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# Multiple-scattering Corrections to Measurements of the Prompt Fission Neutron Spectrum

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The Chi-Nu project, conducted jointly by LANL and LLNL, aims to measure the shape of the prompt fission neutron spectrum (PFNS) for fission of $^{239}$Pu induced by neutrons from 50 keV to 15 MeV with accuracies of 3–5% in the outgoing energy from 50 keV to 9 MeV and 15% from 9 to 15 MeV. In order to meet this goal, detailed Monte Carlo simulations are being used to assess the importance and effect of every component in the experimental configuration. As part of this effort, we have also simulated some past PFNS measurements to identify possible sources of systematic error. We find that multiple scattering plays an important role in the target geometry, collimators, and detector response and that past experiments probably underestimated the extent of this effect.

## I. INTRODUCTION

The Chi-Nu project (for "$X_\nu$", the neutron chi matrix) is a joint effort by Los Alamos National Laboratory (LANL) and Lawrence Livermore National Laboratory (LLNL) to measure the shape of the prompt fission neutron spectrum (PFNS) with improved accuracy. This effort is motivated by discrepancies between previous measurements at both low energies ($E < 1$ MeV) and high energies ($E > 6$ MeV). More details of the project and its motivation can be found in the paper by R.C. Haight *et al.* in these proceedings [1]. The experimental strategy to be employed involves measuring the low-energy ($E < 2$ MeV) part of the PFNS with an array of 22 $^6$Li-glass detectors and the high-energy part ($E > 0.5$ MeV) of the spectrum with an array of 54 liquid scintillator detectors. The overlap energy region between 0.5–2 MeV should provide good relative normalization of the two measurements and result in a combined data set spanning the energy range from about 50 keV to 15 MeV.

## II. LOW-ENERGY MEASUREMENTS

Detailed Monte Carlo modeling is an essential part of the experiment design and data analysis. Previous measurements leading up to the present project [2] demonstrated the importance of detailed modeling of the detector system and the environment in which it is situated. The experimental room in which the present measurements are being performed was designed to minimize background from "room-return" neutrons, which are neutrons that elastically back-scatter from the shield walls and floor and return to the detector position with delayed time-of-flight (TOF). The shield walls for the Chi-Nu measurements are situated a minimum of 3-m from the target position, and the entire target and detector apparatus sits on a thin (1.27-cm thick) aluminum floor spanning a 2.1-m deep pit. The beam and target centerline is 106.7 cm above the floor.

Actinide target samples ($^{235}$U, $^{239}$Pu, $^{252}$Cf) are contained in low-mass parallel-plate avalanche counters (PPAC) [3]. In the case of $^{239}$Pu, approximately 100 mg of material is distributed between ten thin double-sided Ti foils. Each of the ten PPAC cells is independently wired. Detection of a fission fragment in a PPAC cell provides a start signal for the TOF measurement of the outgoing fission neutron(s). Low-energy neutrons are detected in an array of 22 $^6$Li-glass scintillation detectors. The face of each detector is 40 cm from the geometric center of the PPAC. The detectors are arrayed over an upper hemisphere surrounding the PPAC and are held in position by a rigid frame consisting primarily of 1.27-cm thick aluminum plates.

Monte Carlo modeling is being performed using the "MCNPX-PoliMi" modified version of MCNPX [4]. We have taken care to test and include every component that affects the outgoing neutron flux in a statistically significant way. The final model is a high-fidelity reproduction of the PPAC, detector frame, detectors, and all other

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structural components including signal cables and gas lines. In addition, the model extends outward to include a volume of approximately $8 \times 8 \times 8$-m$^3$, which includes the room boundary formed by the shield walls and floor.

The effect of multiple scattering on the neutron energy spectrum (derived from TOF) is illustrated in Fig. 1. This figure compares three versions of a detected neutron spectrum: that from a "perfect" detector, represented by the product of the $^6$Li$(n, \alpha)$ cross section and a Watt input spectrum, a solitary $^6$Li-glass disk viewing a point source, and the full Chi-Nu model, which comprises the experimental room, PPAC, and detector array and all resolution effects. Note that detector "efficiency" (number of detected neutrons) increases substantially due to inscattering as more material is added to and surrounds the detector volume containing $^6$Li atoms.

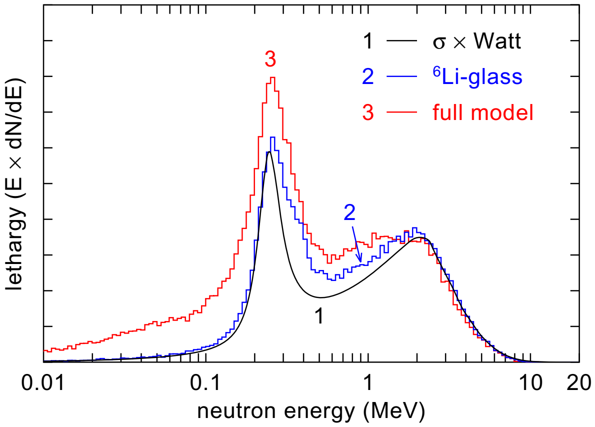

FIG. 1. (Color online) Simulated fission neutron spectra for one detector in the full Chi-Nu array (3), an isolated Li-glass disk (2), and an ideal pure $^6$Li detector (1).

Because multiple-scattering effects are so large, it is important to verify the accuracy of the calculations in as many ways as possible. One step in this process is shown in Fig. 2. In this figure we compare a simulated detector spectrum to some preliminary data for $^{252}$Cf. Since we are interested only in the shape of the spectrum, the relative normalization of the two distributions has been adjusted to give the best visual match. The quality of agreement between calculation and experiment at this stage is satisfying, especially since details of both the Monte Carlo simulations and the experimental data are still being refined.

Figure 2 well represents the daunting task of distilling the PFNS (represented by the "ideal" $\sigma \times$Watt spectrum) from the measured spectrum. The measured spectrum $S(E)$ can be represented by a convolution

$$S(E) = \int R(E, x) W(x) dx, \tag{1}$$

where $R(E, x)$ is a response function and the integral represents all possible paths that a neutron can take between

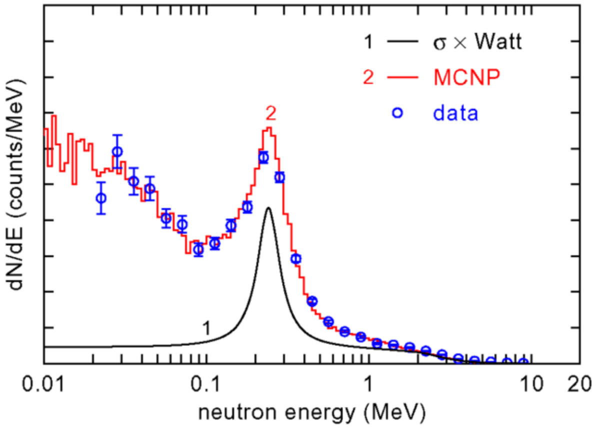

FIG. 2. (Color online) A comparison of an MCNP simulation of one detector in the Chi-Nu array and preliminary data obtained with a one-foil $^{252}$Cf PPAC. Neutron energy is derived from TOF.

source and detector. The response function embodies all experimental efficiency and resolution effects, and $W(x)$ represents the fission output spectrum that we are trying to determine. A convenient form for the response function is the product of a Gaussian resolution function and an efficiency function $\epsilon(E)$,

$$R(E, x) = G(E - x)\epsilon(x). \tag{2}$$

In the limit where the resolution function approaches a delta function,

$$R(E, x) \to \delta(E - x)\epsilon(x). \tag{3}$$

Eq. (1) reduces to the simple proportionality

$$S(E) = \epsilon(E) W(E). \tag{4}$$

Experimental analyses that make use of point-by-point detector "efficiency" functions implicitly assume the validity of the extremely optimistic reduction represented by Eq. (3). In the present case, it is easy to show that this reduction is not valid. The monoenergetic response function for one of the Chi-Nu detectors is shown in Fig. 3 for four outgoing neutron energies. The large low-energy tails on the responses mean that pointwise efficiency curves will not produce valid results. Instead, the underlying PFNS must be extracted by unfolding techniques. Such techniques have been previously applied with some success to extracting gamma-ray spectra from liquid-scintillator data [5]. In the present case, the unfolding procedure will need to be applied to 22 detectors $\times$ 10 PPAC cells = 220 individual measured spectra, and generating the necessary basis functions (as in Fig. 3) will require substantial computing resources. This unfolding technique will yield the PFNS directly. An alternate analysis strategy developed from MCNP sensitivity studies