Neutron Energy Spectrum with Microstructured Semiconductor Neutron Detectors

Brian W Cooper, Steven L. Bellinger, Anthony Caruso, Ryan G. Fronk, William H. Miller, Thomas M. Oakes, J. Kenneth Shultis, Timothy J. Sobering, Douglas S. McGregor

***Abstract*–Microstructured semiconductor neutron detector (MSND) devices have achieved 42% intrinsic efficiency when operated as a dual-detector device. The neutron energy spectrometer has alternating layers of MSND arrays, cadmium, and high-density polyethylene (HDPE) in a linear arrangement. The detector arrays consist of 4 dual-detector devices with 1-cm^2 detector elements in a stacked configuration. A 2 mm thick layer of cadmium separates each detector from the following layer of HDPE. The cadmium layer prevents thermalized neutrons from backscattering into the previous detector. The 3-cm thick HDPE layers act as a moderator for the epithermal and fast neutrons, allowing them to disperse energy within the spectrometer's volume and reach thermal energies to be detected by the MSND arrays. The resultant device is a neutron energy spectrometer with a large surface area for the incident neutron beam.**

Extensive modeling of the spectrometer has been performed using MCNP5. The modeling was used to determine the reference responses for multiple simulated neutron sources, including: TRIGA reactor, ^{252}Cf + D$_2$0, ^{252}Cf, AmBe, and 14 MeV. Also, multiple monoenergetic neutron beams ranging in energies of 1 eV to 10 MeV were simulated. These simulation spectra were compiled into a reference library. With a figure of merit calculation, the most likely reference spectrum and neutron source for an experimental spectrum is readily determined.

The spectrometer was tested using an unmoderated ^{252}Cf source. The experimental ^{252}Cf matches the reference library spectrum well, except for some higher than expected counts from detectors deep in the stack.

I. Introduction

THIN-FILM coated diodes have been researched and fabricated for many decades. These diodes suffer from low efficiency when used as neutron detectors; ^{6}LiF coated detectors generally have no greater than 4.5% intrinsic efficiency [1]. However, current work with microstructured semiconductor neutron detectors (MSNDs) has achieved 42% thermal neutron efficiency [2] with a double-stacked configuration to help reduce neutron streaming (see Fig. 1) [1]-[7]. The detectors are fabricated using KOH solution to etch straight trench patterns into the silicon. The trenches are ~350 micrometers deep and are backfilled with ^{6}LiF powder, followed by a cap layer of ^{6}LiF.

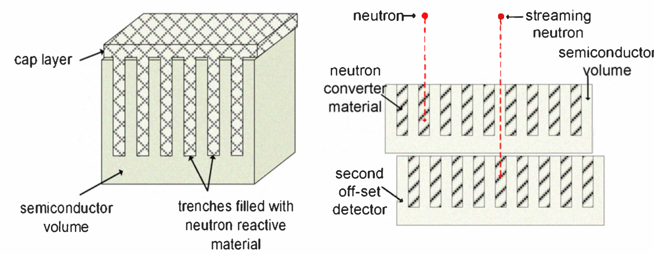

Fig. 1: Illustration of a trench-structured detector filled with neutron reactive material and a dual-detector device. Depicted on the right is the conceptual elimination of neutron streaming through the Si from stacking the 2nd detector off-set from the first detector.

However, because most types of neutron sources have a distribution of energies ranging from thermal through epithermal up to fast neutron energies, it is necessary to design a neutron spectrometer that is capable of detecting neutrons with a wide range of energies. Because ^{6}Li exhibits a 1/v absorption cross section with respect to neutron energy [8], [9], it is necessary to thermalize the epithermal and fast neutron components of the incident neutron beam so that the MSND arrays can detect them.

II. Neutron Energy Spectrometer Design

A. Neutron Spectrometer Design

The proposed neutron spectrometer arrangement is shown in Fig. 2. The spectrometer utilizes a four-plex array of stacked-pair detectors per device section, with as many as 20 detector arrays. Each stacked-pair detector consists of two 1-cm^2 high-efficiency microstructured thermal neutron detectors. Additionally, the counting electronics couple each detector pair together so that the signals are summed. Furthermore, all four dual-detectors are summed. Therefore, the four-plex of dual-detectors operates as a single larger-area detector array. The first detector array measures the thermal component of the incident neutron beam before it undergoes any moderation within the spectrometer. A cadmium layer directly behind the first detector absorbs neutrons below the cadmium cut-off energy preventing them from interacting with detectors deeper in the stack. High-density polyethylene (HDPE) is placed before each subsequent detector and

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cadmium layer to partially moderate the neutron beam. The detector array measures the portion of the beam thermalized within that particular section of the spectrometer. After each successive detector, there is a layer of cadmium to prevent thermal neutrons from neutron backscattering into any of the previous detectors. High-energy, fast neutrons reaching deeper detector locations must pass through enough moderating material to slow to thermal energies before being detected. The outside and back of the moderator stack are lined with a cadmium sheath to prevent sub-cadmium cut-off neutrons from entering any side of the spectrometer (except for the front irradiated face).

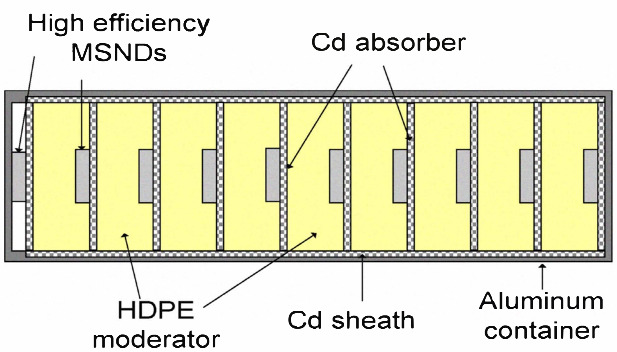

Fig. 2: Neutron spectrometer arrangement. The moderator stack is capable of thermalizing 14 MeV neutrons. Cadmium shielding is used to block backscattered moderated neutrons.

Fig. 3 depicts some possible outcomes as a neutron beam with a distribution of neuron energies travels through the moderator stack. Some of the thermalized neutrons will enter a detector array and be counted. Others may scatter and be absorbed by the cadmium shielding either before they can interact with a detector array or before they escape the spectrometer; any counts corresponding to these absorbed or escaped neutrons are lost. Many higher energy neutrons will undergo several scattering interactions before they lose enough energy thermalize.

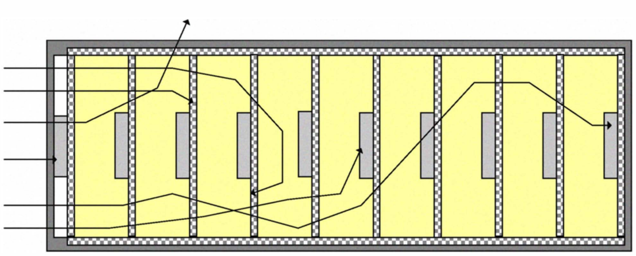

Fig. 3: Some possible trajectories and interactions within the neutron spectrometer as epithermal and fast neutrons lose energy by scattering through the moderator material.

B. MCNP Modeling

Extensive modeling has been conducted using the MCNP5 code to simulate an incident neutron beam traveling through the neutron spectrometer. Several different neutron sources were modeled, including; TRIGA reactor, ^{252}Cf + $D_2$0, ^{252}Cf, AmBe, and 14.1 MeV fusion neutron (Fig. 4). Also, multiple mono-energetic neutron beams, ranging from 1 eV to 10 MeV (Fig. 5), were modeled. For each neutron source an expected reference spectrum was generated. It is important to note that each simulated spectrum was normalized with respect to the second detector location. This eliminates dependence of the responses on source strength. These reference spectra are compiled into one reference library. This library allows a comparison of an experimental spectrum to the reference library for the identification or matching of the most likely neutron source.

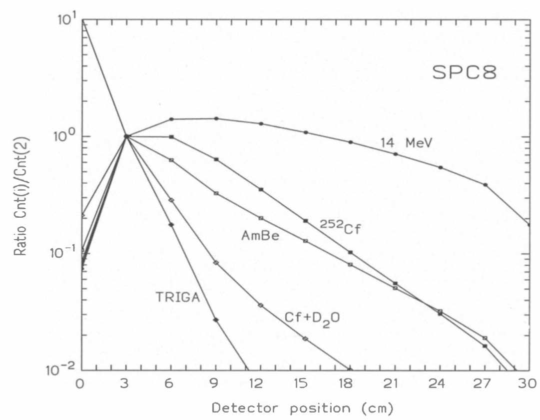

Fig. 4: MCNP simulation results from possible neutron sources, normalized with respect to the second detector.

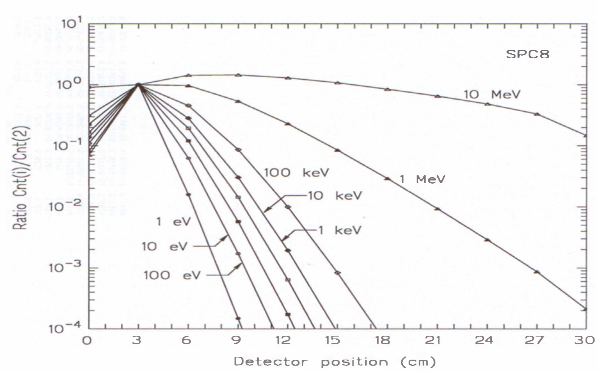

Fig. 5: MCNP simulation results for different monoenergetic neutron beams, normalized with respects to the second detector.

C. Figure of Merit

Figure-of-merit calculations are used to find the most likely neutron source for an experimental spectrum. Compared in Eq. 1 are the observed counts for each detector array R_i and the corresponding simulated counts for detector array S_i^j from reference library spectrum j.

$$FOM_j = \sum_{i=1}^{\det N} \frac{\left(R_i - S_i^j\right)^2}{\sigma^2\left(R_i\right) + \sigma^2\left(S_i^j\right)} \quad (1)$$

For **(1)**, $\sigma^2(R_i)$ is the variance associated with the experimental count R_i and $\sigma^2(S_i^j)$ is the variance associated with the simulated, normalized count S_i^j. Here $\sigma^2(R_i)$ and $\sigma^2(S_i^j)$ are given by

$$\sigma^2(R_i) = \frac{1}{C_i} + \frac{1}{C_{norm}} \quad \textbf{(2)}$$

and

$$\sigma^2(S_i^j) = \sigma^2(\ln(\frac{r_i}{r_{norm}})) = rel_i^2 + rel_{norm}^2 \,. \quad \textbf{(3)}$$

In **(2)**, C_i is the observed count for a particular detector location and C_{norm} is the observed count chosen to be the normalization location. For **(3)**, rel_i is the relative error for the simulated count and rel_{norm} is the relative error for the simulated normalization count.

III. Experimental Procedure

The neutron spectrometer was tested using the unmoderated ^{252}Cf source at the Kansas State University TRIGA Mark II Reactor Facility. The ^{252}Cf had a neutron activity of 1.07x10^9 n/s at the time of testing. The irradiated face of the spectrometer was placed 34 inches away from the source. For proof of concept, only one detector pair was utilized. The detector pair was placed in the thermal detector location and a 10 minute measurement was conducted. The detector pair was then stepped through the deeper detector locations and 10 minute measurements were performed. A NIM bin counter/timer was used for each measurement. To ensure a consistent detector response, care was taken that the detector pair had the same orientation for each measurement.

IV. Results

The total number counts for measurements at each detector location are presented in **Table I.** The experimental results are displayed in Fig. 6 overlaid on the simulated results. It is important to note that each set of results were normalized individually by their respective second detector location count. The experimental data points closely follow the simulated data points for the first 8 detector locations. However, for the last 3 detector locations of the spectrometer, the experimental counts were higher than expected.

Table I. Experimental Results

Experimental Counts per location			
Detector	Counts	Detector	Counts
1	402 +/- 0.0499	7	220 +/- 0.0674
2	2117 +/- 0.0217	8	145 +/- 0.0830
3	2059 +/- 0.0220	9	126 +/- 0.0891
4	1218 +/- 0.0287	10	158 +/- 0.0796
5	654 +/- 0.0391	11	104 +/- 0.0981
6	401 +/- 0.0499		

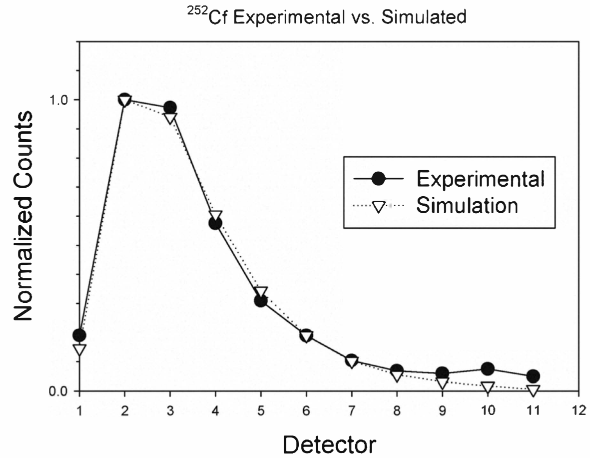

Fig. 6: Depicts the experimental spectrum for ^{252}Cf and the simulated spectrum.

V. Conclusion

The neutron energy spectrometer was able to match the simulated reference response for ^{252}Cf well. The first eight detector locations followed the expected spectrum closely. It was only with the last three locations that differences are observed. It is likely that these deviations were due to room-scattered neutrons entering deeper regions of the spectrometer from the side and undergoing sufficient moderation to thermalize and interact with detectors at deeper locations. Further modeling and testing is planned.

Acknowledgment

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