-MeV incident neutrons and two detector sizes.

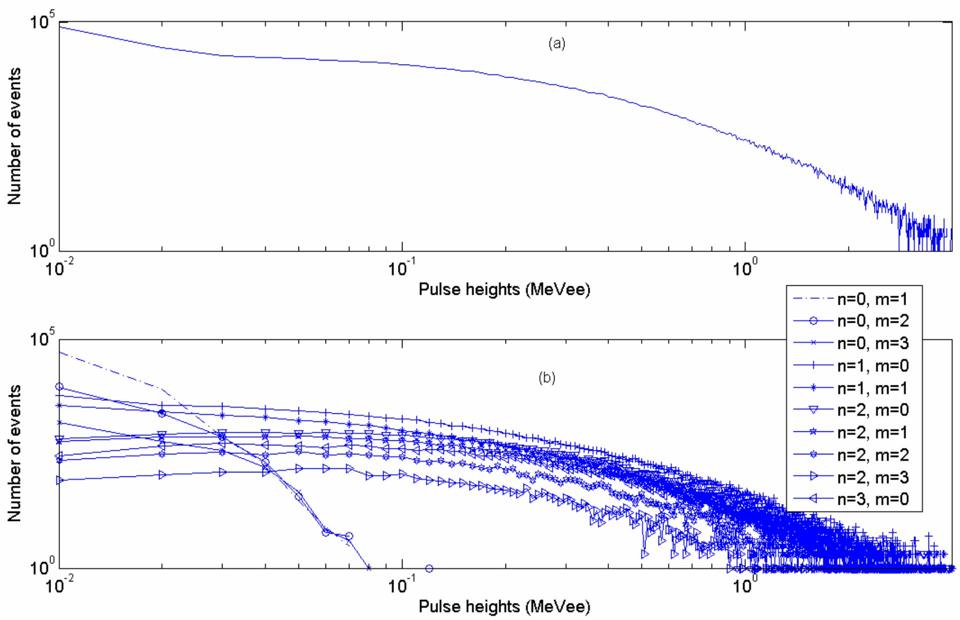


Fig 4. Pulse-height distributions for Cf-252 neutrons. (a) Total pulse-height distribution. (b) The total is subdivided according to the total number of scatterings on hydrogen (n = 0, 1, 2,

and 3) and carbon (m = 0, 1, 2, and 3) in the neutron history. Error bars are not shown for clarity.

Figure 5 shows a comparison between experimental data [3] and simulated data. The experimental data were acquired with the detector threshold set at approximately 0.12 MeVee. As can be seen, the agreement between the simulated and measured data is very good: the average relative error was approximately 6% in the pulse-height range 0.12 to 1.12 MeVee. The comparison shown in Fig. 5 serves as a validation for the Monte Carlo approach.

In addition to providing an estimate of the total pulse-height distribution, Monte Carlo simulations can be used to generate pulse-height distributions for the individual components, such as those shown in Fig. 4b. This ability is essential in the analysis of the response of existing detectors and in the development of new detector types.

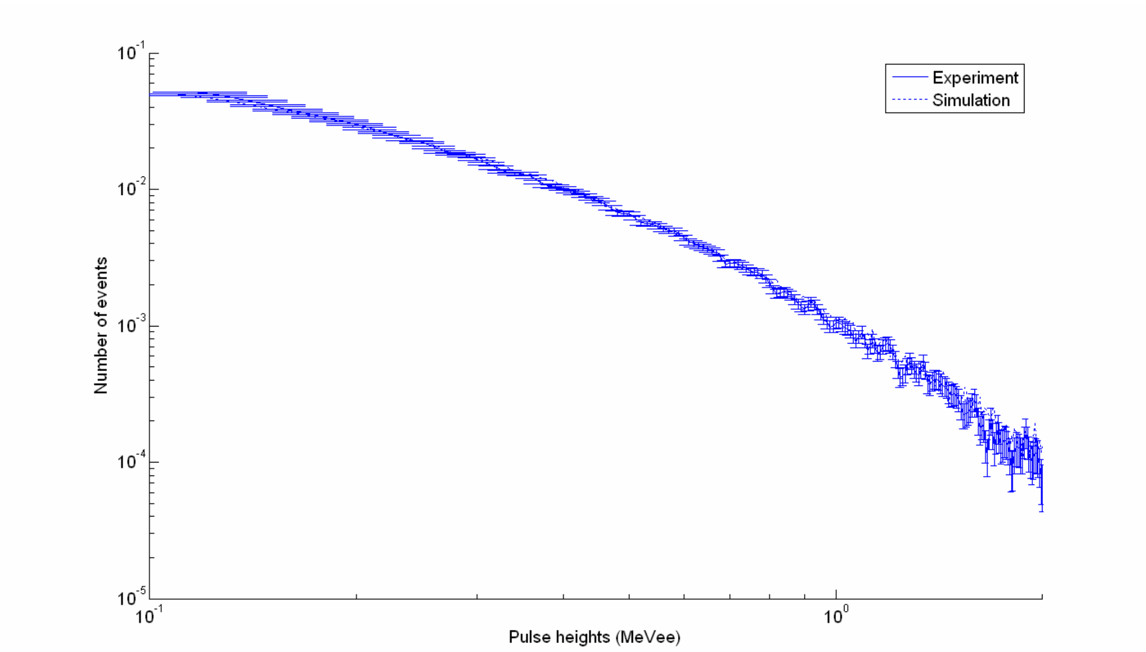


Fig. 5. Comparison between experimental and simulated data for pulse-height distributions for Cf-252 neutrons. Experimental data [3] shown with error bars, simulation shown with dotted line.

ANALYTICAL APPROACH AND DISCUSSION

The distribution of the energy transferred (*T*) by a neutron having incoming energy E_0, in a single collision with hydrogen, is equal to

$$p(T,E_0)dT = \frac{dT}{E_0} \quad , \tag{3}$$

where, as expected, $p(T,E_0)$ is independent of the amount of energy transferred, *T*. It follows that the distribution of light generated in the detector by a neutron having incident energy E_0 is

$$f_1(L, E_0) = \frac{1}{E_0\sqrt{b^2 + 4aL}} \quad , \tag{4}$$

with L lying between 0 and $L_{\max} = aE_0{}^2 + bE_0$. For a given light intensity L in Eq. (4), the transferred energy is given as

$$T(L) = \frac{\sqrt{b^2 + 4aL} - b}{2a} \quad . \tag{5}$$

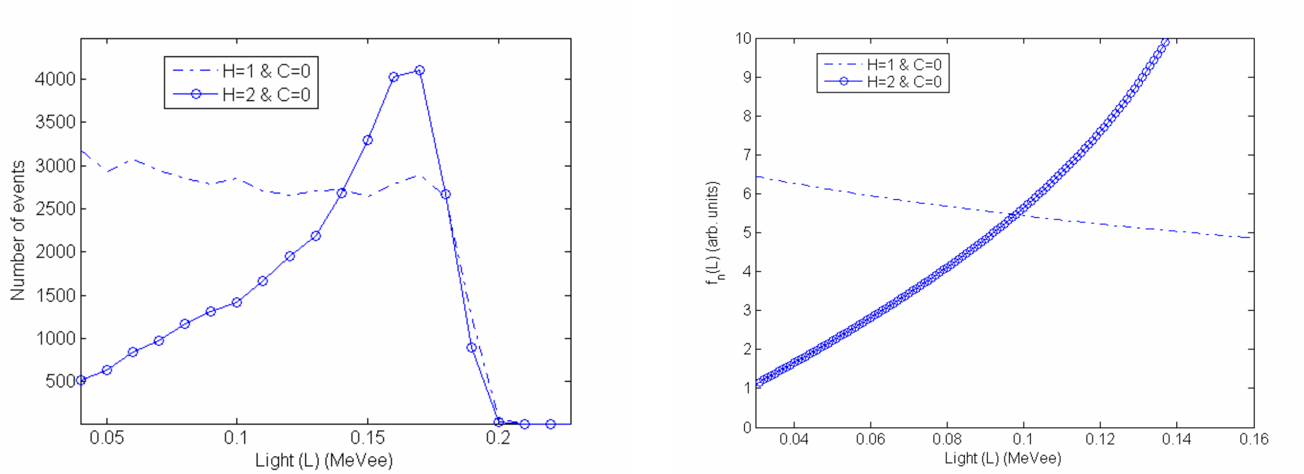
That is, f_1 is relatively flat since $a < b$, and it decreases slowly for increasing light intensities, as shown in Fig. 6(b).

From here the distribution of the light generated by neutrons colliding more than one time with hydrogen can be calculated by convolution-type integrals. For example, the distribution after two collisions, $f_2(L, E_0)$, is

$$\begin{aligned} f_2(L, E_0) &= \int_0^L f_1(L - l, E_0 - T(l))\, f_1(l, E_0)\, dl = \\ &= \frac{1}{E_0} \int_0^L \frac{1}{\left(E_0 - T(l)\right)\sqrt{b^2 + 4a(L - l)}} \frac{1}{\sqrt{b^2 + 4al}} dl \end{aligned} \quad , \tag{6}$$

where $T(l)$ is given by Eq. (5).

The integral in Eq. (6) can be calculated numerically and is shown in Fig. 6b. As can be seen, there is a general agreement in the shape of f_1 and f_2 between the Monte Carlo simulations (Fig. 6a) and the analytical solution (Fig. 6b).



(a) (b)

Fig. 6. Monte Carlo simulation vs analytical solution for light output. (a) Monte Carlo simulation of light output for 1-MeV incident neutrons in the case of one scattering on hydrogen and two scatterings on hydrogen. (6b) Analytical solution of the light output for the case of one scattering on hydrogen and two scatterings on hydrogen (1-MeV incident neutrons).

REFERENCES

1. S. Avdic, S.A. Pozzi, and V. Protopopescu, "Detector Response Unfolding Using Artificial Neural Networks," accepted for publication in *Nuclear Instruments and Methods in Physics Research*, Section A.

2. S.A. Pozzi, E. Padovani, and M. Marseguerra, "MCNP-PoliMi: A Monte Carlo Code for Correlation Measurements," *Nuclear Instruments and Methods in Physics Research A*, 513/3 pp. 550–558, 2003.

3. S.A. Pozzi and S. Avdic, "Neutron and Gamma Ray Pulse Shape Data Acquisition from a Cf-252 Source," ORNL TM 2006/62.