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Improved method for the determination of neutron energies from their times-of-flight

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ABSTRACT

The kinetic energy of a neutron is determined experimentally by measuring its time-of-flight and flight distance from the source to the detector. However, this determination is vitiated by errors since the exact location of the interaction of the neutron within the detector is unknown. Moreover, more than one interaction may be necessary for the deposited energy to reach the detector threshold. We compare the different existing energy determination methods and introduce the method which gives the minimum-variance unbiased estimator of the neutron energy. The method is based of the inversion of the detector response function, for which we propose a universal algorithm. It is shown that the precision of the new method does not deteriorate with the length of the detector, which opens the possibility of conceiving detectors with a higher efficiency.

1. Introduction

1.1. *Importance of neutron detection*

Neutron and light charged particle detection is an essential tool to obtain information on nuclear reaction mechanisms, these particles being reliable witness of the collision/de-excitation process. They allow identifying different sequences during the collision making possible the disentanglement of the different emitting sources: pre-, post-scission, pre-equilibrium, evaporation as well as the separation between peripheral and central collisions [1–3]. Indeed, the neutron and light charged particle multiplicities are negatively correlated to the impact parameter [4,5]. The information delivered by neutrons is often simpler to analyze, as they are not subject to Coulomb repulsion or barrier. At low excitation energy, they may be the only emitted particles, thus the only available probe.

Multi detectors allow multiple source analyzes based on neutron and light charged particle angular and energy distributions in order to identify and characterize the emitting sources of a nuclear process. For example, this approach was used, in the Fermi energy domain, to determine the maximum temperature a nucleus at these energies can reach [6,7].

With the advent of new radioactive, mostly neutron rich, beam facilities, the importance of neutron detection is growing. An accurate determination of the energy of these particles appears thus essential for nuclear physics.

1.2. *Neutron detection*

To be detected and identified, a fast neutron has first to undergo one or a series of nuclear interactions in the detection medium, mainly elastic and inelastic scattering on hydrogens and carbons. New reaction channels open up with increasing energy. As the neutron energy can only be accurately evaluated by measuring its time-of-flight, one has to determine as well as possible the flight distance including the interaction path inside the detector. Unfortunately, the location of the interaction triggering the detector cannot be determined experimentally. Therefore, we are confronted to a difficult trade: on the one hand, the detector must be long enough otherwise its efficiency would be too low (especially for high energy neutrons as the cross-section decreases with energy), on the other hand, the uncertainty on the interaction location increases with the detector length. Organic liquid scintillators are most commonly used to detect fast neutrons. They offer a high intrinsic efficiency and a good neutron/γ discrimination but they are affected by detection threshold. Therefore, the energy deposited by

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the neutron may produce a light amount below the sensitivity of the photosensor, which transforms the light into an electrical signal. If the incident neutron (and possibly the subsequent neutrons produced by nuclear reactions in the detector) interacts one or several times within the scintillator, the detector is triggered when the cumulative amount of produced light exceeds its threshold. Thus, the same detection time may correspond to neutrons with different initial kinetic energies. As a consequence, the neutron energy can only be estimated.

Monte-Carlo simulation codes, Section 2, are useful tools to analyze statistically the relation between the detection time and the kinetic energy. In Section 3, we show how the optimum estimator of the energy can be deduced from the detector response function. The different existing methods used to determine the neutron energy from its measured time-of-flight will be presented in Section 4 as well as a new approach which offers a much higher accuracy. The methods will be compared to each other using simulated data in Section 5 and experimental data in Section 6. The conclusions will be drawn in the last Section.

2. Monte Carlo simulation of a neutron detector

The Monte-Carlo code Menate [8,9] simulates the trajectories of neutrons and γ-rays inside sets of detectors. This simulation code has been used to understand precisely the link between the incident energy of the neutron and its measured time-of-flight. It was also used to calculate the response function of the detectors, i.e. the conditional probabilities $P_{\text{sim}}(t|E)$ for a neutron of energy E to be measured with a time-of-flight t. All possible interactions of neutrons and γ's with the detector medium are taken into account. The neutral particles generated by the interactions are followed in a recursive way and the amount of light deposited by the induced charged particles are calculated. The simulated detector corresponds to a DeMoN [10] cell, which is a cylinder filled with NE213 scintillator with a diameter of 16 cm and a length of 20 cm. The point-like source is placed on the cylinder axis, 60 cm from the front face.

The code generates a large number of neutrons ($N = 10^6$) for each value of the incident energy. The neutrons are emitted isotropically, but inside the solid angle of the detector. For each detected neutron, the trigger time t corresponds to the time when the amount of light deposited by the successive interactions is greater than the detection threshold. The value of the threshold, 0.91 MeV, is the same as for the experimental data used in Section 6. Fig. 1 shows $n(E,t)$, the number of neutrons with energy E detected at time t.

The detection efficiency as a function of the energy is equal to the proportion of detected neutrons, see Fig. 2:

$$\varepsilon(E) = \frac{1}{N(E)} \sum_t n(E,t) \tag{1}$$

The conditional probability to detect a neutron with a time-of-flight t when its energy is E is

$$P_{\text{sim}}(t|E) = \frac{n(E,t)}{N(E)} \tag{2}$$

As all neutrons are not detected, the normalization of this conditional probability is not equal to 1, but

$$\sum_t P_{\text{sim}}(t|E) = \varepsilon(E) \tag{3}$$

These quantities will be used to evaluate the neutron energies.

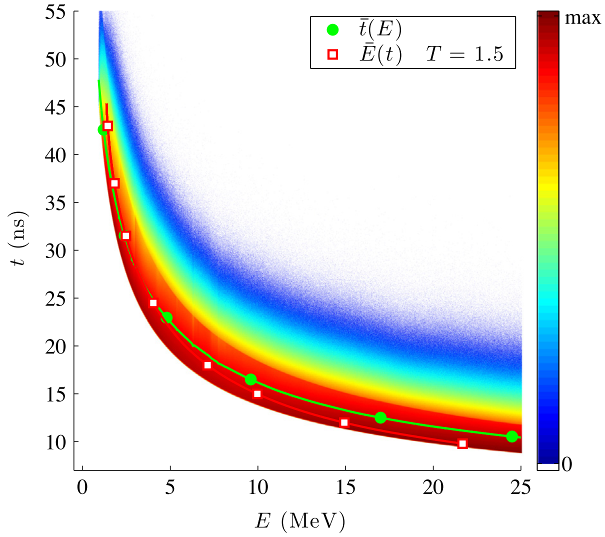

Fig. 1. Detection time distributions $P_{\text{sim}}(t|E)$ as a function of the neutron incident kinetic energy, in a logarithmic color scale, as given by the Menate simulation code. The green dots correspond to the average times at given energies $\bar{t}(E)$, see Eq. (10), and the red squares correspond to the average energies at given times $\bar{E}(t)$, Eqs. (4) and (7), for a Maxwellian source with temperature 1.5 MeV. The detection threshold is 0.91 MeV. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

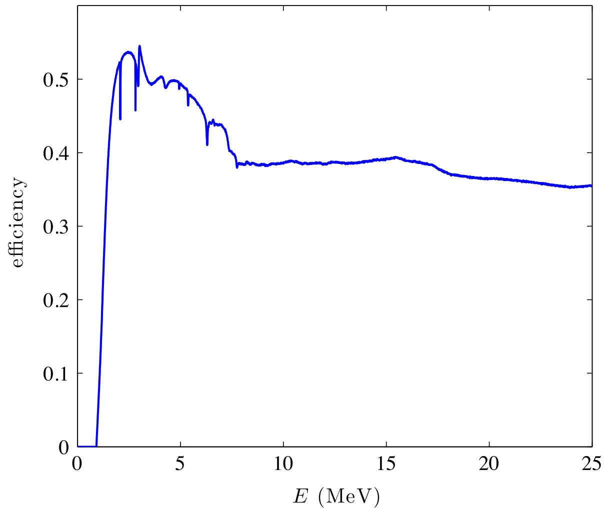

Fig. 2. Efficiency of the detector: probability for a neutron to trigger the detector as a function of the incident energy.

3. Algebraic formalization of the problem

Our objective is to determine the neutron energy from its time-of-flight. The optimum, i.e. with minimum variance, and unbiased estimator of the energy of a neutron with a time-of-flight t is the average value of the energy distribution of all neutrons with a time-of-flight t:

$$\bar{E}(t) = \sum_E E\, P(E|t) \tag{4}$$

Unfortunately, the conditional probability $P(E|t)$ is not known. However, they can be deduced from the reverse conditional probabilities, given by Eq. (2), using the Bayes formula:

$$P(E|t) = P_{\text{sim}}(t|E)\, \frac{P_{\text{sou}}(E)}{P_{\text{det}}(t)} \tag{5}$$

where $P_{\text{sou}}(E)$ is the probability that a neutron emitted from the source has energy E and $P_{\text{det}}(t)$ is the probability that a neutron is detected with time-of-flight t. Using the law of total probability, the