Performance of a Moderating Neutron Spectrometer That Uses Scintillating Fibers

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Abstract

The Bonner sphere is the canonical example of instruments that provide a measure of neutron spectra by using moderating and absorbing materials together with thermal-neutron detectors. For such spectrometers, the instrument response reflects a statistical average of the energy spectrum. Pacific Northwest National Laboratory has developed neutron-sensitive cerium-activated scintillating fibers composed of lithium-silicate glass. These fibers present an enabling technology for efficient neutron spectroscopy. A moderating spectrometer was built as a testbed for identifying materials. Based on the results of Monte Carlo experiments, six fiber layers are separated by polyethylene layers whose thickness was chosen to maximize neutron spectral information. The completed, self-contained instrument, including electronics and a data-logging computer, has a mass less than 35 kg, slightly more than half of which is polyethylene.

This instrument was used to measure various sources representing hard and soft neutron spectra. Because this instrument is a technology testbed, the data are recorded as pulse-height spectra. Results and future directions are presented.

Introduction:

Neutron-energy spectra are frequently measured by indirect methods. This is because of the experimental limitations in detecting fast neutrons. Neutron moderation, combined with sensitive thermal neutron detection, is one approach to measure neutron-energy distributions. The Bonner sphere is the canonical example of such a spectroscopic device. A set of spheres of different diameters is used to obtain spectroscopic information. The instrument response reflects a statistical average of the energy spectrum. Spectral unfolding is required, and the resolution and efficiency are typically poor, although the potential bandwidth is very large (Ref. 1).

Pacific Northwest National Laboratory has developed cerium-activated scintillating fibers composed of lithium-silicate glass. These fibers are sensitive to thermal neutrons because they are enriched in ^{6}Li. The clad fibers form waveguides ~150 um in diameter. This allows for thin detector layers between moderating sheets. This approach should make compact, efficient neutron spectrometry possible.

Monte Carlo calculations determined the design criteria for construction of a moderating neutron spectrometer for use in arms-control applications (Ref. 2). The design was optimized for good energy separation in the 0.1- to 10-MeV range. Also, a quality test was developed to compare the spectrometer responses for two input spectra and provide a measure of the probability that the two responses are statistically different. These calculations demonstrated that neutron sources of

importance to arms control and non-proliferation activities can be distinguished with measurement times of a few minutes.

The detector consists of six fiber layers with seven high-density polyethylene layers forming a monolith (Fig. 1). It is asymmetric in the sense that there are differing thicknesses of polyethylene between the fiber layers from the front and the back faces of the spectrometer. Additionally, there are three removable layers of polyethylene, two on one face and one on the other. The spectrometer and all supporting electronics are contained within a single enclosure that plugs into 120 V power. A separate portable computer, powered by the spectrometer, collects and stores the data. The enclosure is ca. 20-by-40-by-100 cm (Fig. 2 and 3). The spectrometer unit is ca. 35 kg, of which ca. 18 kg is polyethylene. The high-density polyethylene sheets are ca. 30-by-40 cm and 1 or 2 cm thick. From the face with thinner moderator sheets, the sensing layers are 3, 4, 6, 8, 9, and 10 cm deep backed with 4 cm of moderator. These dimensions include the removable moderator, which was included for the measurements reported here. The sensing layers consist of parallel fibers laid ~120 fibers per cm of width to cover as much of the width with the active fiber core as possible. The fibers are bundled and attached to 1.25-cm-diameter single photon counting photomultiplier tubes at either end. The six layers of fiber collect data simultaneously.

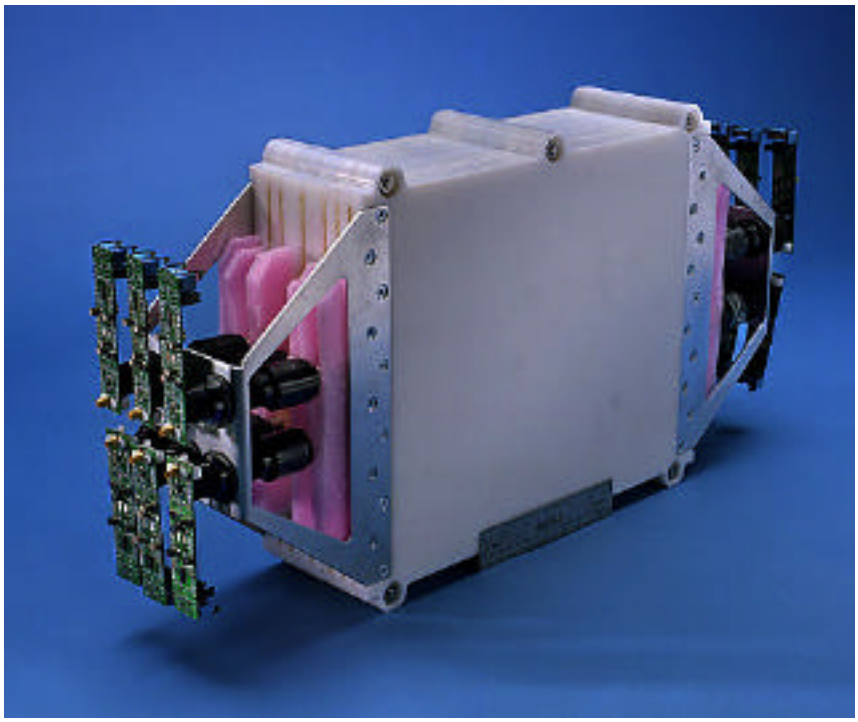

Fig. 1. Photograph of the polyethylene and thermal neutron-sensing fiber monolith with photomultiplier tubes (inside black housings) and amplifier/discriminator circuitry attached (cantilevered green boards).

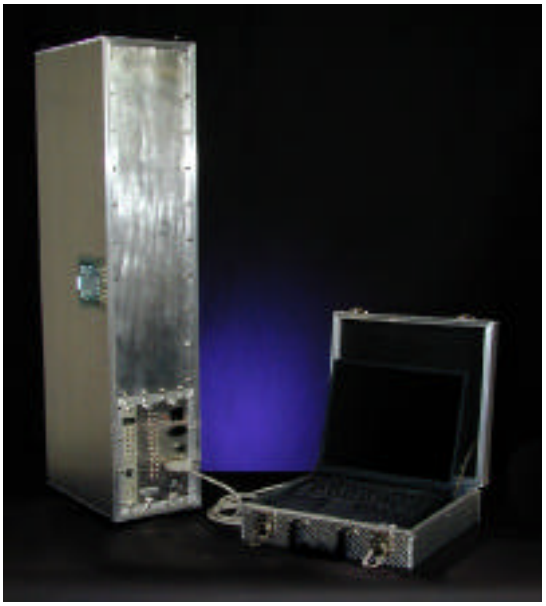

Fig. 2. Photograph of the completed spectrometer with data-logging computer. The polyethylene and sensing fiber monolith is mounted vertically in the upper portion of the detector box with supporting electronics in the bottom portion.

Because the spectrometer is a test-bed device, the output of the fiber-layers is pulse-height spectra, i. e., number of photoelectrons per detection event. The output is presented as a 6-by-16 table showing the total number of photoelectrons recorded for each of the six fiber layers. The software contains the option of requiring coincidence between the two ends of each layer, an approach that has been used in previous fiber-based detectors to improve neutron/gamma-ray discrimination. The coincidence criteria are that data collection will not start until one photoelectron has been detected at each end of the fiber layer. Data collection then proceeds for 200 ns followed by 800 ns of delay before the next detection event can take place (these time parameters are adjustable in the test bed electronics). Gamma-ray interactions in the fiber typically generate no more than one or two photoelectrons. Events that generate four or more photoelectrons are, with high probability, generated from neutron interactions. This approach collects a large quantity of data that are being used to assess the optimal spectral combinations for classifying different radiation sources. The use of pulse heights allows the incorporation of gamma-ray information without collecting gamma-ray spectra.

Fig. 3. Photograph of spectrometer unit together with AT-400R container in a typical measurement configuration.

Experimental:

The spectrometer was set up in a relatively low-background environment consisting of an ca. 6-meter-by-6-meter metal-walled room with two exterior walls. The geometric center of the polyethylene is ca. 0.6 m above the floor. The test sources are AmLi, PuO_2, ^{252}Cf, and PuBe. The AmLi emits a total of ~$2.4 \cdot 10^4$ n/s; the PuO_2 is a 100-g weapons-grade plutonium oxide source emitting a total of ~$4 \cdot 10^5$ n/s, about equally from spontaneous fission and alpha-neutron reactions; the ^{252}Cf is a collection of button sources emitting a total of ~$9.5 \cdot 10^4$ n/s; and the PuBe is a 1-g ^{239}Pu source emitting a total of ~$1.3 \cdot 10^5$ n/s. Test sources were located 1 m from the spectrometer face and were ca. 0.5 m above the floor. Measurements were taken for 30-sec, 1-min, and 5-min intervals with and without coincidence and with each side of the spectrometer facing the source. Background measurements, with the sources ca. 50 m from the test area in a borated-paraffin-lined storage container, were performed between each change of sources.

The primary question being addressed with this pilot study experiment is "Can the spectrometer differentiate between sources using multidimensional count-rate data?" Two count-rate statistics, neutron dominant and a neutron/gamma-ray mix, were computed for each of the six layers. Neutron events produce more photoelectrons than gamma-ray events. Previous experience with fiber detectors indicates that the one and two photoelectron events are gamma-ray related. Events that are four photoelectrons or brighter have a greater than 99.99% confidence that they were generated by a neutron. The sources differed in emission rates, and, in a field setting, the emission rate would be an unknown. Consequently, the count rates were adjusted for emission rate and relative detection efficiency by holding the total counts in photoelectron bins 3 and 4 of Layer 1 constant. This ensured that any discriminative ability was due solely to a spectral signature and not gross activity.

Figure 4 summarizes the marginal discriminative ability of the spectrometer by the neutron/gamma-ray mix. This summary gives two 6-dimensional spectral signatures (Layers 1 through 6 for neutron dominant and neutron/gamma-ray mix) for each source. From this evidence, we may conclude that any one layer cannot effectively differentiate between the sources; however, Layer 6 shows promise as a single discrimination statistic. Taken in tandem, as a 4-dimensional spectral representation, good discriminative ability appears likely.

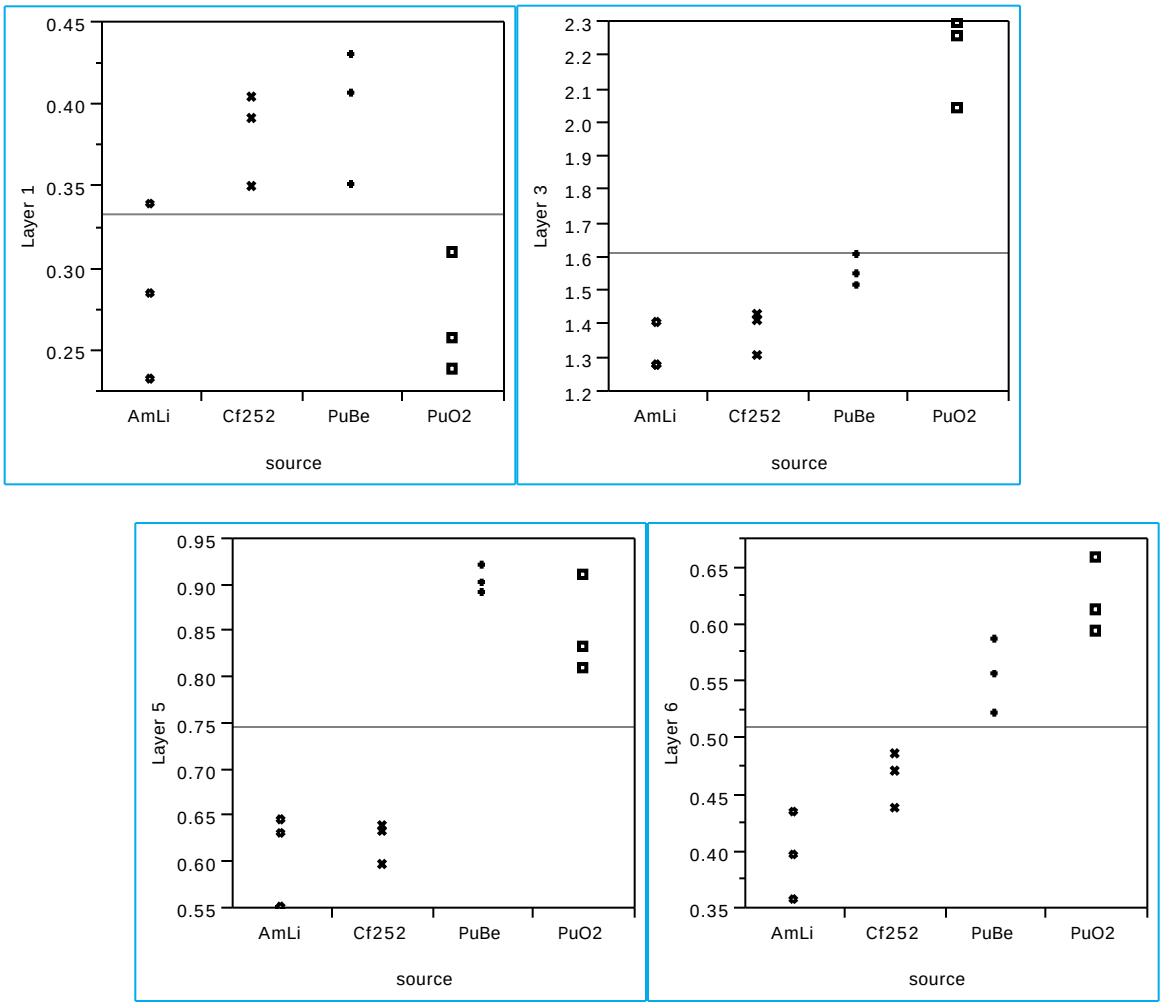

Fig. 4. Neutron/gamma-ray mix spectral signatures as a function of source. The plots strongly suggest that the neutron spectrometer can be used to discriminate between radioactive sources.

Linear discrimination analysis (LDA) is a commonly used statistical discrimination technique that is known to be consistently accurate. LDA was performed on these data to further confirm the discriminative ability of a multidimensional spectral signature. The apparent predictions from the application of LDA are given in Table 1. An accurate assessment of error rates will be completed from future in-depth experiments using cross-validation techniques. The statistics presented in

Fig. 2 are apparent and do confirm the strong promise of the spectrometer as a tool to detect and differentiate between radioactive sources. An equivalent analysis for the neutron-dominant statistics is given in Fig. 6 and Table 2. These data offer positive conclusions on discrimination ability.

		Predicted Source			
		AmLi	^{252}Cf	PuBe	PuO
True Source	AmLi	3			
	^{252}Cf		3		
	PuBe			3	
	PuO				3

Table 1. Apparent-source predictions from an application of Linear Discrimination Analysis to 4-dimensional Neutron/gamma-ray mix spectral signatures (Layers 1, 3, 5, 6). The table strongly suggests that the neutron spectrometer can be used to discriminate between radioactive sources.

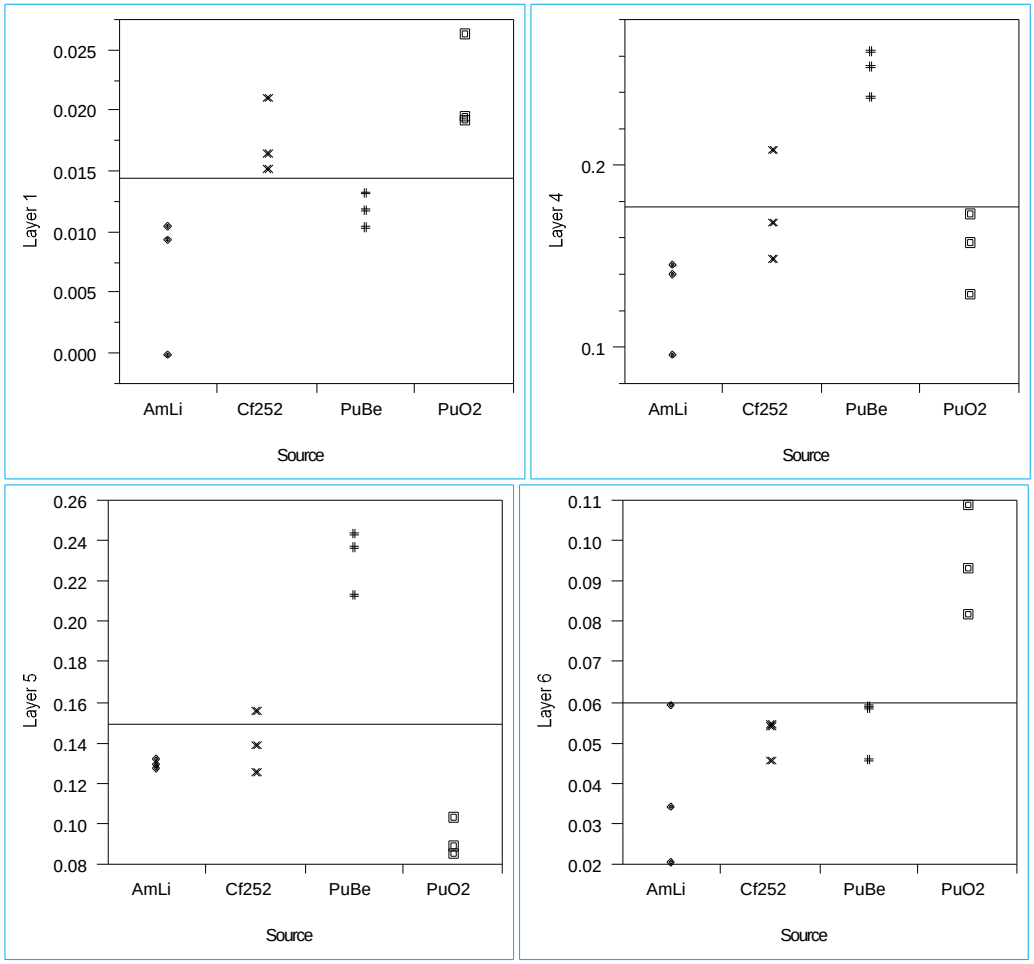

Fig. 6. Neutron-dominant spectral signatures as a function of source. The plots strongly suggest that the neutron spectrometer can be used to discriminate between radioactive sources.

		Predicted Source			
		AmLi	^{252}Cf	PuBe	PuO
	AmLi	3			
True	^{252}Cf		3		
Source	PuBe			3	
	PuO				3

Table 2. Apparent source predictions from an application of Linear Discrimination Analysis to 4-dimensional neutron-dominant spectral signatures (Layers 1, 4, 5, 6). The table strongly suggests that the neutron spectrometer can be used to discriminate between radioactive sources.

Discussion of Results

The neutron spectrometer is highly efficient. At this stage of development, it distinguishes between sources with different spectra with a high degree of statistical confidence. It is available for testing and demonstration of its potential in field settings.

Endnotes

1. Pacific Northwest National Laboratory is operated for the U.S. Department of Energy by Battelle under Contract DE-AC06-76RL01830.

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