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Method for measuring multiple scattering corrections between liquid scintillators

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ABSTRACT

A time-of-flight method is proposed to experimentally quantify the fractions of neutrons scattering between scintillators. An array of scintillators is characterized in terms of crosstalk with this method by measuring a californium source, for different neutron energy thresholds. The spectral information recorded by the scintillators can be used to estimate the fractions of neutrons multiple scattering. With the help of a correction to Feynman's point model theory to account for multiple scattering, these fractions can in turn improve the mass reconstruction of fissile materials under investigation.

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1. Introduction

In this paper, we are primarily studying the effect of fast neutrons scattering between different scintillators, a phenomenon also known as neutron crosstalk. The reason why this study is important is that if a neutron scatters and deposits enough energy in multiple liquid scintillators to record multiple counts, it will not only artificially increase the count rate but also the numbers of two- and three-neutron correlations. For neutron multiplicity counting (NMC) applications, masses of nuclear materials undergoing fissions can be determined using ^{3}He tubes measuring thermal neutrons [1–4]. Cifarelli and Hage's [2] theoretical mass reconstruction is based on moments of count distributions, which are very sensitive to two-, three- and higher order correlations. The theory underlying the mass reconstruction assumes neutrons are only counted once, which is a correct assumption for ^{3}He tubes. However, because fast neutrons can scatter multiple times between scintillators [5–8] and register artificially correlated counts, this traditional moment method unfortunately fails for scintillators. Using modified expressions for the moment method to theoretically account for multiple scattering, it was shown [9,10] that the calculated fractions of neutrons scattering multiple times can be used to apply corrections to the masses of nuclear materials undergoing fission.

A summary of this paper is as follows. In Section 2, we describe the experimental setup, and characterize the scintillators. In Section 3, we discuss the time-of-flight method and the modified moment equations to determine the multiple scattering fractions for different neutron kinetic energies. Experimental measurements of these fractions are given in Section 4. In Section 5, we explain how the spectrum of energy deposited by the fast neutrons in the scintillators can be used to determine the multiple scattering fractions, and in turn to improve the fissile material mass and multiplication reconstruction.

A list of symbols used throughout the text is available in the appending nomenclature.

2. Detector characterization

Figures 1 and 2 show the geometrical configuration of the detectors, which are composed of different scintillating materials: EJ-301 and EJ-309 [11] cylindrical cells 4 in diameter by 3 in thick; backed by two kinds of photomultiplier tubes: Photonis [12] and Hamamatsu [13].

The liquid scintillators were calibrated in energy using a ^{137}Cs source placed in the middle of the line between the trigger detector and the wall of timer detectors. To reconstruct the spectra of energies deposited by the photons in the scintillators from the

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Nomenclature

LO	electron-equivalent energy deposited by fast neutrons and measured by scintillators
I_{ADC}	integral of ADC counts recorded by the PMT pulse digitizer
a	proportionality coefficient between LO and I_{ADC}
$(x_{\mathrm{src}}, y_{\mathrm{src}}, z_{\mathrm{src}})$	euclidean coordinates of the spontaneous fission source
$(x_\gamma, y_\gamma, z_\gamma)$	euclidean coordinates of trigger detector
(x_n, y_n, z_n)	euclidean coordinates of a timer detector
ΔT	time interval between gamma ray detection and fast neutron detection
c	speed of light
v_n	speed of the fast neutron
$E_{\mathrm{k,n}}$	kinetic energy of fast neutron
T	time gate duration
$b_n(T)$	probability to get n counts in a random time gate of duration T
$\bar{C}(T)$	number of counts averaged over all time gates of duration T
R_1^*	the hypothetical count rate which one would measure if individual neutrons could not be counted multiple times
$Y_{2F}(T)$	the excess over unity of the variance to mean ratio of $b_n(T)$, or physically speaking the correlated pairs relative to the counts, sometimes referred to as the Feynman correlated moment
$Y_2(T)$	$Y_{2F}(T)$ multiplied by $\bar{C}(T)$
$Y_{3F}(T)$	the skewness to mean ratio of $b_n(T)$, or physically speaking the correlated triples relative to the counts
$Y_3(T)$	$Y_{3F}(T)$ multiplied by $\bar{C}(T)$
f_2	probability of counting individual neutrons twice
f_3	probability of counting individual neutrons thrice
D_n	nth combinatorial moment of induced fission multiplicity distribution
$D_{n\mathrm{sp}}$	nth combinatorial moment of spontaneous fission multiplicity distribution
E_p	energy of proton recoil
$\tilde{g}(E_d)$	measured liquid scintillator spectrum
$g_{E_i}(E_d)$	probability that a source neutron of initial energy E_i will deposit an electron-equivalent energy within bin E_d. Basis functions for spectral reconstruction
$g^r(E_d)$	reconstructed liquid scintillator spectrum using basis functions $g_{E_i}(E_d)$

Greek

ϵ	neutron detection efficiency, or probability to detect a neutron
$\bar{\nu}$	average number of neutrons produced in induced fission
$\bar{\nu}_{\mathrm{sp}}$	average number of neutrons produced in spontaneous fission
α	inverse fission chain evolution time scale

integral of the ADC counts I_{ADC} recorded by the PMT pulse digitizer, the following linear expression was used:

$$LO = a \times I_{\mathrm{ADC}} \text{ [keVee]} \tag{1}$$

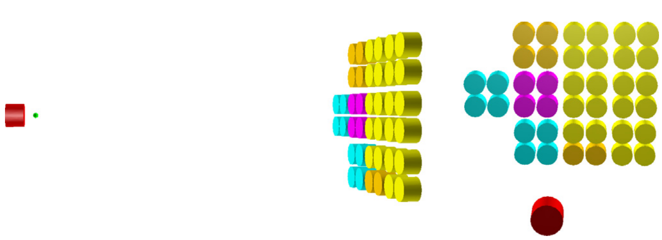
where a is a coefficient that depends on the scintillator/PMT assembly and is in units of keV/(integral of ADC counts). Given the energy of the gamma ray emitted by the ^{137}Cs, the spectra exhibited a Compton edge at 477 keV. This edge was detected by an algorithm described in Ref. [14]. Fig. 3(a) shows the measured energy spectra for all scintillators for the ^{137}Cs source. The quasi-straight line between the orange and yellow regions in Fig. 3(b) is the location of the ^{137}Cs Compton edge.

To determine whether the detector responses are indeed linear, we fit four Compton edges from three sources: 477 keV Compton edge from ^{137}Cs which emits 661.7 keV photons; 1062 and 341 keV Compton edges from ^{22}Na which generates 1274.5 keV and 511 keV photons, and 2382 keV Compton edge from ^{232}Th with its 2615 keV photons. For LS01 for instance, the coefficients a obtained are

0.308321 (2382 keV Compton edge of ^{232}Th),
0.310952 (1062 keV Compton edge of ^{22}Na),
0.314823 (477 keV Compton edge of ^{137}Cs) and
0.311387 (341 keV Compton edge of ^{22}Na).

Normalized by the mean $\langle a \rangle$ for LS01, they become 0.9902, 0.9986, 1.0111 and 1.0001, which indicates a small spread in the coefficient a. Repeating this procedure for each one of the scintillator/PMT assemblies, we determine how the coefficients are distributed for all detectors. Fig. 4(a) shows the distribution of these coefficients relative to their mean for the different Compton edges. The spread of the distributions are very small (standard deviation <1%). To the extent that such a small error can be neglected for our application, these distributions prove that the detector responses are indeed linear over the energy range 341 through 2382 keV. Fig. 4(b) shows the detector response of a liquid scintillator detector to a ^{22}Na source. The two Compton edges can clearly be identified.

The neutrons are discriminated from the photons using pulse shape discrimination (PSD) described in Ref. [15]. Fig. 5(a) shows neutron scores computed by the PSD algorithm for different detection events, as a function of the electron-equivalent energy deposited by the event. We can clearly distinguish two bands: the upper one filled with neutrons and the lower one with photons. For electron-equivalent energies greater than 2 MeVee, the two bands do not overlap significantly, leading to good discrimination. Below 2 MeVee, discrimination worsens, it becomes more difficult to distinguish neutrons from photons. The magenta outline in this plot defines a region where events are most likely neutrons, and will be tagged as



(a) Side view. (b) View from back of trigger detector.

Fig. 1. Geometry used to measure the multiple scattering fractions with a ^{252}Cf source. The ^{252}Cf source (in green) is located 5 cm from the trigger detector (in red, EJ-301/photonis PMT) and 254 cm from the front face of the wall of timer detectors: EJ-301/photonis PMT (yellow), EJ-301/hamamatsu PMT (orange), EJ-309/photonis PMT (magenta) and EJ-309/hamamatsu PMT (cyan). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)