Conf-910503--8

WHITE SOURCE GAMMA-RAY PRODUCTION SPECTRAL MEASUREMENT FACILITIES IN THE U.S.A.

LA-UR--91-1633

DE91 012216

D.C. Larson and J.K. Dickens
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831-6356 USA

and

R.O. Nelson and S.A. Wender
Los Alamos National Laboratory
Los Alamos, New Mexico 87545 USA

Abstract: The two primary neutron sources for measuring gamma-ray production (GRP) cross sections for basic and applied work in the U.S.A. are the Oak Ridge Electron Linear Accelerator (ORELA) located at the Oak Ridge National Laboratory (ORNL) and the Weapons Neutron Research (WNR) facility located at the Los Alamos National Laboratory (LANL). ORELA is based on a 180-MeV electron linear accelerator, while the WNR facility uses the Los Alamos Meson Physics Facility 800 MeV proton beam to produce neutrons. The facilities collectively cover the neutron-energy range from thermal to over 700 MeV. The paper describes the present capabilities for GRP measurements at each facility.

(gamma-ray production measurements, neutron white sources, gamma-ray detectors, ORELA, WNR)

Introduction

Gamma-ray-production (GRP) cross sections play an important role in applied neutronics work. Nuclear heating studies, transport calculations and radiation shielding design all require GRP cross-section input. Radiation damage studies requiring cross sections for reactions which are difficult to measure directly also benefit from GRP work since GRP measurements for these reactions, when coupled with nuclear model calculations, provide unique information on these difficult cross sections.

Pulsed high-intensity white neutron sources have the advantage of providing neutrons over a wide energy range thus data may be acquired simultaneously at all incident neutron energies. Because the energy dependence of GRP cross sections is of primary interest, white sources have a definite advantage over monoenergetic sources.

Historically, much of the early GRP data was obtained at ORNL and LANL. Dickens et al. [1] at ORELA reported GRP measurements for $0.1 < E_n < 20$ MeV for 22 materials at 125 deg, using a NaI detector system. Drake et al. [2] at LANL measured GRP cross sections at 14.2 MeV for 20 samples at three angles between 90 and 130 deg, also using a NaI detector system. While these measurements formed the basis for GRP cross sections in ENDF/B-IV, the gamma-ray energy resolution was generally inadequate to extract cross sections for individual gamma-ray lines. Both facilities have continued to improve their GRP measurement systems, and in the following sections we outline GRP measurement systems currently in use.

ORELA GRP Measurement Systems

General

The ORELA facility is a pulsed neutron source which is used over 4000 h/yr for neutron experiments, providing data for both basic and applied research. It has two neutron-producing targets and ten evacuated flight paths with 18 underground detector stations ranging in length from 9 to 200 m. The ORELA facility is described in detail most recently by Bockhoff et al. [3]. GRP measurement facilities are currently located at seven of the stations, with flight paths ranging from 18 to 155 m. Properties of these seven systems form the basis of the ORELA section of this paper. Since 1970, over 150 papers and reports have been published describing GRP and radiative capture measurements performed at ORELA [4]. In addition, these data have been heavily utilized by evaluators for the ENDF/B nuclear data evaluation system. Priorities in the ORELA GRP measurement program are strongly influenced by user requests contained in the U.S. DOE Data Request List [5].

High Resolution Germanium Detector System

A high-resolution gamma-ray detection system is located on Flight Path (FP) 8 at the 20-m station. It uses a well-shielded intrinsic germanium detector with a nominal volume of 150 cm^3, located 40-cm from the center of the beam and at 125 deg with respect to the incident neutron direction. Since gamma-ray angular distributions of bound states are symmetric about 90 deg and since the second term of the Legendre expansion polynomial $P_2(125) = 0.0$, multiplying the differential measurement results by 4π gives the total GRP cross section to a good approximation (for decaying states with $J = 0$, 1/2, 1, or 3/2 the results are exact). A response function has been measured using sources in situ for the detector, giving an absolute efficiency of 8×10^{-5} at 1332 keV. The detector has an intrinsic efficiency of 26% at $E\gamma = 1332$ keV relative to the standard 7.5 cm × 7.5 cm NaI detector 25 cm from the source. The measured energy resolution is nominally 2 keV for a 1-MeV gamma ray, while the timing resolution is measured to be 7 ns for a 511-keV gamma ray.

The beryllium block ORELA target is normally used to provide neutrons for experiments with this system, covering the energy range from $0.1 < E_n < 40$ MeV. The gamma-ray energy range is $0.1 < E_\gamma < 8$ MeV, using several amplifier gain settings as needed to study higher-energy gamma rays created in different samples.

The electronics provide pulse-height (ph) analysis from the detector, and correlate the detector event with the time-of- flight (tof) of the neutron inducing the event. About thirty tof-vs-4096 channel ph spectra are generally acquired, covering the energy range of interest. The data-acquisition system [6], based on an IBM PS/2 personal computer, provides up to 15 tags for looking at backgrounds, coincidence events, etc. The ph information is digitized at the 20-m experimental station with the 12 bits of information transferred to the counting area to essentially eliminate noise contributions from the ORELA rf to the detector resolution.

The incident neutron flux is measured with a 0.6-cm diam × 0.6-cm long NE-110 plastic scintillator placed in the beam and coupled to a photomultiplier tube via a 5-cm light pipe. Pulse height vs tof information is sent

through the electronics and stored in the PS/2 system for later analysis. Response functions for flux analysis are provided by the SCINFUL code [7].

Data reduction consists of removing any sample-out background (< 1% of sample-in counting rate), performing deadtime corrections appropriate for a one stop/start system, obtaining the photopeak areas (generally done with a version of TPASS [8]), and folding in the flux to obtain the GRP cross sections and associated uncertainties. The system routinely extracts integrated cross sections as low as 1 mb for $E_\gamma = 1$ MeV. Measurements have been completed for $^{10,nat}B$, V, $^{nat,53,54}Cr$, $^{56,57}Fe$, Co, and $^{58,60,nat}Ni$. A paper by Dickens et al. at this conference presents results from the ^{56}Fe measurement. Measurements are planned for Ti and Cu.

A second germanium detector system, very similar to this one, is currently located on FP-6 at the 20-m station. It is being used in a collaborative experiment with the National Institute for Science and Technology to measure the $^{10}B(n, \alpha\gamma)$ cross section. A paper by Schrack et al. at this conference describes this measurement.

C_6D_6 Detector System

This low gamma-ray energy resolution system, located on FP-7 at the 40-m station, is a modification of an earlier C_6F_6 system. Its primary use is to measure pulse-height spectra from capture gamma rays, and from these data obtain GRP cross sections and the neutron capture cross section. The neutron energy range normally covered is the resonance region from 1 keV to 1 MeV, while the photon energy range is normally $0.1 < E_\gamma < 10$ MeV. The flight path is 40 m from the neutron source to the sample and 8 cm from the sample to the C_6D_6 detectors.

Two diametrically opposed 10-cm diameter C_6D_6 detectors are located at 90 deg to the incident neutron direction. They each have a volume of 550 cm^3 and subtend a solid angle of about 2.4 sr. The measured energy resolution is 9% for a 1-MeV photon, and the timing resolution is <1 ns for a ^{60}Co source. The efficiency for $E_\gamma > 1.5$ MeV is essentially flat and is about 4%. The region around the sample and detectors is constructed from low-Z materials and has all excess mass removed.

The neutron flux is monitored by a Li-glass detector viewed by two phototubes located 50-cm before the sample. Absolute normalization is done via the saturated gold resonance technique.

The data-acquisition system is based on a PS/2 personal computer, which stores ph vs tof information for the two C_6D_6 detectors, the summed signal, and detector coincidences. Similar information is retained for the two phototubes viewing the lithium-glass monitor detector. Tags are used for storing information useful for data reduction.

Data reduction consists of the usual background and deadtime corrections. Detector responses are calculated with the electron gamma-ray transport code EGS [9], incorporating a careful modeling of material in the vicinity of the sample and detectors. Using these responses, ph spectra can be unfolded and corrected for attenuation and multiple scattering and normalized to obtain GRP cross sections in the resonance region. The calculated responses can also be used to form weighting functions which, when applied to the ph spectra, provide capture yields for resonances. Prior to replacement of the C_6F_6 detectors by the present ones, an earlier version of this system [10] was used by R. L. Macklin to measure capture cross sections for over 170 isotopes. An earlier version of the present system was used to measure the capture cross section for the 1.15 keV resonance in ^{56}Fe, reported at the Mito Conference [11]. Future work includes measurement of capture cross sections and spectra for the structural materials.

BaF_2 Multicrystal Spectrometer/Multiplicity Detector

The initial use of this new system, located on FP-4 at the 20-m station, will be to measure the neutron energy dependence of capture and fission cross sections by recording capture and fission gamma-ray multiplicities. In addition, it will be used to measure capture GRP spectra and cross sections for structural materials. The detector system consists of 12 hexagonal BaF_2 crystals, each with volume of 826 cm^3. The measured energy resolution of the system is 14% for a ^{137}Cs source with a system timing resolution of < 1 ns. The system efficiency is about 80% for a ^{60}Co source. Data acquisition is done via a Multibus/Camac based system which uses a PS/2 based system for storage. Information is sorted according to pulse height, tof, and number of detectors fired (multiplicity). If desired, the system can also do event-by-event recording to Exabyte high-density tape. Measurement of the incident neutron flux is via a parallel plate BF_3 counter, located 1 m ahead of the sample with the tof spectra stored in the PS/2. At present, data reduction is in progress for the first measurement which is the ratio of capture to fission for ^{235}U from 0.005 eV to 100 eV.

NE-213 Based Neutron and Gamma-Ray Emission Measurement System

A three-detector system to measure neutron and gamma-ray production cross sections has been implemented on FP-9 in the Shield Test Station. Neutrons are provided by the beryllium block ORELA target. Detector events are recorded for $1 < E_n < 25$ MeV incident neutron energy, and $1 < E_\gamma < 10$ MeV gamma-ray energy. The source to sample flight path is 47 m, with the sample to detector distances ranging from 5 to 20 cm. Three NE-213 detectors are currently in use; 5.1-cm-diameter detectors are located at 30 and 64 deg with respect to the incident beam direction, and a 12.7-cm-diameter detector is located at 125 deg.

Pulse shape discrimination (PSD) is used to separate the detected neutrons and photons, and 2048 channel ph spectra are stored as a function of incident neutron tof in a PS/2 based data-acquisition system. This system and its associated software also provide for storing PSD window information including the capability to adjust the bias channel for each PSD window. Tags can be used to store results from different detectors, coincidences, etc.

Flux determination is done via a ^{238}U fission chamber located at 27 m and a small NE-110 plastic scintillator located at 45 m which has been intercalibrated with the fission chamber.

Data reduction for the first measurement with this system (on a sample of iron) is in progress. Future work will focus on measurement of (n, xn) and $(n, x\gamma)$ cross sections for the structural materials for $1 \le E_n \le 25$ MeV.

Other Systems

Two other systems at ORELA which measure gamma-ray spectra, but do not provide GRP cross sections directly, are available. The first of these is a large liquid scintillator tank, located on FP-6 at the 150-m station, used to measure capture cross sections for fissile and fertile isotopes. The neutron-energy range covered is typically 0.01 eV $< E_n <$ 200 keV, with photons of energy $0.2 < E_\gamma < 15$ MeV being registered. The detector, located 155 m from the neutron source, is filled with 3000 liters of NE-224 loaded with trimethylborate and surrounded by 32 12.7-cm photomultiplier tubes. To reduce backgrounds, the tank is optically divided in half so any event must produce two gamma rays to be counted. The system energy resolution is 40% for a ^{60}Co source, has a system timing resolution of 6 ns and an efficiency of 85% for $E_\gamma > 1.5$ MeV. Flux measurement is via a 1-mm-thick ^6Li glass detector located 15 cm ahead of the tank. Pulse heights from the detectors are summed and stored in a PS/2 data acquisition system, along with the corresponding tof. Results obtained with this system include capture measurements for ^{238}U, and older capture data for ^{235}U and ^{239}Pu.

The second system is a C_6F_6 NE-213 detector system located on FP-5 at the 20-m station. It is used primarily to measure capture and fission cross sections in the actinide region. The neutron energy range covered is 0.01 eV $< E_n <$ 400 keV, where photons of energy $0.1 < E_\gamma < 10$ MeV are registered. Two diametrically opposed, 10-cm diameter, 400-cm^3 C_6F_6 detectors are located at 90 deg to the incident beam direction. The system has 9% energy resolution at 1 MeV with a timing resolution of 3 ns and an efficiency of 4% for $E_\gamma > 1.5$ MeV. Two NE-213 detectors with PSD are also located in the plane of the C_6F_6 detectors to detect fission neutrons, if desired. Neutron flux is measured by a parallel plate ^{10}B ionization chamber located 50 cm ahead of the sample. Data acquisition is done via a PS/2 system storing ph, tof, and PSD information. Calculated detector responses provide weighting functions which, when applied to the ph spectra, give the desired capture yields for observed resonances. This system has been used to measure capture cross sections of ^{237}Np, ^{239,240,241}Pu, and ^{241,243}Am.

WNR GRP Measurement Systems

General

Two spallation neutron sources are available at Los Alamos National Laboratory. The Weapons Neutron Research (WNR) facility provides high-energy neutron beams spanning the energy range from ~1 to over 700 MeV, and the Los Alamos Neutron Scattering Center (LANSCE), a moderated neutron source, produces intense beams of thermal and epithermal neutrons. These neutron sources are described in detail by Lisowski et al. [12].

Two flight paths at the WNR facility are used for gamma-ray measurements. One is located at 15 degrees to the right with respect to the incident proton beam (15R) and has a detector station at 18 m. The second flight path is located at 30 degrees to the left (30L) with a detector station at 40 m. A second detector station will be installed this year at 22 m on the 30L flight path. At LANSCE, flight paths of 8 m and 21 m are used for gamma-ray measurements of capture on radioactive samples and for the investigation of parity non-conservation in neutron resonances.

The neutron flux is measured during experiments by thin, fission ionization chambers using foils of both ^{235}U and ^{238}U for all of the measurements performed at the WNR facility [13]. The $^{235,238}U(n,f)$ cross sections have been measured with good precision up to 100 MeV at our laboratory relative to the $H(n,p)$ reaction [14].

The data are acquired using VAXstation/CAMAC based data acquisition systems using the Indiana University Cyclotron Facility's version of the XSYS code. The data acquisition systems provide the capability of storing large 2-dimensional arrays of neutron time of flight (tof) versus gamma-ray pulse height as well as storing data event by event on 8mm tape with a capacity of 1.5 GB per cassette. To reduce the deadtime associated with CAMAC readout the data are buffered in the CAMAC crate and read out between macro pulses.

High-Resolution Germanium Detector System

High gamma-ray energy resolution measurements similar to those performed at ORELA have been performed at the WNR facility for incident neutron energies up to 400 MeV, and with samples of interest to a wide variety of programs, including the Mars Observer mission to map the elemental composition of the Martian surface. Results of these experiments will be used to improve both the models used in calculating and predicting reaction cross sections, and the resulting evaluated data bases.

The Ge detectors are located at 90 and 125 degrees with respect to the neutron beam. A typical timing resolution is 5 ns for $E_\gamma = 1$ MeV. The gamma-ray energy resolution is typically about 2.5 keV. The detector efficiencies have been measured with calibrated radioactive sources at energies from 122 keV to 2.6 MeV. From 2.6 to 8 MeV the efficiencies are calculated with the Monte Carlo code CYLTRAN [15]. The measured absolute efficiencies (times the solid angle subtended) for $E_\gamma = 1332$ keV range from 7 to 35 $\times 10^{-4}$.

The data are stored in two-dimensional arrays, typically having 512 channels of neutron tof versus 4096 channels of gamma-ray pulse height. The raw event datum with the full ADC resolution of 8192 channels is usually written to a disk and then automatically transferred to 8 mm magnetic tape. This allows re-sorting the data with better dispersion if needed.

The data analysis includes: correcting for dead times, binning both the fission chamber beam monitor tof spectra and the Ge detector tof spectra into suitable neutron energy bins, extracting the areas under the peaks, and calculating the cross section from the extracted yields, taking into account the flux measured with the fission chamber, the sample size and thickness, and the measured detector efficiency. Finally corrections are made for neutron multiple scattering and gamma-ray attenuation in the sample.

Measurements of the strong transitions in natural B, C, N, O, Mg, Al, Si, S, Ca, Ti, Cr, Fe, and Mn have been made for the Mars Observer mission. Scoping studies have looked at the neutron-induced gamma-ray yields in Y, ^{238}U, and ^{232}Th. More detailed measurements have been performed for ^{14}N, ^{56}Fe, and ^{204,206,207,208}Pb.

BGO Five-Crystal Spectrometer

This detector system has been used to measure gamma-ray production cross sections for ^{nat}C, ^{10,11}B, ^{14,15}N, ^{nat}Eu, ^{nat}Gd, and ^{181}Ta. BGO was chosen because the ratio of gamma-ray to neutron sensitivity for BGO is generally greater than for other scintillators. The cylindrical BGO crystals are 7.6 cm diameter and 7.6 cm long. A typical gamma-ray energy resolution for these detectors is 5% at $E_\gamma = 15$ MeV. These detectors are usually used in the gamma-ray energy range, $0.5 < E_\gamma <$ 16 MeV, and have a timing resolution of about 1.5 ns. This setup has been used on the 15R, 18 m flight path. The neutron energy range covered is normally $\sim 1 < E_n <$ 400 MeV. The detectors span the angular range from 40 to 145 degrees.

The data acquisition setup is similar to that for the Ge detectors. Due to the lower gamma-ray energy resolution of the detectors the two-dimensional spectra have a typical size of 1024 channels of tof with 512 channels in pulse height.

Response functions for these detectors have been calculated with the CYLTRAN code. The calculated response functions have been verified with measurements at the tagged photon facility at the University of Illinois.

The analysis procedure involves the following steps: (1) Subtraction of the time-random background and the background from slower neutrons produced by a previous beam pulse, (2) Subtraction of blank and sample-out backgrounds, (3) Binning the data into suitable neutron and gamma-ray energy bins, (4) Unfolding the detector response using the deconvolution code, FERD [16], and (5) Calculating the cross sections using the flux (determined from the fission chamber data), the sample thickness, the detector efficiency, and corrections for neutron multiple scattering and gamma-ray attenuation in the sample. The cross-section data are fit to the obtain the coefficients of the usual Legendre polynomial expansion as a function of the incident neutron energy.

BGO Fast Neutron Capture Spectrometer

This system was designed to extend our capabilities to measure higher energy gamma rays. It has been used in the energy range $4 < E_\gamma < 50$ MeV. The spectrometer consists of a 10 × 15 cm BGO crystal surrounded by a plastic anti-coincidence shield and a large amount of Pb and polyethylene shielding. The entire system is mounted on a carriage which rotates about the sample to allow the measurement of angular distributions. This spectrometer is located at 19 m on the 15R flight path. The BGO crystal front face is 61 cm from the sample. The timing resolution is nominally 2.0 ns. The energy resolution is 8% at 4.44 MeV, and the efficiency calculated using the EGS code for a 1.2 MeV wide window around the full energy peak is 11% at $E_\gamma = 40$ MeV. The cosmic-ray rejection provided by the shield is ~99%.

This system has been used to measure the $^{40}Ca(n,\gamma)$ cross section and angular asymmetries to extend measurements beyond the region of the isovector giant quadrupole resonance. The analysis consists of determining the cross sections from the peak corresponding to the ground state capture gamma ray. Data were measured at 55, 90 and 125 degrees. From the 55 and 125 degree data the asymmetry is calculated.

High-Energy BaF_2-NaI Gamma-Ray Telescope

Because the background due to neutrons scattered from the sample into the detector is often the most difficult background to properly subtract in gamma-ray experiments at a spallation neutron source, a neutron insensitive detector is especially desirable. In the gamma-ray energy range from 15 to 200 MeV the pair production mechanism can be exploited to reduce the neutron sensitivity of a detector. We are currently constructing such a detector, similar to the one described by Bertholet et al. [17].

This detector will be used this year on the 15R, 18-m flight path to measure high-energy gamma rays from the neutron-proton Bremsstrahlung process. Two identical detectors will be located at +90 and −90 degrees with respect to the beam. Each detector will be composed of segmented 1-cm-thick BaF_2 pair converters in front, followed by 2 thin, segmented plastic "delta-E" detectors backed by a calorimeter of 16 rectangular, 10 × 10 × 40 cm NaI crystals. By measuring the energy loss in the delta-E detectors the photon events can be selected. A gamma-ray energy resolution of 15% and an absolute efficiency of 30% at $E_\gamma = 150$ MeV were calculated for this detector using the CYLTRAN code.

These data will be acquired event by event. Events corresponding to photon-electron showers will be selected by setting conditions on the various spectra. We plan to measure the inclusive gamma-ray production cross section using a liquid hydrogen target this year.

BaF_2 Capture Spectrometer

The construction of a 4π solid angle, BaF_2 spectrometer system is currently nearing completion [18]. The spectrometer consists of 8 cubic crystals (15 × 15 × 15 cm) with a square 4-cm aperture for the neutron beam and a square 4-cm entrance for a sample holder. The planned use for this system is to measure capture cross sections on small quantities of radioactive samples in the resonance region using an 8-m flight path at LANSCE. The measurements will span the neutron energy range, 0.025 eV $< E_n <$ 30 keV, and the gamma-ray energy range from 6 to 10 MeV. Tests have demonstrated a system timing resolution of 250 ps. The efficiency is ~100% for gamma-ray energies less than 10 MeV. The system was designed with the aid of Monte Carlo codes.

The flux for these experiments will be measured using a ^6Li sample located 22.5 cm behind the radioactive sample by measuring the known $^6Li(n,\alpha)$ reaction using a silicon surface barrier detector. These data have applications to nuclear astrophysics, reactor physics (both fission and fusion), and accelerator transmutation of waste. Two of the BaF_2 crystals have also been used in a pilot study to examine parity non-conservation in neutron resonances through the capture reaction.

Summary

GRP measurement systems based on the ORELA white neutron source cover the complete neutron-energy range from thermal to 40 MeV and measure gamma rays from 0.1 to 15 MeV. GRP cross sections for $(n,x\gamma)$ reactions are measured with a high-resolution germanium detector system, and low-resolution spectra at three angles are obtained as a byproduct of the NE-213 based (n,xn) system. Capture gamma-ray spectra in the resonance region can be measured with the new C_6D_6 detector system or the BaF_2 based multicrystal spectrometer. Papers by Dickens et al. and Schrack et al. at this conference provide examples of GRP measurements at ORELA.

The WNR facility is presently used for GRP measurements in the neutron energy range from ~1 MeV to over 400 MeV, but neutrons with energies of over 700 MeV are produced. Instruments are available, or are being constructed to measure gamma rays in the energy range from 0.1 to 200 MeV. Spectrometers available include: high-resolution Ge detectors, BGO crystals for angular distribution and fast neutron capture measurements, and a gamma-ray telescope to study high-energy gamma-ray production. Unique measurements of capture gamma rays from radioactive samples and parity violating resonances are planned using a large volume BaF_2 calorimeter at LANSCE. The neutron energy range covered is from thermal to 100 keV.

Acknowledgements

Research at Oak Ridge National Laboratory is sponsored by the Office of Energy Research, Division of Nuclear Physics, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. Research at the Los Alamos National Laboratory is under the auspices of the U.S. Department of Energy under contract W-7405-ENG-36.

References

1. J. K. Dickens, G. L. Morgan, G. T. Chapman, T. A. Love, E. Newman, and F. G. Perey, *Nucl. Sci. Eng.* **62**, 515 (1977).
2. D. M. Drake, E. D. Arthur, and M. G. Silbert, *Nucl. Sci. Eng.* **65**, 49 (1978).
3. K. H. Bockhoff, A. D. Carlson, O. A. Wasson, J. A. Harvey, and D. C. Larson, *Nucl. Sci. Eng.* **106**, 192 (1990).
4. R. W. Peelle, J. A. Harvey, F. C. Maienschein, L. W. Weston, D. K. Olsen, D. C. Larson, and R. L. Macklin, *Neutron Research and Facility Development at the Oak Ridge Electron Linear Accelerator 1970-1995*, ORNL/TM-8225 (July 1982), and report in preparation for the period 1982-1991.
5. P. F. Rose and A. Daly, editors, U.S. DOE Nuclear Data Committee "Compilation of Requests for Nuclear Data," BNL-NCS-52028 (January 1987), current under update.
6. B. D. Rooney, J. H. Todd, R. R. Spencer, and L. W. Weston, *A Data Acquisition Work Station for ORELA*, ORNL/TM-11454 (September 1990).
7. J. K. Dickens, *SCINFUL: A Monte Carlo Based Computer Program to Determine a Scintillator Full Energy Response to Neutron Detection for E_n Between 0.1 and 80 MeV: User's Manual and FORTRAN Listing*, ORNL-6462 (March 1988).

8. J. K. Dickens, *TPASS, A Gamma-Ray Spectrum Analysis and Isotope Identification Computer Code*, ORNL-5732 (March 1981).
9. W. R. Nelson et al., Report SLAC-265, Stanford Linear Accelerator Center (December 1985).
10. R. L. Macklin and B. J. Allen, *Nucl. Inst. Methods* **91**, 565 (1971).
11. F. G. Perey, J. O. Johnson, T. A. Gabriel, R. L. Macklin, R. R. Winters, J. H. Todd, and N. W. Hill, *Proc. Int. Conf. on Nuclear Data for Sci. and Tech., May/June 1988, Mito, Japan*, p. 379, Saikon, Tokyo (1988).
12. P. W. Lisowski, C. D. Bowman, G. J. Russell, and S. A. Wender, *Nucl. Sci. Eng.*, **106**, 208 (1990).
13. S. A. Wender, R. C. Haight, R. O. Nelson, C. M. Laymon, A. Brown, S. Balestrini, W. McCorkle, T. Lee, and N. W. Hill, *A Fission Ionization Detector for Neutron Flux Measurements at a Spallation Source*, LA-UR-90-3399 (1990).
14. P. W. Lisowski, "Fission Cross Sections in the Intermediate Energy Range", *Proc. NEANDC Specialists' Meeting on Neutron Cross Section Standards for the Energy Region above 20 MeV, Uppsala, Sweden, May 21-23, 1991*, to be published.
15. J. A. Halblieb, Sr., and W. H. Vandevender, *CYLTRAN*, Sandia Laboratories, SAND 74-0030 (1974).
16. B. W. Rust, D. T. Ingersoll, and W. R. Burrus, *A User's Manual for the FERDO and FERD Unfolding Codes*, ORNL/TM-8270 (1983).
17. R. Bertholet, M. Kwato Njock, M. Maurel, E. Monnand, H. Nifenecker, P. Perrin, J. A. Pinston, F. Schussler, D. Barneoud, C. Guet, and Y. Schutz, *Nucl. Phys.* **A474**, 541 (1987).
18. P. E. Koehler and H. A. O'Brien, *Cross Section Measurements on Radioactive Targets*, LA-UR-90-3491 (1990).