ORTEC®

AN34 Experiment 16

The Total Neutron Cross Section and Measurement of the Nuclear Radius

Equipment Needed from ORTEC

- 113 Scintillation Preamplifier
- 266 Photomultiplier Tube Base
- 4001A/4002D Bin and Power Supply
- 556 High Voltage Power Supply
- 575A Amplifier
- Easy-MCA 2k System including a USB cable, a suitable PC and MAESTRO-32 software (other ORTEC MCAs may be substituted)
- Coaxial Cables and Adapters:
  - One C-24-1/2 RG-62A/U 93-Ω coaxial cable with BNC plugs on both ends, 15-cm (1/2-ft) length.
  - One C-24-12 RG-62A/U 93-Ω coaxial cable with BNC plugs on both ends, 3.7-m (12-ft) length.
  - Two C-24-4 RG-62A/U 93-Ω coaxial cables with BNC plugs on both ends, 1.2-m (4-ft) length.
  - One C-36-12 RG-59B/U 75-Ω cable, with SHV female plugs on both ends, 3.7-m (12-ft) length.

Equipment Required from Other Manufacturers

- Oscilloscope (bandwidth $\geq$100 MHz).
- Fast Plastic Scintillator and PM tube: e.g., a 2.5-cm x 2.5-cm KL-236 Scintillator Mounted on an RCA 6342A Photomultiplier Tube (or equivalent). Alternative organic (plastic) scintillators are: NE-102, BC-400 or BC-408. Optionally, a BC-501A liquid scintillator can be used to achieve neutron vs. gamma-ray discrimination via pulse-shape analysis. The BC- models are available from Saint-Gobain.
- 1- to 3-Ci Am-Be neutron source.
- Pure-element absorber rods (6 cm diameter x 7 cm long): 1 each AlRd-3 (aluminum), FeRd-1 (iron), CuRd-1 (copper), PbRd-1 (lead), PnRd-1 (paraffin). May require custom fabrication.
- High Transmission Stand, HTS-1: to securely position and hold the absorber rods, while contributing minimal neutron scattering. May require innovation or custom fabrication.
- Ref. 1: D.J. Hughes and R. B. Schwarz, Neutron Cross Sections, BNL-325. 2nd Edition (Rev) (1958). Available from National Technical Information Service, U.S. Dept. of Commerce, Springfield, Virginia.
- Small flat-blade screwdriver for tuning screwdriver-adjustable controls, or an equivalent potentiometer adjustment tool.

Purpose

In this experiment the total cross section, σ_T, the fundamental nuclear radius, R_0, and the neutron de Broglie wavelength, λ, will be determined from absorption measurements with several elements: aluminum, iron, copper, and lead.

Introduction

This experiment is based on the use of a 1-Ci Am-Be source, probably the most common of the neutron sources. The measurement of the neutron total cross section for an element is quite similar to the gamma-ray mass attenuation coefficient measurement made in Experiment 3. In this experiment, the data for calculations will be obtained by measuring the intensities of the neutrons from the source, both without an absorber and with an absorber placed between the source and the detector. (The method is described in greater detail in ref. 5.) Figure 16.1 shows the experimental arrangement of the source, absorber, and the detector for this measurement. The diameter of the organic scintillator on the photomultiplier tube defines the solid angle of neutrons accepted from the neutron source.

The distance from the source to the detector should be ~100 cm. The absorbers will be introduced, one at a time, at about the midpoint between the source and the detector.

SAFETY WARNING: *Handle the Am-Be source cautiously. One Curie (1 Ci) of this material produces in excess of* 10^6 *neutrons/s. Minimize your exposure time, and maintain as much distance as possible between the source and any part of your body. Choose the location for the source to minimize exposure to other people in the laboratory, or people passing by outside the laboratory. Access to the immediate area of the source should be restricted with a radiation boundary rope barrier, with radiation warning signs posted. When the source is outside of its shielded enclosure, it can be positioned by handling it with tongs at least 3-ft long, or by a long string. Instructions for the safe handling of the neutron source are supplied by the manufacturer of the source. These instructions should be read carefully before using the source.*

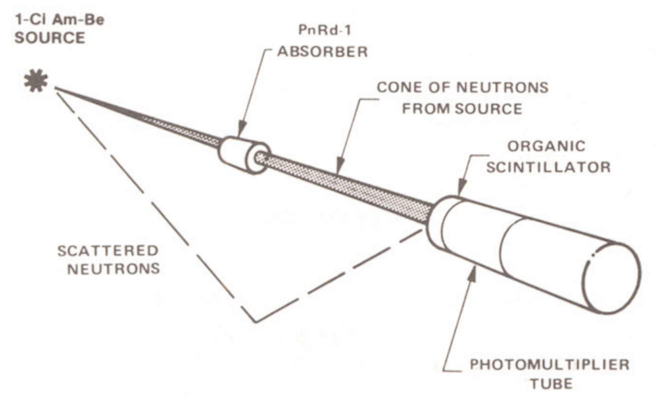

Fig 16.1 System for Measuring the Total Neutron Cross Section.

Figure 16.2 is a typical neutron energy spectrum from an Am-Be source. It was measured with a ^{3}He neutron spectrometer[†]. Obviously, the neutron spectrum is rather complicated. For this experiment, the neutron energies below 7 MeV will be rejected to minimize interference from gamma-rays and to simplify the calculation. The average neutron energy from 7 MeV to the end of the spectrum is approximately 8.5 MeV. A detailed analysis of

---

[†] Note that the ^{3}He (n, p) ^{3}H reaction inherent in the operation of the ^{3}He neutron spectrometer adds Q = 764 keV to the energy recorded in the spectrum. Q is the kinetic energy derived from a change in the total rest-mass energy of the constituents before the nuclear reaction to the total rest-mass energy of the products after the reaction.

the mathematical treatment of the neutron spectrum, as well as the total cross section, can be found in refs. 5 and 6. In this experiment, the total neutron cross section will be measured for a range of elements, and for an average neutron energy of 8.5 MeV. The experimental values should be compared with the accepted cross sections listed in ref. 1.

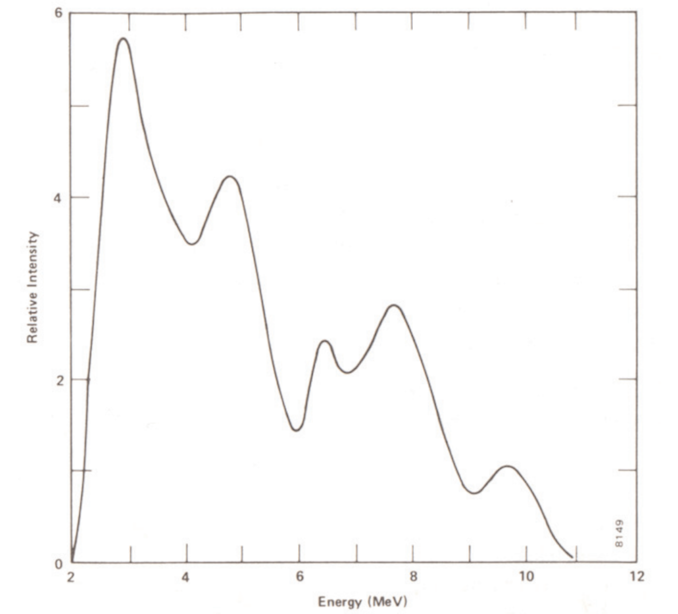

Fig 16.2 Typical Am-Be Neutron Source Energy Spectrum Measured with a ³He Semiconductor Spectrometer.

The Total Neutron Cross Section (TNCS)

The TNCS measurement is a transmission measurement. Referring to Fig. 16.1, the number of neutrons incident upon the front surface of the absorber rod at x = 0 is designated N_0. After transiting a distance x along the axial dimension of the cylindrical rod, the number of neutrons that have avoided absorption and scattering is designated N. In the differential interval from x to x + dx, the number of neutrons that are removed from the beam by absorption or scattering out of the beam is dN. Note that dN is proportional to both N and dx. The proportionality constant μ_x is known as the *linear absorption coefficient*. This relationship is expressed mathematically in Eq. (1).

$$dN = -\mu_x N\, dx \qquad (1)$$

Dividing both sides by N, then integrating the left side from N_0 to N_L, and the right side from 0 to L, leads to:

$$N_L = N_0\, e^{-\mu_x L} \qquad (2)$$

Where L is the total length of the absorber, and N_L is the number of neutrons in the beam that survived transit through the absorber.

The total cross section, σ_T, is defined from μ_x as

$$\sigma_T = \frac{\mu_x}{n} \qquad (3)$$

Where n is the number of nuclei per cm^3 of the absorber.

If we substitute Eq. (3) back into (2), the following relationship is obtained.

$$T = \frac{\left(\frac{N_L}{t_\ell}\right)}{\left(\frac{N_0}{t_\ell}\right)} = \frac{N_L}{N_0} = e^{-\sigma_T nL} \qquad (4)$$

Where the transmission, T, is the fraction of the incident neutrons that avoid absorption and scattering while travelling through the rod, and t_ℓ is the live time during which the neutrons are counted. Note that N_0/t_ℓ is equivalent to the neutron counting rate before the absorber is inserted, and N_L/t_ℓ is the counting rate measured after the absorber is inserted.

If T is measured, and both n and L are known, the total cross section can be calculated by casting Eq. (4) into the form:

$$\sigma_T = -\frac{\ln T}{nL} \qquad (5)$$

The samples to be used as absorbers are cylinders that are approximately 6 cm in diameter by a length, L ≈ 7 cm. The nL values for Eq. (5) can be calculated for each sample. These nL values are the number of nuclei/cm^2 for each absorbing sample. The transmission in Eqs. (4) and (5) is simply a ratio of the neutron counting rate with and without the absorber. For pure-element absorbers, the value of n can be calculated from

$$n = \frac{\rho\, N_{Avogadro}}{M_A} \qquad (6)$$

Where ρ is the density of the pure-element rod in g/cm^3, $N_{Avogadro} = 6.023 \times 10^{23}$ is Avogadro's number, and M_A is the gram-atomic mass of the pure element.

From the Optical Model Theory in ref. 4, the total cross section can be expressed as

$$\sigma_T = 2\pi\,(R + (\lambda/2\pi))^2 \qquad (7)$$

Where

$R = R_0\, A^{1/3}$

R_0 = the fundamental nuclear radius ($\approx 1.4 \times 10^{-13}$ cm),

A = the atomic weight of the pure-element scattering sample,

$(\lambda/2\pi)$ = the de Broglie wavelength divided by 2π for 8.5 MeV neutrons (ref. 4).

With the appropriate substitution, equation (7) can be rearranged to yield:

$$\sqrt{\sigma_T / 2\pi = R_0\, A^{1/3} + \lambda/2\pi} \qquad (8)$$

Or, the fundamental nuclear radius can be expressed as

$$R_0 = \frac{\sqrt{\sigma_T / 2\pi - \lambda/2\pi}}{A^{1/3}} \qquad (9)$$

As is evident in Eq. (8), if $(\sigma_T/2\pi)^{1/2}$ is plotted as a function of $A^{1/3}$ for the set of absorbers, the slope of the line is R_0. Furthermore, the intercept of the straight line at $A^{1/3} = 0$, yields an estimate of $\lambda/2\pi$, where λ is the de Broglie wavelength of the neutron. Beyond being an estimate of the size of the neutron, the de Broglie wavelength is a key parameter when the structure of materials is studied via slow-neutron diffraction. The de Broglie wavelength depends on the energy of the neutron, viz.,

$$\lambda = \frac{h}{\sqrt{2\,mE}} \qquad (10)$$

Where

λ is the de Broglie wavelength in meters,

$h = 6.6252 \times 10^{-34}$ Joule-seconds is Planck's constant,

$m = 1.6747 \times 10^{-27}$ kg is the mass of the neutron, and

E is the energy of the neutron in Joules (Note: 1 eV = 1.6021×10^{-19} Joules)

The purpose of this experiment is to measure σ_T for aluminum, iron, copper, and lead, and to determine R_0 by plotting the data per Eq. (8). R_0 will be determined from the slope of the straight line through the data points and compared to the accepted range of values from 1.34×10^{-13} cm to 1.48×10^{-13} cm. The value of $\lambda/2\pi$ from the graphical intercept will be compared to the accepted value of 1.56×10^{-13} cm derived from Eq. (10).

Procedure

1. Setup the electronics as shown in Fig. 16.3, and position the source and detector as shown in Fig. 16.1, separated by approximately 1 meter and located on a common optical axis. The high transmission stand (HTS-1) that will hold the absorbers and the shadow bar should be placed half-way between the source and the detector. The source, stand, and detector can be aligned on axis with a tight string, or, if available, a small laboratory laser. Do not leave an absorber in the stand at this point. The cables that connect the detector to the supporting electronics are at least 3 meters in length. This allows one to locate the supporting electronics a long distance away from the neutron source to minimize exposure to the experimenters.
2. Make the following cable connections among the electronics modules.
   a. Ensure the NIM bin power and the HV Power Supply are turned off.
   b. Connect the ANODE output of the 266 PMT Base to the INPUT of the 113 Scintillation Preamplifier using the 15-cm C-24-1/2 RG-62A/U 93-Ω cable. Set the INPUT CAPacitance switch on the 113 to zero.
   c. Connect the 113 Preamplifier power cable to the PREAMP POWER connector on the rear panel of the 575A Amplifier. Check that the time constant switches accessible through the side panel of the 575A Amplifier are all set to 0.5 µs.
   d. Insert the 575A Amplifier and the 556 HV Power Supply in the NIM bin.
   e. Connect the 113 Preamplifier OUTPUT to the 575A Amplifier INPUT using the 3.7-m C-24-12 RG-62A/U 93-Ω cable. Set the amplifier input polarity to NEGative.
   f. Using the 3.7-m C-36-12 RG-59B/U 75-Ω cable with two SHV female plugs, connect the OUTPUT of the 556 HV Power Supply to the POS HV input of the 266 PMT Base. Check that the POLARITY switch on the rear panel of the 556 is set to POSitive. Set the front-panel voltage controls on the 556 to their minimum values.
   g. Connect the Bipolar output of the 575A Amplifier to the analog INPUT of the Easy-MCA using the 1.2-m C-24-4 RG-62A/U 93-Ω cable.
   h. Turn on power to the NIM bin and the computer that supports the Easy MCA.
3. Adjust the controls on the instruments as follows:
   a. Set the 556 high voltage to the value that is recommended for the scintillation detector. Turn on the 556 HV POWER.
   b. Set the amplifier gain for a maximum bipolar output amplitude of approximately +5 V, as observed on the 1-MΩ input of the oscilloscope. Check that the FOCUS control on the related 266 PMT base has been adjusted to maximize the above pulse height. If the FOCUS control gets tweaked to maximize the signal, readjust the amplifier gain to achieve the +5-V amplitude. Reconnect the 575A BIpolar OUTput to the analog INPUT of the Easy-MCA.
4. Connect the UNipolar OUTput of the 575A Amplifier to the 1-MΩ input of the oscilloscope. Set the horizontal scale of the oscilloscope to 50 µs/cm and the vertical scale to 100 mV/cm. With a small, flat-blade screwdriver, adjust the PZ ADJ on the

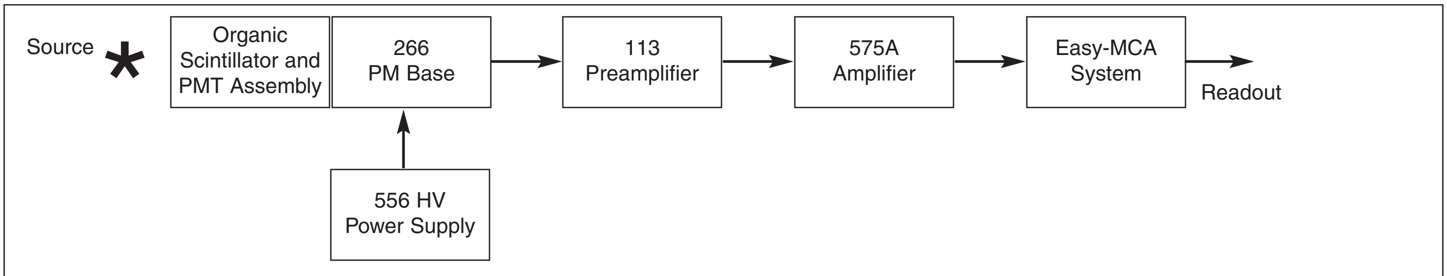

Fig. 16.3 Electronics for Total Neutron Cross-Section Measurement.

575A Amplifier to make the pulses on the UNIpolar OUTput return to baseline as quickly as possible without undershooting the baseline between pulses. For further guidance on the Pole-Zero Cancellation adjustment, consult the instruction manual for the amplifier, or the introduction to the amplifier product family on the ORTEC web site at www.ortec-online.com.

5. Via the Acquire menu and the ADC tab in the MAESTRO-32 software that operates the Easy-MCA, select the Gate Off option, and adjust the Upper Level discriminator to its maximum value. Adjust the Lower Level discriminator as low as possible without causing excessive counting rate on the noise. It may be useful to temporarily turn off the 556 High Voltage for the Lower Level discriminator adjustment. Under the Preset tab, clear all data fields, and do the same for the MDA Preset option (if supported). Clearing those fields will default to manual control for starting and stopping spectrum acquisition. Select the analog-to-digital conversion range to be 2048 channels for a 0 to +10-V input. Familiarize yourself with the software controls for setting up, acquiring and erasing spectra.
6. Accumulate a spectrum on the MCA. It should look like Fig. 16.4.*

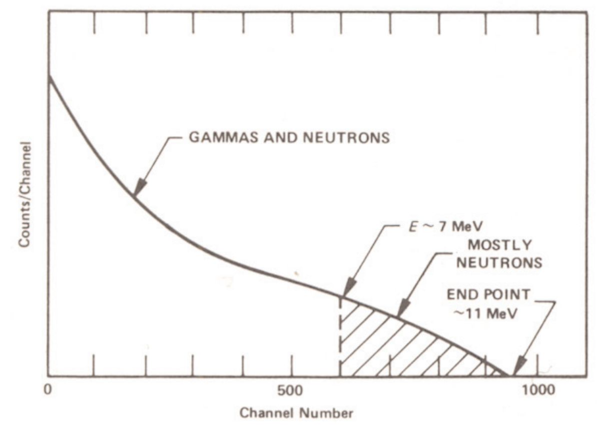

Figure 16.4 Typical Neutron Energy Spectrum Taken with the Organic-Scintillator Neutron Detector.

7. Set a region of interest (ROI) on the spectrum from approximately 7 MeV to slightly above the end-point energy at approximately 11 MeV. The 7-MeV point in the spectrum can be determined by a linear interpolation since the end point of the spectrum will be ≈11 MeV, and channel zero corresponds to zero energy. See the location marked E ~7 MeV in Fig. 16.4. Many of the pulses from the detector that represent energies below this level are gammas rather than neutrons. But, most of the pulses for energies ≥7 MeV are generated by neutrons only.
8. Accumulate a spectrum in the MCA until there are ~3000 counts in the area defined by the region of interest.

EXERCISES

a. Compare the spectrum with Fig. 16.4. In Table 16.1, record the i) number of counts in the area defined by the region of interest and ii) the **live time***, t_ℓ, required to accumulate the counts. Use the first line for “No absorber.”

b. Place the aluminum absorber in the stand (on the axis) as shown in Fig 16.1 and repeat the measurement made in step 8. Record the counts and the live time in table 16.1. Repeat this measurement for each of the other absorbers and for the paraffin shadow bar. The shadow bar effectively attenuates all of the direct neutrons from the source. Any counts that are accumulated when it is in position will be those scattered into the detector from the floor or other surroundings. This is background, and the counting rate recorded with the shadow bar must be subtracted from each of the other counting rates in Table 16.1 before these data are used.

c. For each absorber, divide the counts by the live time in Table 16.1 to calculate and record the counting rates. Subtract the

Table 16.1

Sample	Counts	Time, t_ℓ	σ_T	
			Measured	Accepted (from ref. 1)
No absorber				
Aluminum				
Iron				
Copper				
Lead				
Shadow Bar				

---

*The organic scintillator is rich in hydrogen content, which offers a lot of protons for the neutrons to interact with. The neutrons scatter from the protons like billiard-ball collisions. The energy transferred to the recoiling protons ranges from the full neutron energy all the way down to a negligible fraction of the incident neutron energy. As the positively-charged protons recoil through the scintillator they lose energy by causing ionization and lifting electrons into excited states. As the electrons relax back to their original ground states a scintillation of light is emitted. The amount of light is approximately proportional to the original proton recoil energy. The light flashes are converted to a proportional number of photoelectrons at the cathode of the photomultiplier tube. The PMT amplifies this signal and delivers the result to the preamplifier. As a result, the recorded pulse-height (energy) spectrum is a continuum that ranges from the maximum neutron energy all the way down to zero.

*The live time clock accumulates elapsed time only when the MCA is not processing a previous pulse and is available to accept the next pulse. Thus, dividing the measured counts in the spectrum by the elapsed live time corrects for dead time losses. This is important for eliminating the counting-rate distortions caused by dead time losses, which are significant at high counting rates. The Easy-MCA provides a display of the percent dead time losses, so that the operator can keep the losses below 62%.

paraffin shadow bar counting rate from the counting rates obtained with each of the absorbers and the "No absorber" case.

d. Calculate the transmission, T, for each absorber using the ratio of the corrected counting rates in Table 16.1 and Eq. (4). Calculate the measured σ_T from the transmission values using Eq. (5). Record these values in Table 16.1 as the "Measured Cross Section." Look up the accepted values for E_n = 8.5 MeV in ref.1 and record these in the last column of Table 16.1. Compare the measured values with the accepted values.

e. Plot $(\sigma_T/2\pi)^{1/2}$ versus $A^{1/3}$ on linear graph paper or on an Excel spreadsheet graph. Determine R_0 from the slope of the straight line through the points and $\lambda/2\pi$ from the intercept of the line at $A^{1/3}$ = 0. Figure 16.5 shows some typical data that were measured by this method.

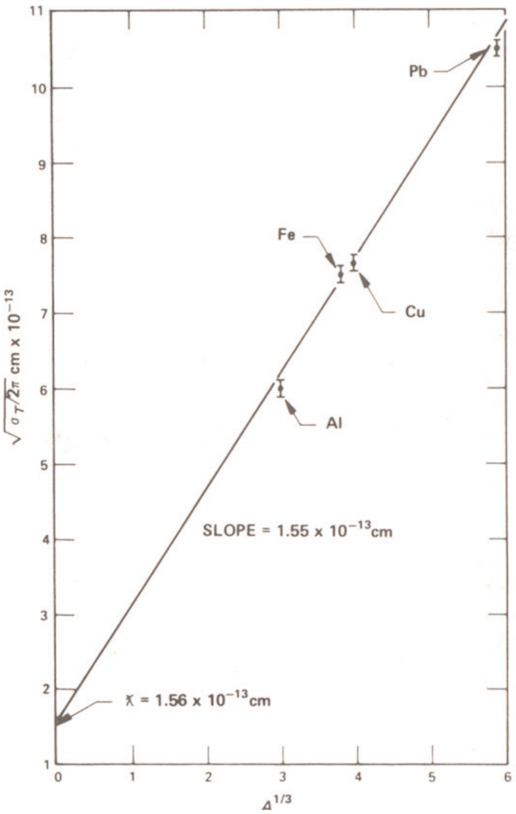

Fig 16.5 Plot of $(\sigma_T/2\pi)^{1/2}$ versus $A^{1/3}$ for Am-Be Neutron Energies ≈ 8.5 MeV.

f. Compare your measured values for R_0 and $\lambda/2\pi$ to the accepted values. Comment on the reasons for any disagreement. How large are the errors contributed by counting statistics?

Optional Detectors: The conventional neutron long counter that is found in many laboratories could be used to count the neutrons in this experiment. These counters can be set so that they are relatively insensitive to gamma rays, and the system can be operated to measure a wider portion of the spectrum than just the part from 7 to 11 MeV. The gamma-ray interference can also be minimized by using pulse shape discrimination with a BC-501A liquid scintillator. A pulse-shape discriminator can be constructed with an ORTEC 552 Pulse Shape Analyzer/SCA and a 567 TAC. See ref. 8 for details. However, accepting the entire range of neutron energies will require integrating the reference cross sections over the total energy spectrum of the neutron source.

References

1. D.J. Hughes and R. B. Schwarz, *Neutron Cross Sections*, **BNL-325**. 2nd Edition (Rev) (1958). Available from National Technical Information Service, U.S. Dept. of Commerce, Springfield, Virginia.
2. H.H. Barschall, "Studies of Intermediate and Heavy Nuclei with Neutrons", Am. J. Phys., **22** (8) 517-523 (1954).
3. J.B. Marion and F.C. Young, *Nuclear Reaction Analysis*, John Wiley and Sons, New York (1968).
4. J.B. Marion and J.L. Fowler, Eds., *Fast Neutron Physics*, **1** and **2**, Interscience, New York (1960-1963).
5. T. C. Minor, *et.al.*, "Undergraduate Experiments to Find Nuclear Sizes by Measuring Total Cross-Section for Fast Neutrons," Am. J. Phys., **37** (6) 649 (1969)
6. W. K. Robinson, J. L. Nagi, and J.L. Duggan, "A Time-of-Flight Neutron Experiment for the Undergraduate Laboratory," Am. J. Phys., **37** (5) 482 (1969).
7. R. D. Evans, *The Atomic Nucleus*, McGraw-Hill (1955).
8. Application notes, technical papers, and introductions to each product family at www.ortec-online.com.

ORTEC®
www.ortec-online.com
Tel. (865) 482-4411 • Fax (865) 483-0396 • ortec.info@ametek.com
801 South Illinois Ave., Oak Ridge, TN 37831-0895 U.S.A.
For International Office Locations, Visit Our Website

AMETEK®
ADVANCED MEASUREMENT TECHNOLOGY