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Calculation of the light pulse distributions induced by fast neutrons in organic scintillation detectors

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ABSTRACT

We develop a fully analytic and self-contained description of the amplitude distribution of light pulses in an organic scintillation detector due to a monoenergetic source of fast neutrons. To this end, two classes of problems have to be handled. One is a formula for the light pulse amplitude distribution for the complete life history of neutrons slowing down in a mixture of hydrogen and carbon as a statistical average over all collision sequences that can occur, accounting also for neutron leakage. A complete solution is given in terms of a non-recursive convolution integral expansion with respect to the various possible collision histories. These latter are dependent on the collision probabilities of neutrons of a given energy. The second is the calculation of this collision probability from analytical expressions for the geometry of the detector, in the present case a right cylinder. This quantity was taken from Monte Carlo simulations in previous work. Recursive formulae are derived for the probabilities of arbitrary collision sequences, and quantitative results are given for up to five consecutive collisions of all combinations. These probabilities can be used to determine how to truncate the non-recursive expansion of the full light amplitude distribution in quantitative work. The calculational method serves to lend insight and understanding into the structure of the pulse height spectra, as well as it provides a computationally cheap method of generating a large number of such spectra for various detector compositions, sizes and neutron energies, for the development and test of new spectrum unfolding techniques.

1. Introduction

One possible method of detecting and identifying nuclear materials in non-proliferation and homeland security applications is based on the measurement of the energy spectrum of the neutrons emitted from the sample. The two main options for neutron spectrometry are the use of time-of-flight spectra and pulse height spectra, respectively. The pulse height spectra are measured by organic scintillation detectors, in both liquid and plastic form [1]. For safeguards purposes, especially in field applications, neutron spectrometry by unfolding the light pulse height distributions has definite advantages over the time-of-flight method.

For the unfolding of a measured pulse height distribution, one has to have access to the so-called response matrix of the detector, which is determined by calculating the pulse height spectra for various incoming neutron energies. Calculation of such response matrices and their use in unfolding an unknown neutron spectrum has been investigated extensively in the past [2] (for an extensive review, see Ref. [3] and the references therein). The method of calculating the pulse height spectra is by Monte Carlo simulations, which are practically the only method to produce high-fidelity and accurate results for realistic cases. The unfolding is based on Bayesian methods and maximum entropy principles.

The subject of this paper is to present a self-contained method of calculating the pulse height distributions through an analytical model. No simplifications are made what regards the detector geometry and the neutron cross-sections, but some mild approximations are made regarding the detection process. Also, no mixed radiation fields (neutron and gamma) are considered, only neutrons are assumed to reach the detector. Although the method is not fully capable to reach the same accuracy as the Monte Carlo simulations, the results are still rather accurate, and reproduce the characteristics of the pulse shape distributions quite well.

Besides of the challenge in the complete analytical calculation of the light pulse distributions, the motivation for the work comes from two directions. One is that, through the transparency of the analytical treatment and the step-by-step following of the slowing down process, the method lends insight into the physics of light pulse distributions generated by neutrons in various

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collision histories. The understanding of the structure of the light pulse spectra and its dependence on various detector parameters and neutron energies might help also the development of methods of spectrum unfolding.

The second motivation is related to the development of alternative spectrum unfolding methods. One novel possibility of spectrum unfolding is the use of artificial neural networks (ANN). ANNs need a large number of training sets, i.e. a large number of light pulse spectra for a number of different input parameters. The analytical method elaborated here supplies a fast and computationally simple method for generating such training sets.

Light pulse height distributions generated by individual collision sequences (such as HCC, CHC etc.) of mono-energetic source neutrons in an organic scintillation detector, consisting of a mixture of H and C atoms were calculated in recent work by the present authors and collaborators in both an analytical model and by Monte Carlo simulations [4]. The initial model was validated successfully against light pulse distributions calculated using MCNP-PoliMi. In this work we now extend the description in two ways. One is that, instead of considering individual collision sequences, the complete process will be treated by taking a statistical average over the collision sequences that can occur, such that the calculations become comparable with experiments. Due to the non-recursive character of the resulting formulae, only a finite number of terms can be calculated in a collision number expansion. However, in a typical detector accounting for a maximum of five collisions before absorption or leakage is completely satisfactory.

In contrast to the previous work, now the change of the neutron spectrum during the slowing down process, due to leakage and absorption, is also taken into account, in an analytic way. Another extension is an analytical calculation of the collision probability of the neutrons of a given energy in the detector with a specific geometry, which appears in several parts of the formulae. In earlier work this quantity was obtained from the same Monte Carlo simulations, of whose results for the light amplitude distribution the analytical results were compared. Hence the quantitative evaluation of the analytical approach was not completely independent from the Monte Carlo simulations. In the present work such a dependence of the analytical model on the Monte Carlo simulations is eliminated.

The quantitative work will be focused on the calculation of the probabilities of the various collision sequences, which can be analytically given in form of integrals over the spectra of neutrons after the last collision. The spectra themselves can be represented by recursive integrals over preceding members of the collision sequence. The quantitative results from the analytic model in form of collision probabilities are compared to simulations with MCNP-PoliMi, differences there are discussed as part of the foundation of the analytical method and any approximations made.

2. Theory

The light intensity produced in a scintillation detector by fast neutrons will depend on the energy transferred, which is, in turn, dependent on the nuclei with which the neutrons collide. In a detector consisting of different nuclei, the probabilities of the various collision sequences will depend on both the different constituents and the geometry of the detector. The scintillation light is generated by multiple scattering on hydrogen (H) and carbon (C), the main constituents of the scintillator. This type of detectors are also sensitive to gamma rays, but with the use of pulse shape discrimination techniques one can reject those pulses when pure neutron pulse analysis is required [1,2].

In each collision during the slowing down of the neutron, energy is transferred which is transformed into light in the detector. Although a separate light quantum is generated in each individual collision, only the total light intensity by a single neutron can be detected, because the individual collisions cannot be temporally resolved by the scintillator and the light collection procedure. However, the different pulses by the different neutrons can be distinguished, and the light intensity distribution of a flux of incoming neutrons can be experimentally determined. The analytical method calculates the light spectrum generated by a single neutron, by following up its possible collisions and the accounting for the stochastic character of the neutron slowing down process.

2.1. Collision probabilities

In this work, the collision probabilities will be calculated as being due to neutrons born uniformly distributed in the

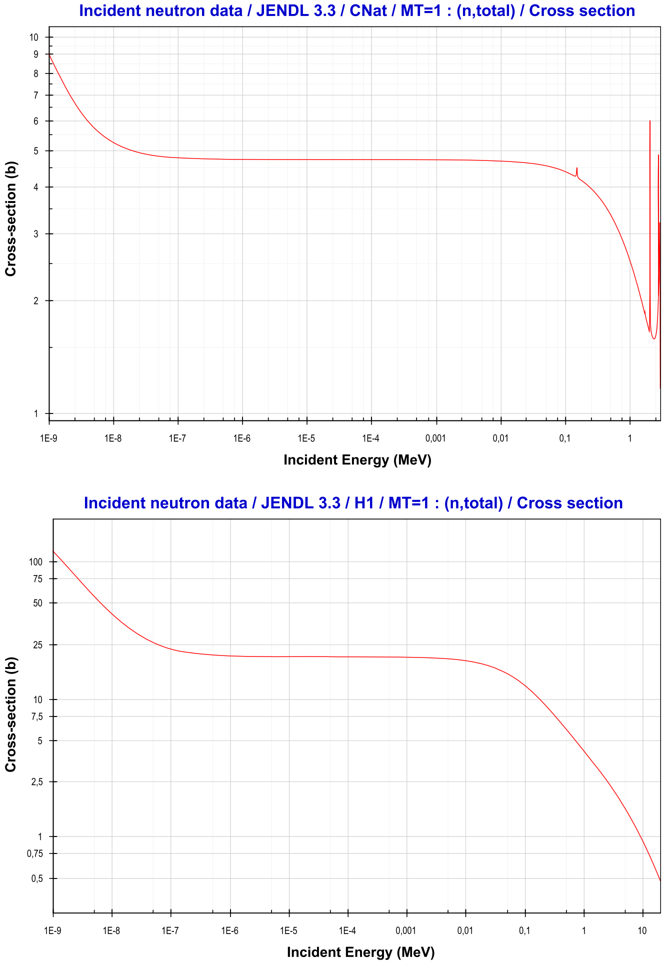

Fig. 1. Scattering cross-sections of hydrogen and carbon up to 1 MeV neutron energy.

Table 1
Detector dimensions for a right cylinder, expressed in centimeters and in mean free paths for a neutron energy of 1 MeV.

cm	MFPs
Detector dimensions: $h=d$	
1	0.308022
5	1.54011
10	3.08022
15	4.62033