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SIMULTANEOUS DETERMINATION OF FAST-NEUTRON SPECTRA BY TIME-OF-FLIGHT AND PULSE-HEIGHT UNFOLDING TECHNIQUES*

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Abstract

Proton-recoil spectrometers have frequently been used in the past few years to measure spectra for neutron energies greater than approximately 1 MeV with the results depending strongly on the adequacy of the response matrix used in unfolding pulse-height spectra. By simultaneously measuring a fast-neutron spectrum by time-of-flight and by pulse-height unfolding, the adequacy of the response matrix and unfolding code could be determined. Spectra of several shapes and measurements with different time-of-flight resolution were used to validate the spectra obtained by unfolding the pulse-height spectrum.

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Three problems associated with the development of a proton-recoil neutron spectrometer are (1) obtaining the correct energy calibration of the system, (2) discriminating against gamma rays, and (3) determining the correct detector response so that the energy spectrum can be obtained from unfolding the pulse-height data. The first step in an experiment employing a neutron spectrometer should be determining the extent to which the solution to these problems has been found. This, of course, is not always easy, but the techniques employed here help to check all the characteristics of the system.

In a series of measurements at the ORELA (Oak Ridge Electron Linear Accelerator) Shielding Facility, neutron spectra were determined simultaneously using both time-of-flight (TOF) and pulse-height spectra (PHS) unfolding techniques. Deciphering the time-of-flight measurements requires only the knowledge of the absolute efficiency of the detector, whereas the unfolding of pulse-height results to obtain neutron spectra depends on the adequacy of the response matrix utilized. Since the beam is relatively free of gamma rays after the initial gamma flash, discrimination against gamma rays may be done by time of arrival in the TOF measurement, but must be removed by some other means in the PHS measurement.

The radiation source for the ORELA Shielding Facility consists of a 140-MeV electron linear accelerator capable of producing up to 15 amps of electron current per pulse, 1000 pulses per second, and pulse widths of 2.3 ns to 1 μsec, depending on the repetition rate. Neutrons produced in a water-cooled tantalum converter are observed at an angle of 165° to the electron beam. Experimental areas are located at 30 and 50 meters from the source.

ORELA is designed for multiple experiments; thus some of these measurements were made when others were the principal investigators. Because of differing intensity requirements by the other investigators, various filters were placed in the beam to reduce the intensity to a tolerable level. These filters were placed approximately 9 meters from the linac target. The detector, a 4.65-cm-diam. by 4.22-cm-high NE-213 liquid scintillator, was placed on the beam centerline at 48.5 meters. The filters were always bigger in diameter than the collimated beam to prevent leakage around the sample. Because of the good geometry of the experiment, i.e., there was a long distance between the filter and both the source and the detector, the energy distribution of the radiation transmitted is determined by the total cross section of the filter or filters. (Inscattering is small because of the small solid angle of the filter and the detector.) Thus, the shape of the measured spectrum can be altered significantly by choosing different materials.

A block diagram of the electronics employed is shown in Fig. 1. There are three main paths of logic in the circuitry: (1) a gamma-flash detector which determines the fiducial point for the time-of-flight measurement also provides a "looking interval" pulse; (2) a fast signal from the anode of the RCA-8575 photomultiplier tube on the NE-213 detector provides a signal for determining the time of an event, a signal for a pileup detector, and a signal for the pulse-shape discrimination circuit; and (3) a linear signal obtained from dynode 9 of the photomultiplier tube is proportional to the amount of light produced in the scintillator and provides the pulse height and the zero crossing timing for the pulse-shape discrimination (PSD) circuit. There are several characteristics of

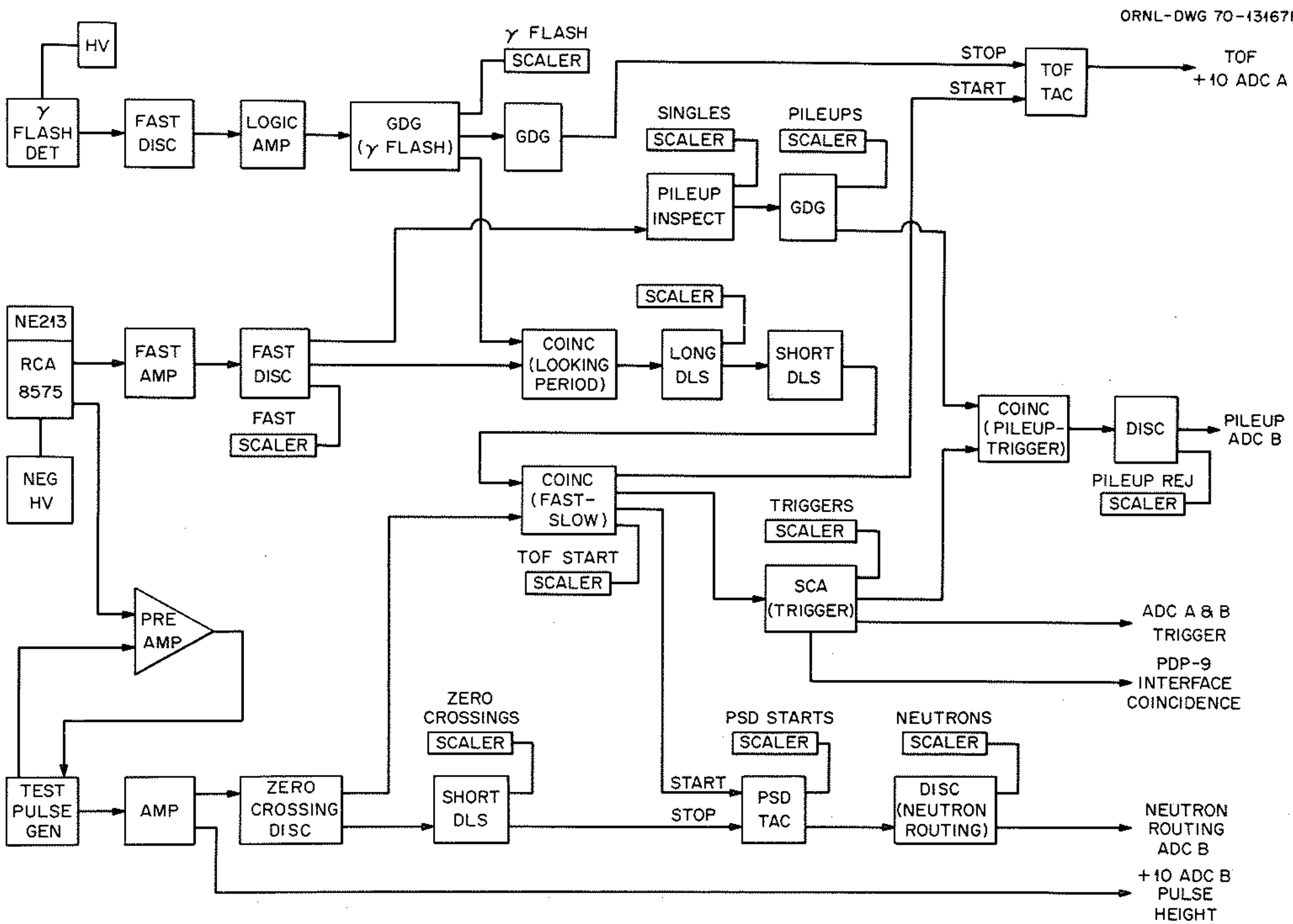

Fig. 1. Block Diagram of the Electronics Employed in the Simultaneous Measurement of Fast-Neutron Spectra by TOF and PHS Techniques.

this system that should be noted. First, by choosing a looking interval, i.e., a length of time after the gamma flash for which data accumulation is desired, the gamma events in the detector due to the gamma flash may be "time discriminated" as well as any long-time background pulses. The TOF time-to-pulse-height converter is started with an event in the NE-213 detector and stopped with the delayed gamma-flash pulse. The pulse pile-up circuit is used to determine if two or more pulses occur within a set interval (in our case, the looking interval). If two pulses do occur, then both events are counted and thrown away. This scheme removes the necessity of making a time-dependent pulse-pile-up correction.

The pulse-shape discrimination (PSD) circuit separates neutron and gamma-ray induced pulses by examining the time between the start of a pulse (fast-discriminator output) and the time at which the pulse crosses through zero after going through a double-delay-line amplifier. The output of the PSD time-to-amplitude converter is then fed through a single-channel analyzer which sets a routing flag if the lower level is exceeded.

Both the TOF and PHS analog-to-digital converters (ADC) are externally triggered only if there is both a TOF and PHS pulse. (The discriminator on the linear signal controls the lower level.) Thus, only pairs of pulses are stored. An on-line PDP-9 computer is used to sort the data and to store neutron TOF, gamma-ray TOF, "high-gain" PHS and "low-gain" PHS, as well as the two-dimensional TOF and PHS data. The "high-gain" signal is a factor of 10 times the "low-gain." (The two-dimensional data will not be discussed here.) Both "high" and "low" gain are taken simultaneously by attenuating the linear signal until a 10-volt pulse falls in channel

2560 of the ADC having a conversion gain of 4096. The high-gain data are obtained from the first 255 channels, and the low-gain data are obtained by binning 10 channels into one.

Energy calibration of the system is obtained by using a ^{22}Na gamma-ray source. A sample calibration curve is shown in Fig. 2. The maximum compton electron energies for the 0.511- and 1.277-MeV gamma rays are 0.341 and 1.064, respectively. Figure 2 shows the high-gain linear signal. Note that the lower level cuts off at about channel 6, which corresponds to approximately 0.03 ^{60}Co light units (^{60}Co light units were originally adopted as an energy unit.)[1,2] As an indication of the ability to separate the neutron and gamma-ray pulses by using a fixed discriminator for all pulse heights, Fig. 3 shows the PSD output for neutrons and gamma rays from an Am-Be source. The gain and bias level were the same as that used when the ^{22}Na calibration,shown in Fig. 3, was taken. (This corresponds to a dynamic range of approximately 35 in neutron energy.) Figure 4 shows similar results for a ^{252}Cf source. These results are typical of those obtained with the method of discrimination described here. If the lower level is reduced another factor of 2 the valley between the peaks begins to fill in. Two-parameter data indicate that the valley has not shifted over; it just appears to be less deep for the lower pulse heights since the pulse heights become comparable in size to the noise.

There have been several measurements of the absolute efficiency and of the response functions for the NE-213 detector.[3-6] The response matrix which we have used at ORNL since 1966 was based on a set of measurements at the ORNL Van de Graaff and on Monte Carlo calculations.[1,2] Although later measurements were made at ORNL[4] and elsewhere,[5,6] the response matrix

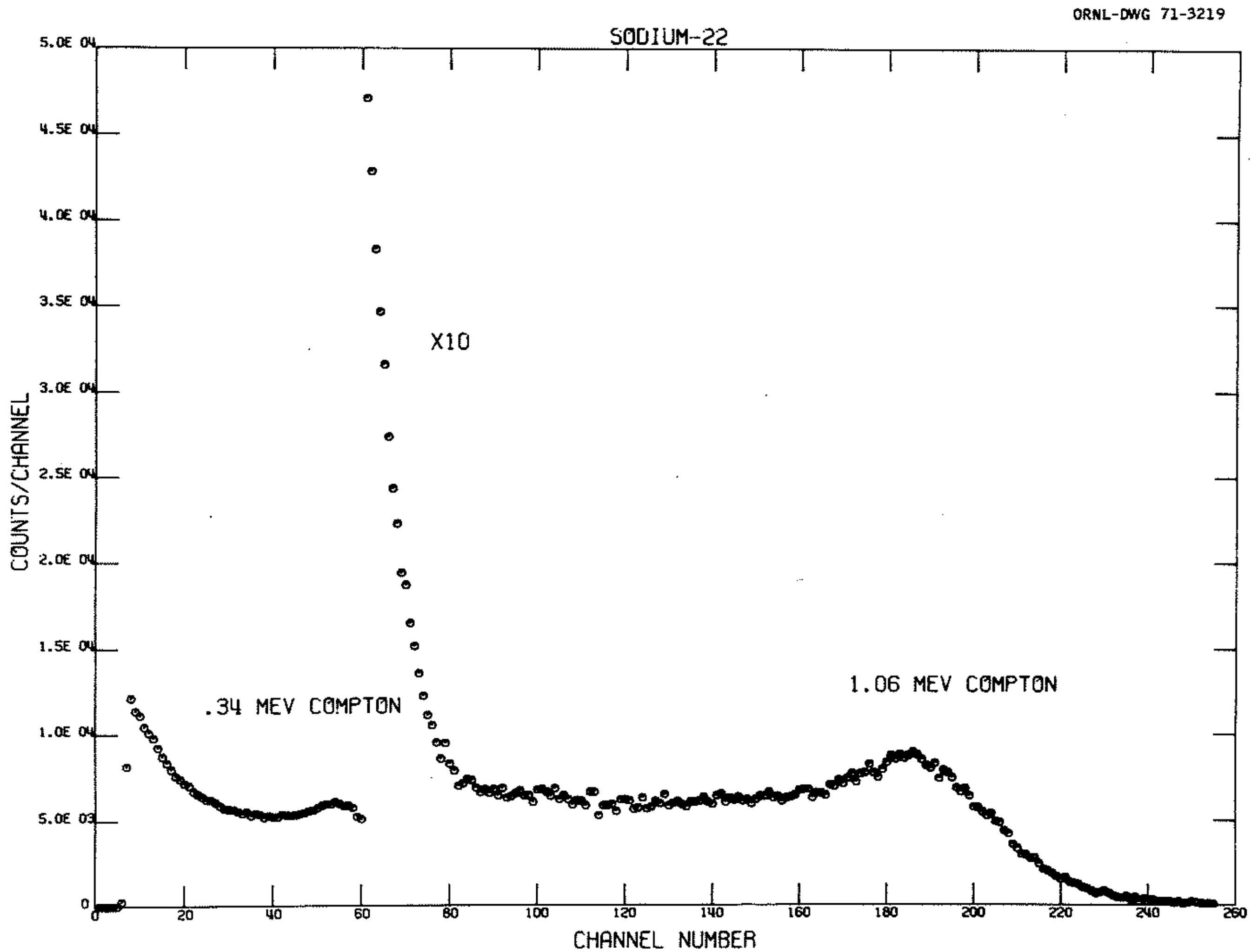

Fig. 2. Energy Calibration Curve Using a ^{22}Na Gamma-Ray Source.

(Note change in scale at channel 60.)

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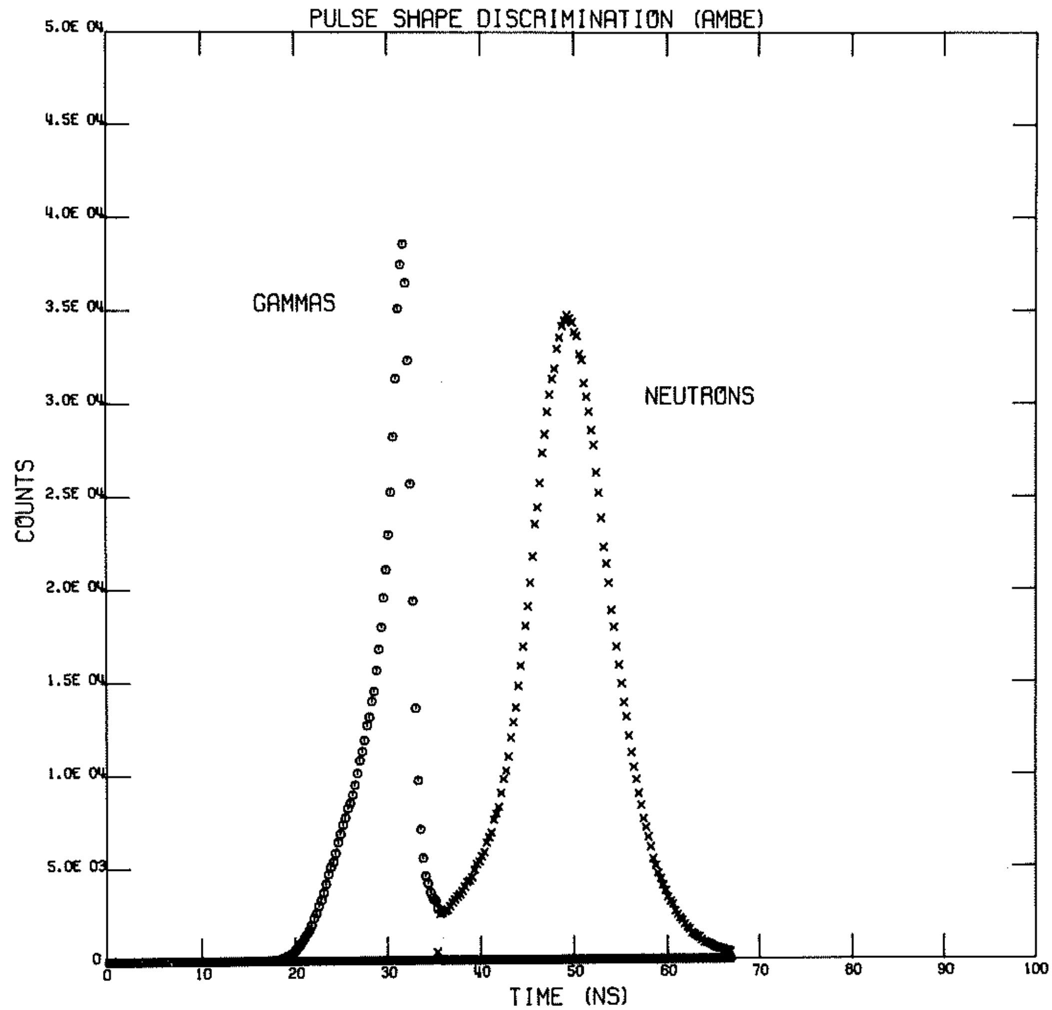

Fig. 3. Separation of the Neutron and Gamma-Ray Pulses by Pulse-Shape Discrimination for an Am-Be Source.

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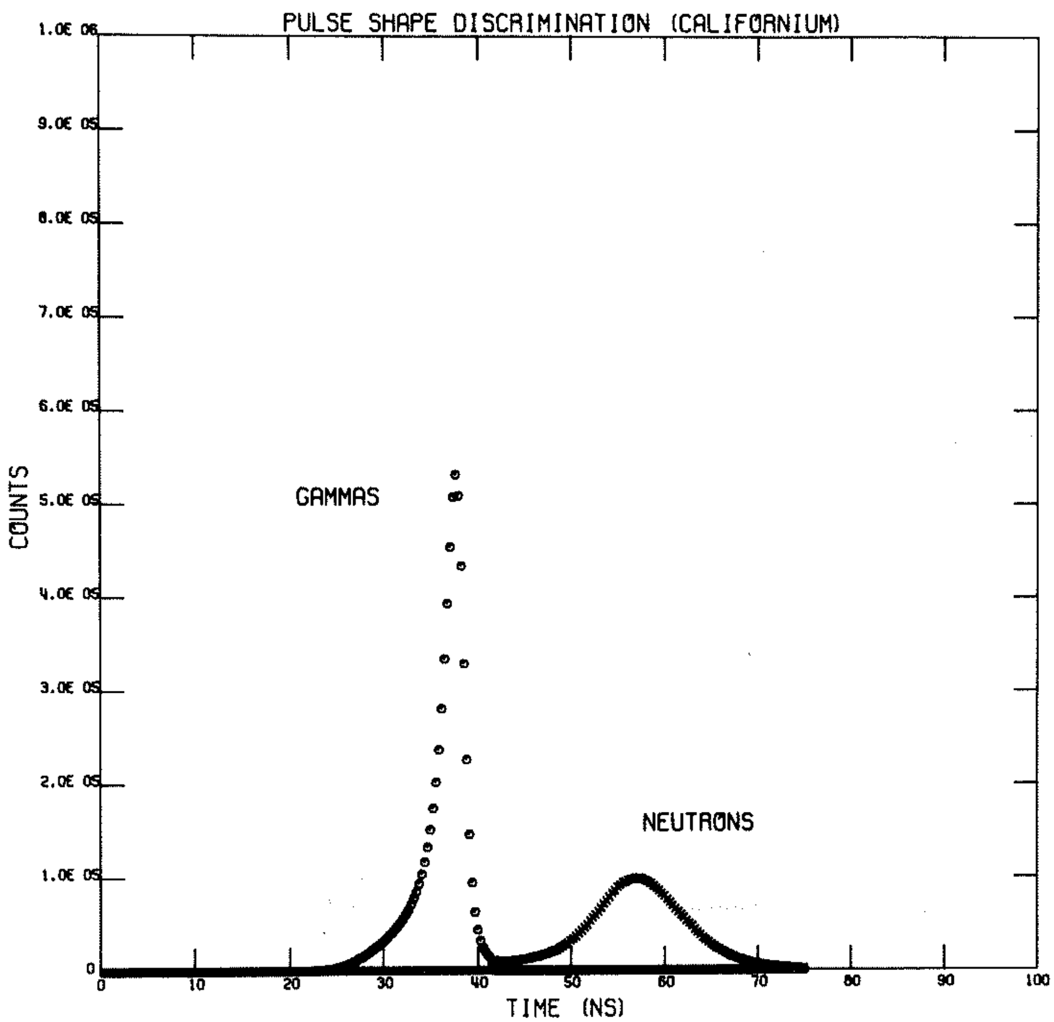

Fig. 4. Separation of Neutrons and Gamma Rays by Pulse-Shape Discrimination for a ^{252}Cf Source.

has not been changed. Many sets of experimental data have been unfolded with this response, and confidence has been gained in its accuracy;[7-10] nevertheless, a measurement of the type reported here is very definitive in determining its accuracy.

Measurements were performed at the ORELA Shielding Facility to determine the neutron spectrum resulting from the electron photon cascade in the water-cooled Ta target and to check out the data acquisition system. A 8.9-cm ^{238}U filter was used to reduce the beam intensity and to attenuate the gamma flash. (The initial gamma flash was time discriminated.) Figure 5 shows results of the neutron energy spectrum obtained through analysis of the TOF and PHS data. The three curves shown are the TOF results ($\approx$ 20 nsec per channel), the TOF results that have had the resolution broadened with a Gaussian function whose FWHM is the same as that used in unfolding the pulse-height data, and the spectral results from FERDoR[2] of the unfolded pulse-height data. The area between the bands (45° cross hatch) indicates the range in values for which there is a 68% probability that the results would fall if the run was repeated. Note that for this run the discrimination on the linear signal (PHS results) was significantly higher than that previously shown; thus results from unfolding the pulse-height distribution could not be obtained for neutron energies less than 1.2 MeV. The agreement between the two measurements is considered very good, but it is fairly obvious that the absolute intensity and energy calibration could be wrong and the agreement still exists (for example, imagine the pulse-height curve translated to the right and down). The spectrum was altered by introducing an additional filter, 20.3 cm of H_2O. These results are shown in Fig. 6. Again, there is

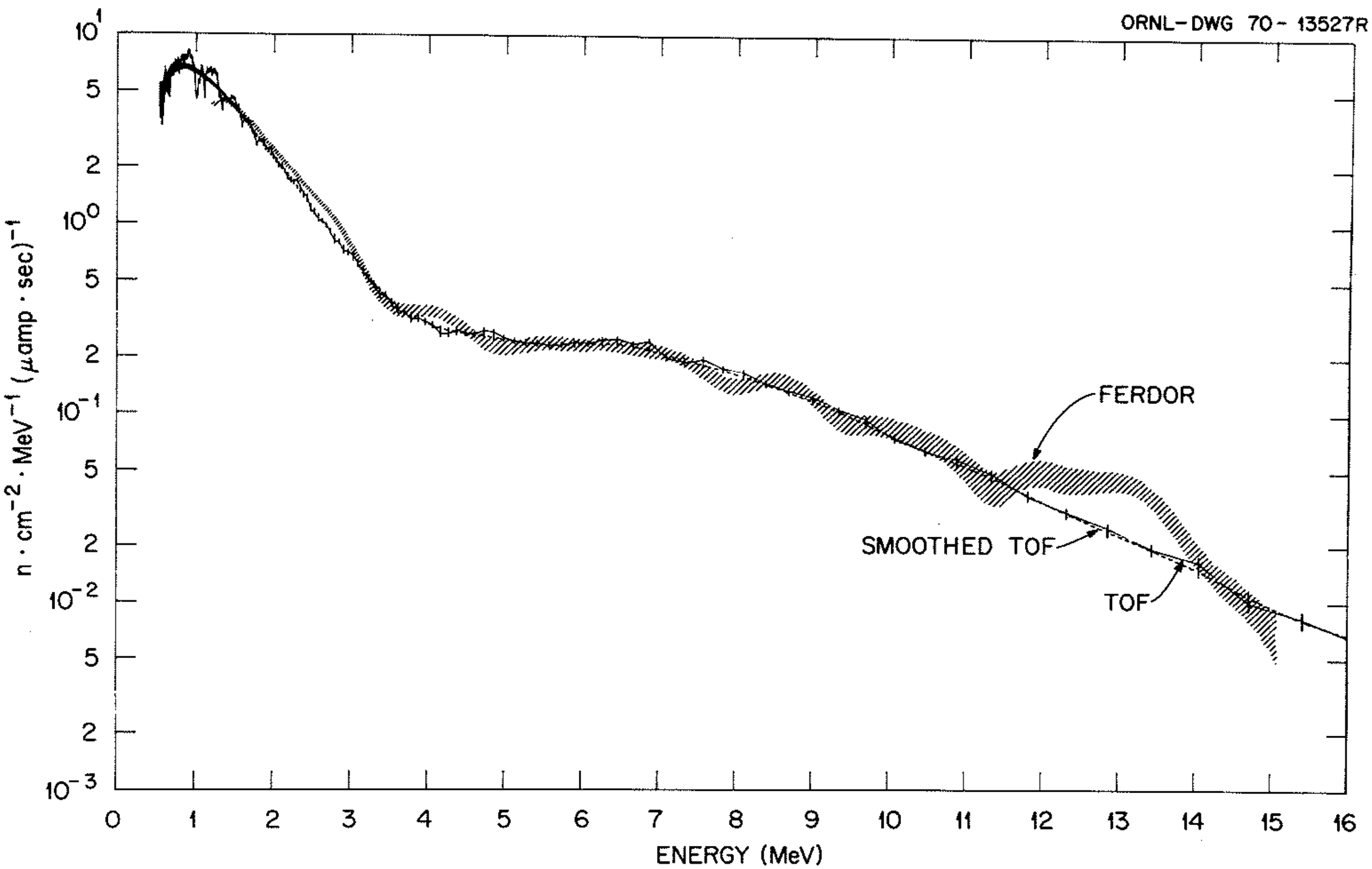

Fig. 5. Comparison of the TOF, Smoothed TOF, and PHS Results for a 8.9-cm ^{238}U Filter.

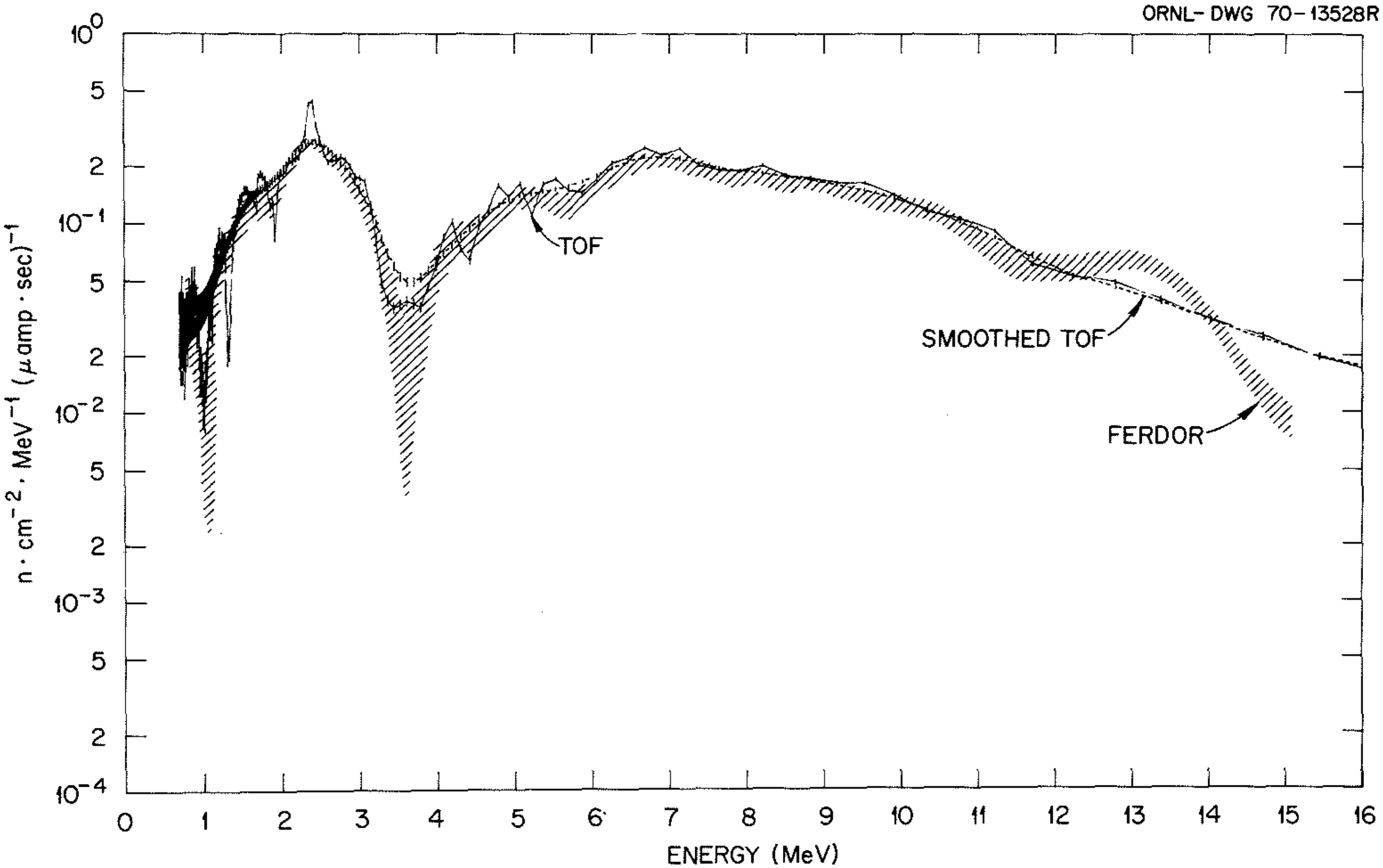

Fig. 6. Comparison of the TOF, Smoothed TOF, and PHS Results for a 8.9-cm ^{238}U and 20.3-cm H_2O Filter.

good agreement between the two types of measurements.

The persistent structure in the unfolded pulse-height data at high energies ($\approx$ 13 MeV) was bothersome, so another filter was introduced to provide known structure in the spectrum at higher energies. Figure 7 shows the results for 8.9 cm of ^{238}U and 20.3 cm of C. The TOF, smoothed TOF and PHS, results are shown. Without showing the smoothed results the conclusion would be that there is good agreement everywhere except near 8 MeV. With the smoothed TOF curve one sees that the apparent energy shift at 8 MeV is due to the much different energy resolution of the two techniques and that there appears to be a 10-20% discrepancy in the 2- to 3-MeV range. To further determine if resolution was indeed the cause of the disagreement near 8 MeV, a high-resolution TOF run was made ($\sim$ 2.5 nsec/channel). Figure 8 shows the results for the 8.9 cm of ^{238}U and 20.3 cm carbon filter. If one smooths the high-resolution TOF to the low-resolution TOF, good agreement is found as there is when it is smoothed to the resolution of the unfolded PHS data.

Attempts at extending the useful range of the detector system were made and Fig. 9 shows results for 8.9 cm of ^{238}U and 12.7 cm of Pb. (When the linac was running at high power for another investigator, a gamma-ray shielding material was frequently used instead of a neutron shielding material.) However, the choice of Pb was made here so that the peak at 0.5 MeV, due to a valley in the Pb total cross section, could serve as an indication of the lower level cutoff. The agreement between the two techniques is excellent over the range of 0.8 to 15 MeV. (In order to obtain good statistics in the PHS at high energies, data were accumulated for about 12 hours.)

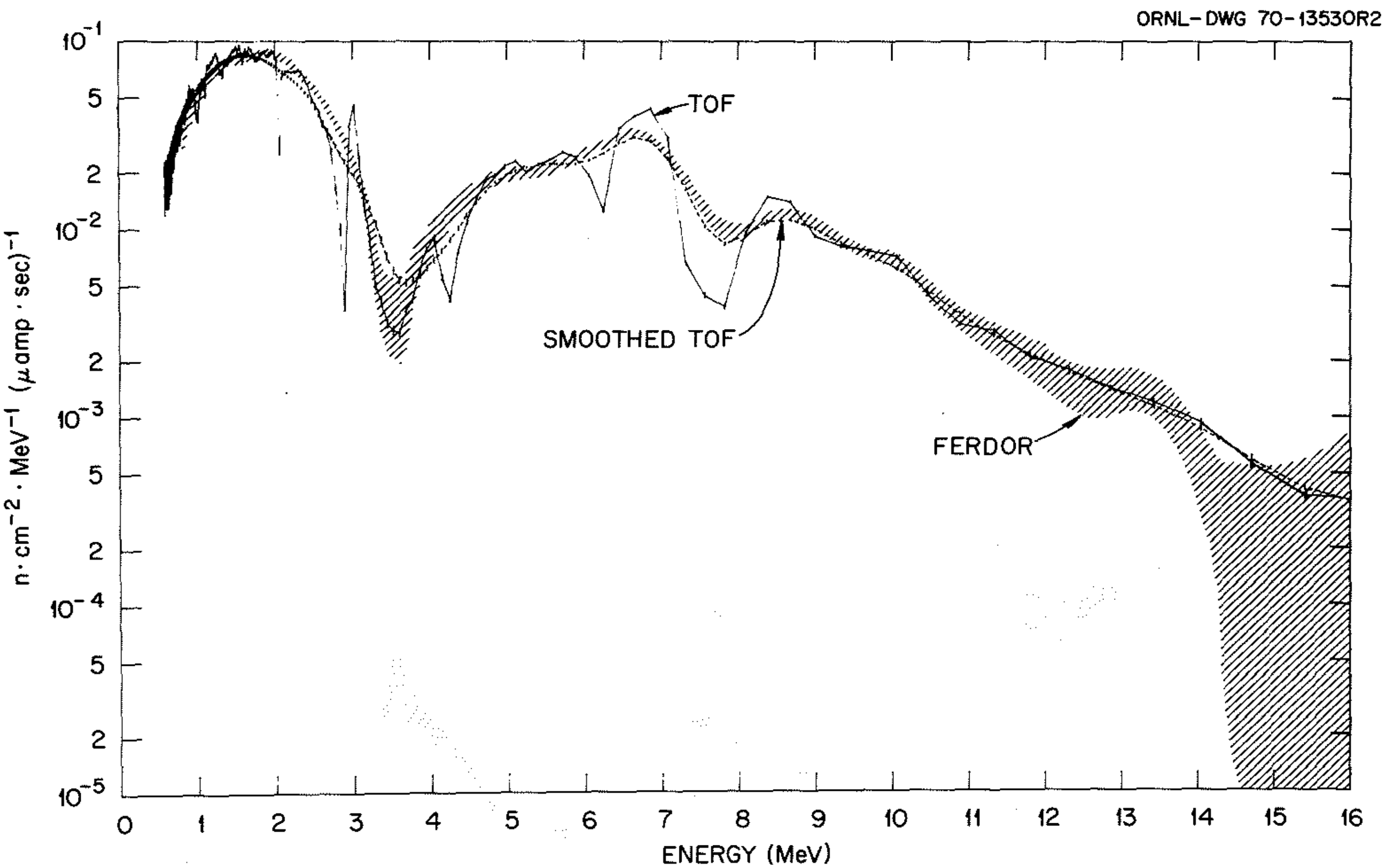

Fig. 7. Comparison of Low-Resolution TOF, Smoothed TOF, and PHS Results for a 8.9-cm ^{238}U and 20.3-cm Carbon Filter.

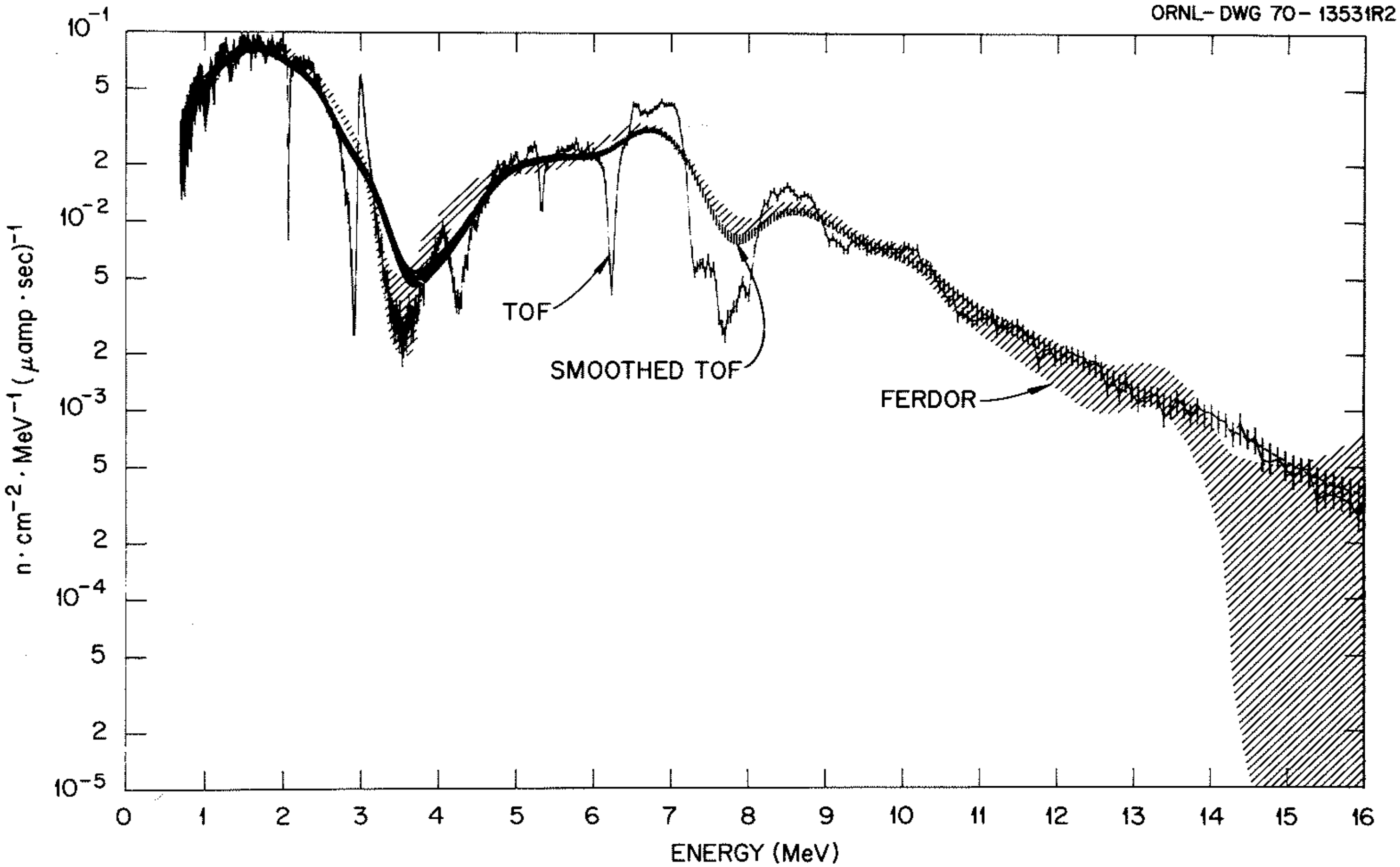

Fig. 8. Comparison of High-Resolution TOF, Smoothed TOF, and PHS Results for a 8.9-cm ^{238}U and 20.3-cm Carbon Filter.

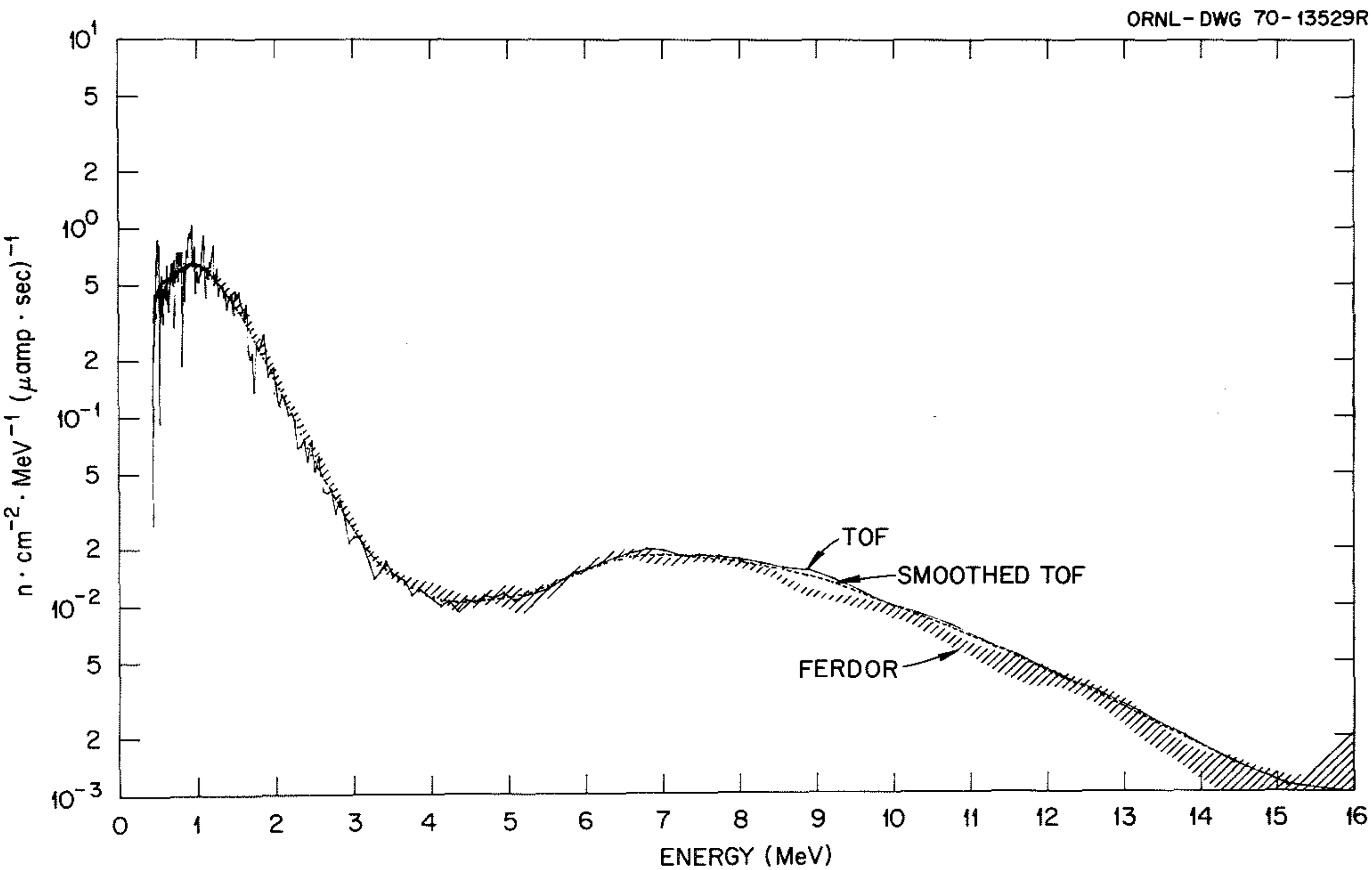

Fig. 9. Spectral Results for 8.9-cm ^{238}U and 12.7-cm Pb Filter for an Extended Energy Range.

The excellent agreement between the determination of spectra of various shapes by both TOF and PHS unfolding techniques indicates that the energy and time calibration of the system is accurate, that gamma-ray discrimination did not introduce a bias in the results, and that the detector response function is accurate in both shape and magnitude.

References

1. V. V. Verbinski _et al_., "The Response of Some Organic Scintillators to Fast Neutrons," _Proceedings of the Special Session on Fast Neutron Spectroscopy_, American Nuclear Society, ANS-SD-2 (1965).

2. W. R. Burrus and V. V. Verbinski, "Recent Developments in the Proton-Recoil Scintillation Neutron Spectrometer," _Proceedings of the Special Session on Fast Neutron Spectroscopy_, American Nuclear Society, ANS-SD-2 (1965).

3. T. A. Love _et al_., "Absolute Efficiency Measurements of the NE-213 Organic Phosphors for Detecting 14.5- and 2.7-MeV Neutrons," Rev. Sci. Instr. _39_ (4), 541-547 (1968).

4. V. V. Verbinski _et al_., "Calibration of an Organic Scintillator for Neutron Spectrometry," Nucl. Instr. Methods _65_, 8-25 (1968).

5. B. A. Pohl _et al_., "A Method for Determining Scintillator Response Functions for Fast Neutrons," UCRL-50653, Lawrence Radiation Laboratory (1969).

6. A. A. O'Dell, C. W. Sandifer, and R. B. Knowlen, "Neutron Counting Efficiency and Charged Particle Response of an NE-213 Fluor Detector," EGG-1183-2172, EG&G, Inc. (1968).

7. C. E. Clifford, E. A. Straker, F. J. Muckenthaler, V. V. Verbinski, R. M. Freestone, Jr., K. M. Henry, and W. R. Burrus, "Measurements of the Spectra of Uncollided Fission Neutrons Transmitted Through Thick Samples of Nitrogen, Oxygen, Carbon and Lead: Investigation of the Minima in Total Cross Sections," Nucl. Sci. Eng. _27_, 299-307 (1967).

8. E. A. Straker, "Experimental Evaluation of Minima in the Total Neutron Cross Sections of Several Shielding Materials," Nucl. Sci. Eng. _34_, 114-121 (1968).

9. V. R. Cain, "Comparisons of Monte Carlo Calculations to Measurements of Neutron Leakage From the TSF-SNAP Reactor," Nucl. Sci. Eng. 41, 310 (1970).

10. F. R. Mynatt, F. J. Muckenthaler, and P. N. Stevens, "Development of Two-Dimensional Discrete Ordinates Transport Theory for Radiation Shielding," CTC-INF-952, Union Carbide Corporation (1969).

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