Benchmark Evaluation of the Livermore Pulsed Sphere Experiment on ^{6}Li

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INTRODUCTION

The objective of this paper is to present a benchmark evaluation of the measurement of a high-energy neutron transmission spectrum through a spherical target made of ^{6}Li (~95% of the lithium mass) with a 14-MeV pulsed neutron source at the center. The measured data may be used to test the integral accuracy of the neutron transport codes and/or the associated cross-section data. The neutron count rate at the detector as a function of time provides information on the energy of the neutrons scattered in the sphere's material and on the adequacy of the cross sections used.

A series of 54 experiments was performed in the late 1960s and early 1970s at Lawrence Livermore National Laboratory to measure the neutron emission spectra through different materials of interest [1]. The experiments were performed on different materials relevant for shielding, fusion, and other fields. In these experiments an almost isotropic source of ~14-MeV neutrons obtained by bombarding a tritium target with a monodirectional beam of deuterons was placed at the center of a spherical assembly of target material. The ratio of intensities, I/I_0, with and without the spherical targets, was measured in each case at a certain angle with respect to the direction of the incident deuteron beam.

For the experiment analyzed here, the transmission spectrum at 116.7° through the ~0.5 mean free path thick ^{6}Li spherical material (for 14-MeV neutrons) was measured by using the time-of-flight technique over the energy range 2–15 MeV with a 2- × 2-in. NE213 detector at 1.6 MeV ("low ^{22}Na") bias.

A careful examination of the uncertainties introduced by the target assembly and lithium sphere, collimator and detector assembly materials and geometry, air scattering, source and detector characterizations, as well as the nuclear data used in simulations was performed to assess the reliability of the spectrum measured. To simplify the comparison between different sets of computed values, we followed a similar approach as in previous evaluations [2, 3] to define three "partial spectral indices" roughly corresponding to three energy ranges.

DESCRIPTION OF THE EXPERIMENT

Figure 1 (reproduced from ref. [2]) shows the schematic setup of the experiment. Only the 120° beamline (116.7° with respect to the deuteron beam direction) was used for this experiment. The spectrum collected by the detector (Fig. 2) is typical of time-of-flight (or time-of-arrival) experiments with about ¾ of the pulses corresponding to energies beyond 12 MeV.

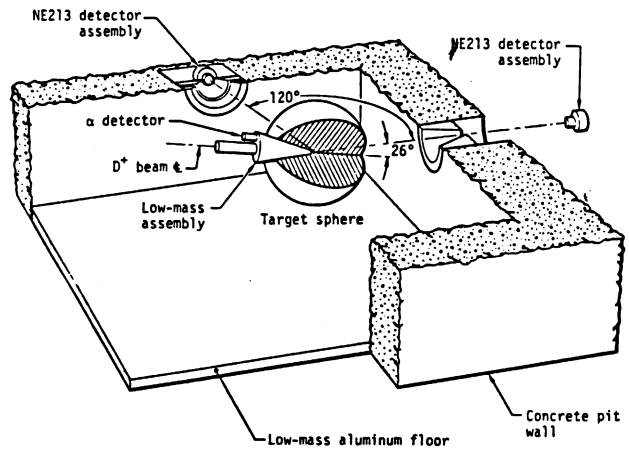

Fig. 1. Schematic view of the Livermore pulsed sphere experimental setup [2].

The characterization of the geometry and materials used is very good and is demonstrated to have little impact on the spectrum's uncertainty. The neutron source is produced via the T(d,n)^{4}He reaction on a T-Ti target below 400-keV deuteron energy, where it is isotropic in the center-of-mass system. The most probable energy of the reaction is 200 keV.

Three major sources of uncertainties are identified by experimenters: the time dependence of the D^+ ion beam, the energy spread induced by the D^+ ion energy loss in the T-Ti target, and the time spread due to electronics and detector size. It is suggested that these three uncertainty sources combine to give a (nearly) Gaussian time resolution function. The full width at half maximum (FWHM) of this distribution was inferred from the width of the neutron peak with the lithium sphere removed and is assessed to be 4 ns for this experiment

The accuracy of the efficiency curve of the NE213 detector was estimated by the experimentalists to be 7%. Since the measurements are relative, only the shape of the efficiency curve is important. This was estimated to have an accuracy of 4%. Unfortunately, the experimenters did not provide an explanation of how the variation between curve shapes was quantitatively assessed.

The experimental results are the count rates for each 2-ns interval divided by the total count with the sphere removed. Also reported are the statistical errors associated with the detector count rates for each 2-ns time bin.

SIMULATIONS

The simulations were performed using the MCNP5 code [4]. The scalar flux at the detector is assessed for the cases with the lithium sphere in place and removed and the experimental count rates are simulated by calculating for each time t in a 2-ns time interval the following ratios:

$$\frac{I}{I_0} = \frac{[R(E)]\times[\Phi(E(t))]}{\int_{t(E=1.6MeV)}^{t(E=15MeV)} [R(E)]\times[\Phi_0(E(t))]dt} \qquad (1)$$

In the above equation, $R(E)$ is the detector efficiency, while $\Phi(E)$ and $\Phi_0(E)$ are the neutron fluxes with and without the lithium sphere, respectively.

To assess the impact of the uncertainties on the measurements, we considered two classes of uncertainties: The first class is related to the insufficient or possibly imprecise information on the geometry description of the experimental configuration and the characterization (mainly densities) of the relevant materials. This class includes the material and geometry uncertainties related to target assembly, lithium sphere, collimator and detector assembly, and the environmental air. The second class of uncertainties consists of those related to the physics of the neutron production, transport, and detection. Specifically, it addresses the uncertainty associated with neutron source characterization, the detector response and the neutronic cross sections used in the transport simulation. For each category enumerated, a standard deviation in the final results (the three spectral indices) is assessed. Finally, these standard deviations are compounded considering the perturbations statistically independent to obtain the uncertainties in the spectral indices. The uncertainties of the spectral indices are then transferred to the pointwise (or bin-wise) data to obtain curve bounds for the simulated spectrum.

RESULTS AND CONCLUSIONS

Bounding curves corresponding to experimental and simulated values of the quantity I/I_0, as calculated in Eq. 1 are shown in Fig. 2. The calculations are, in general, in good agreement with the experimental values. The region of largest discrepancy is in the energy range 8–12 MeV.

The two sets of simulated bounding curves in Fig. 2 correspond to the case when the uncertainty in cross-sections is not accounted for and that when it is taken into account. As observed, the uncertainties considered cannot fully account for the discrepancy in the 8–12-MeV range. It can be shown that the chance of having a discrepancy greater than 9% between the measurements and calculations (non overlapping bands in Fig. 2), had the discrepancy been due to random errors, is ~10%. Further, if we assume that the code used for analysis does not have any internal coding problems that would lead to anomalous results and that there are no systematic errors in measurements, then there is a 90% chance that the uncertainties in cross sections are responsible for the differences between measurements and computations.

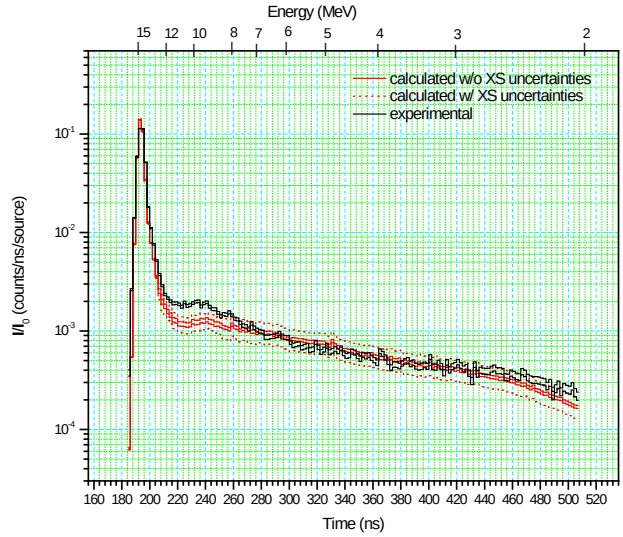

Fig. 2. Time-of-flight spectra bounding curves for the experiment and simulations.

It is concluded that the experiment described can be used as a benchmark to assess the accuracy of the evaluated cross-sections for ^{6}Li. The precision of the comparison (combined experimental and simulated uncertainties) is about 9% at a confidence level of ~90%. Comparison with evaluations for similar experiments is recommended.

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