**Status Report to the DOE
Nuclear Data Committee**

F. G. Perey
J. C. Gentry

MASTER

OAK RIDGE NATIONAL LABORATORY
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Neutron Physics Division

STATUS REPORT TO THE DOE NUCLEAR DATA COMMITTEE

Compiled and edited by:

F. G. Perey
J. C. Gentry

Date Published - April 1978

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ABSTRACT

This report was prepared for the DOE Nuclear Data Committee and covers work performed at ORNL since March 1977 in areas of nuclear data of relevance to the U.S. applied nuclear energy program. The report was mostly generated through a review of abstracts of work completed to the point of being subjected to some form of publication in the open literature, formal ORNL reports, ORNL technical memoranda, progress reports, or presentation at technical conferences. As much as possible we have reproduced the complete abstract of the original publication with only minor editing. In a few cases progress reports were written specifically for this publication. The editors have selected the materials to be included in this report on the basis of perceived interests of DOE Nuclear Data Committee members and cannot claim completeness.

A. CROSS SECTION MEASUREMENTS

1. Gamma-Ray Production Data

- a. The Na(n,x γ) Reaction Cross Section for Incident Neutron Energies Between 0.2 and 20.0 MeV* (D. C. Larson and G. L. Morgan)

Differential cross sections for the neutron-induced gamma-ray production from sodium have been measured for incident neutron energies between 0.2 and 20.0 MeV. The Oak Ridge Electron Linear Accelerator (ORELA) was used to provide the neutrons and a NaI spectrometer to detect the gamma rays at 125°. The data presented are the double differential cross section, $d^2\sigma/d\Omega dE$, for gamma-ray energies between 0.35 and 10.6 MeV for coarse intervals in incident neutron energy. The integrated yield of gamma rays of energies greater than 350 keV with higher resolution in the neutron energy is also presented. Finally, the excitation function for the 440-keV gamma ray is given for incident neutron energies between 400 keV and 20 MeV. The experimental results are compared with the Evaluated Nuclear Data Files (ENDF).

- b. Absolute Measurement of the ${}^7\text{Li}(n,n'\gamma){}^7\text{Li}^*$ (0.478-MeV) Cross Section** (D. K. Olsen, G. L. Morgan and J. W. McConnell)

Measurements were performed using a Ge(Li) detector at 125° to a neutron beam whose energy ranged from 0.5 to 5.0 MeV. The neutron flux was measured using a proton recoil detector based on polyethylene foils and a silicon surface barrier detector. The cross sections are accurate to a relative error of about 6% and an absolute uncertainty of about 8%. This isotropic gamma-ray has potential as a secondary standard for inelastic scattering (n,n' γ) cross sections.

*Abstract of ORNL/TM-6281.

**Abstract of paper to be presented at the ANS Meeting, San Diego, June 1978.

c. The Decay of $^{99}\text{Mo}^*$ (J. K. Dickens and T. A. Love)

Relative intensities for K x-rays and gamma rays emanating from ^{99}Mo in equilibrium with its $^{99}\text{Tc}^*$ daughter have been measured using several Ge photon detectors. Combining these intensities with an evaluated set of electron-conversion coefficients has provided a set of absolute intensities for the observed gamma rays. The absolute intensity for the dominant 140.5-keV gamma ray in ^{99}Tc was determined to be $90.7 \pm 0.6/100$ ^{99}Mo disintegrations for ^{99}Mo decay in equilibrium with decay of the $^{99}\text{Tc}^*$ daughter.

2. Capture Cross Sections

a. Resonant Neutron Capture in ^{45}Sc below 100 keV**
(M. J. Kenny,† B. J. Allent and R. L. Macklin)

The neutron capture cross section of ^{45}Sc has been measured with 0.2% energy resolution in the range 2.5-100 keV. Many new $\ell > 0$ resonances are observed and the average s- and p-wave radiative widths and standard deviations are $\langle \Gamma_\gamma \rangle_s = 0.84 \pm 0.46$ eV and $\langle \Gamma_\gamma \rangle_p = 0.5 \pm 0.3$ eV. No significant correlation is observed between the reduced neutron widths and radiative widths of the s-wave resonances.

b. $^{51}\text{V}(n,\gamma)$ Reaction in the keV Incident Neutron Energy Range†
(R. R. Winters,¶ R. L. Macklin and J. Halperin)

The $^{51}\text{V}(n,\gamma)$ cross section has been measured at the Oak Ridge Electron Linear Accelerator capture facility. This very high resolution experiment has allowed the extraction of capture areas for some 130 resonances for incident neutron energies 2.5-215 keV. The capture data combined with spin and parity assignments and a few neutron widths from the literature provide full sets $(E_\lambda, \Gamma_\lambda, \Gamma_n)$ of the resonance parameters for forty-five s-wave resonances. Analysis of these parameters has yielded values for the s-wave strength function $\langle S \rangle_{J=3}^{\ell=0} = (8.3_{-2.5}^{+4.0}) \times 10^{-4}$ and $\langle S \rangle_{J=4}^{\ell=0} = (7.0_{-2.2}^{+3.8}) \times 10^{-4}$ (10-90% confidence interval). The level spacing found for the $J^\pi = 4^-$ levels is $\langle D \rangle_{J=4}^{\ell=0} = (10.2_{-0.5}^{+0.8})$ keV. However, the spacing of the $J^\pi = 3^-$ levels shows "non-statistical" effects

*Abstract of ORNL/NUREG-11.

**Aust. J. Phys. 30, 605 (1977).

†AAEC Research Establishment, Private Mail Bag, Sutherland, N.S.W.
2232, Australia.

‡Submitted for publication in Phys. Rev. C.

¶Denison University, Granville, Ohio 43203.

as measured by the Dyson-Mehta Δ_3 statistic and is well described by two average values; $\langle D \rangle_{J=3}^{\ell=0} = (6.1_{-0.8}^{+1.1})$ keV below 90 keV and $\langle D \rangle_{J=3}^{\ell=0} = (8.1_{-1.1}^{+1.4})$ keV above 115 keV. The s-wave total radiation widths are large and fluctuate widely; $\langle \Gamma_\gamma \rangle_{J=3}^{\ell=0} = 1467 \pm 183$ meV and $\langle \Gamma_\gamma \rangle_{J=4}^{\ell=0} = 1629 \pm 352$ meV. The variances of these distributions are consistent with Chi-squared distributions of 5 degrees of freedom for the 3^- resonances and 2 degrees of freedom for the 4^- resonances. The reduced neutron widths and the total radiative widths for the 4^- s-wave resonances exhibit strong correlation ($\rho = 0.93$, significant at $>99.9\%$ confidence level), but the 3^- s-waves are less significantly correlated ($\rho = 0.42$ significant at the 96% confidence level). The contribution of these resonances to the thermal capture cross section is determined to be 3.11 b, approximately 50% of the measured thermal value. The capture resonance integral derived from this work is in good agreement with the published value.

The 30-keV Maxwellian averaged cross section (30 ± 2) mb is of interest in stellar nucleosynthesis.

c. Neutron Capture Cross Section of Manganese* (J. B. Garg,**
R. L. Macklin and J. Halperin)

Neutron capture cross-section measurements in the natural sample of manganese ($_{25}\text{Mn}^{55}$, $I=5/2^-$) were made in the energy interval of 2.5 keV to about 600 keV using neutron time-of-flight techniques with the Oak Ridge Electron Linear Accelerator neutron facility, and a pair of nonhydrogenous liquid scintillator gamma-ray detectors. Resonance energies and capture areas were determined for about 143 resonances up to 110 keV neutron energy using the LSFIT program. The resonance structure above this energy becomes too complicated to be analyzed by this technique. For the analysis of these data, the neutron widths of broad $\ell=0$ resonances were used from published total cross-section data, and the values of radiation widths (Γ_γ) were determined using the LSFIT program. Although the values of Γ_γ for individual resonances vary widely, a mean value of $\langle \Gamma_\gamma \rangle_{\ell=1} = (400 \pm 100)$ and $\langle \Gamma_\gamma \rangle_{\ell=0} = (754 \pm 153)$ meV were determined from these results. (A correlation analysis between Γ_γ and Γ_n^0 for $\ell=0$ resonances gave a value of $\rho = (0.64 \pm 0.14)$, which is statistically significant at the level of confidence of 99.9%. An overall statistical uncertainty of less than 10% was achieved in both the derived resonance parameters and the average capture cross sections.

*Submitted for publication in Phys. Rev. C.

**S.U.N.Y. at Albany, Albany, New York.

- d. Neutron Capture Cross Section of ^{57}Fe * (B. J. Allen,**
A. R. de L. Musgrove,** R. Taylor† and R. L. Macklin)

The neutron capture cross section of ^{57}Fe has been measured with 0.2% energy resolution from 2.5 to 200 keV. s-wave resonances are fitted in a two-channel multi-level analysis of the elastic and inelastic scattering cross sections. A correlation is observed between the s-wave reduced neutron widths and the corresponding radiative widths, which is consistent with the expected valence component.

- e. Neutron Capture Resonance Parameters and Cross Sections for the Even-A Isotopes of Cadmium† (A. R. de L. Musgrove,**
B. J. Allen** and R. L. Macklin)

The neutron capture cross sections for all the stable even-A isotopes of Cd were measured with high energy resolution ($\Delta E/E \lesssim 0.2\%$) between 3 and 90 keV neutron energy at the 40-m station of ORELA. Average neutron resonance parameters were evaluated and differ from previously accepted values.

Both s- and p-wave radiative widths decrease strongly between ^{106}Cd and ^{116}Cd as the neutron binding energy decreases. The average p-wave radiative widths are greater than the s-wave radiative widths for all isotopes. This is interpreted in terms of the configurations of the low-lying states.

Both s- and p-wave neutron strength functions decrease as neutron number increases. This behavior is attributed to an isospin term in the absorptive part of the optical model potential.

- f. Resonant Neutron Capture in ^{139}La † (A. R. de L. Musgrove,**
B. J. Allen** and R. L. Macklin)

The neutron capture cross section of ^{139}La has been measured with high energy resolution between 2.5 and 90 keV using the capture cross section facility at the 40-m station at ORELA. Individual resonances were analyzed to 15 keV and the average s- and p-wave radiative widths deduced were $\langle \Gamma_\gamma \rangle_s = 55 \pm 6$ meV and $\langle \Gamma_\gamma \rangle_p = 40 \pm 7$ meV. The p-wave neutron strength function obtained was $S_1 = (0.30 \pm 0.10) \times 10^{-4}$. The s-wave resonances decay strongly to final f-wave states via a postulated doorway state mechanism. The transition strengths for these decays are not correlated with the neutron widths of the initial states.

*Abstract of paper presented at Specialists' Meeting on Neutron Data of Structural Materials for Fast Reactors, CBNM, Geel, December 1977.

**AAEC Research Establishment, Sutherland, N.S.W. 2232, Australia.

†James Cook University, Townsville, Qld., Australia.

‡Submitted for publication in Journal of Physics G (U.K.).

††Aust. J. Phys. 30, 599 (1977).

g. Neutron Capture Cross Section of ^{159}Tb from 2.6 to 700 keV*
(M. Mizumoto,** R. L. Macklin and J. Halperin)

The $^{159}\text{Tb}(n,\gamma)$ cross section was measured using a neutron time-of-flight facility. The average capture cross section was deduced from 2.6 to 700 keV and in combination with recently reported transmission results, was well fitted with energy independent strength functions. Resonance parameters for many of the observed peaks from 2.6 to 3.4 keV were determined by a nonlinear least-squares fitting program. The γ -ray multiplicity for average capture was measured, giving the relatively low value, 2.45 ± 0.01 at 4 keV, implying a high proportion of two-step cascades. The fluctuations in the cross section about that computed from strength functions were analyzed. No significant nonrandom structure in the cross section was indicated.

3. Total Cross Sections

a. ^7Li Neutron Total Cross Section (J. A. Harvey, N. W. Hill and K. Rush)

Neutron transmission measurements have been made upon three samples of ^7Li ($N = 0.109, 0.3187$ and 0.4675) loaned from LASL from ~ 100 eV to 40 MeV. The low-energy measurements were made at an 80-meter flight path using both a ^6Li glass detector and a 2-cm NE-110 detector. The 200-meter data were obtained with a 7.5-cm thick NE-110 detector using 5 nsec electron bursts. Of particular interest is the structure around 5 MeV.

b. Strength Functions for s-, p-, and d-wave Neutron Resonances in $^{40}\text{Ca}^\dagger$ (J. L. Fowler and C. H. Johnson)

In analyzing data on the total cross section of ^{40}Ca obtained with the good energy resolution of the ORELA time-of-flight facility, we have assigned J and ℓ values for the resonances in the energy region 50 keV to 1000 keV. The heights of the resonances give the J values and their shapes, resulting from level-level interference or from interference between resonant and potential scattering, allow ℓ value assignments. We calculate the reduced neutron widths from the observed widths of the resonances by using penetration factors for a radius of interaction of 7.2 fm ($\leq 2.1 \cdot A^{1/3}$). At this radius the depth of the Woods-Saxon potential appropriate for ^{40}Ca (radius = 4.0 fm and diffuseness = 0.77 fm) is 1.5% of the central depth. We find the strength function, $\langle \gamma^2 \rangle / \langle D \rangle$, in dimensionless units for $s_{1/2}$, $p_{1/2}$, $p_{3/2}$ and $d_{3/2}$ states to be respectively: $(.090 \pm .010)$, $(.0037 \pm .0004)$, $(.0038 \pm .0004)$, $(.0125 \pm .0020)$.

*Accepted for publication in Phys. Rev. C.

**Visitor from Japan Atomic Energy Institute, Tokai-mura, Japan.

†Abstract of paper presented at APS Meeting, Miami, Florida, November 1977.

c. Multilevel Analysis of s-wave Neutron Resonances in ^{40}Ca *
(C. H. Johnson and J. L. Fowler)

In analyzing data on the high resolution total cross sections of ^{40}Ca obtained with the ORELA time-of-flight facility, we have fitted the 23 s-wave resonances between 30 and 1020 keV by a multilevel R-function for a boundary radius, $r = 7.2$ fm, essentially outside the nuclear potential. The sum of reduced widths is 16% of $\hbar^2/\mu r^2$. A stair-step plot shows that the average strength function, $\langle \gamma^2/D \rangle$, increases with energy: $s(E) = 0.06 + 0.16 \text{ MeV}^{-1}E$ for $E > 0.08$ MeV. The fit required the contribution to the R-function from levels outside our region to increase nonlinearly from about 0.3 at 30 keV to 1.0 at 1020 keV. We account for this by subtracting the integrated R-function for the average strengths from a constant, $R = 0.59$. Thus, the average is first subtracted and then replaced by the 23 explicit levels. The R is to be interpreted by an optical model potential.

d. Total Cross Section Measurements of the Isotopes of Zinc and Chromium (J. B. Garg,** J. A. Harvey and N. W. Hill)

Neutron transmission measurements have been made from 50 eV to 500 keV on samples of the 5 isotopes of zinc and also 2 thin natural zinc samples. The low-energy measurements were made with a ^6Li glass detector with an energy resolution of $\sim 1/1200$. Above ~ 10 keV an NE-110 detector was used at the 30-meter flight station and 5-nsec electron bursts. The data have been analyzed to give neutron widths and strength functions of the individual isotopes.

Transmission measurements have also been made upon 3 of the isotopes of chromium ($^{52,53,54}\text{Cr}$) with an NE-110 detector at 80 meters.

e. Neutron Total Cross Section and Resonance Parameters of ^{58}Fe
(J. B. Garg,** S. Jain** and J. A. Harvey)

Neutron total cross section measurements in the energy range from 30 eV to ~ 500 keV have been made using the ORELA neutron facility with a 78.2-m flight path and a nominal resolution of ~ 0.07 nsec/m. From the analysis of the data up to 350 keV we have obtained values of s- and p-wave neutron strength functions and mean level spacings. These are: $S_0 = 3.2 \pm 1.4$, $S_1 = 0.70 \pm 0.13$ in units of $10^{-4} \text{ eV}^{-1/2}$ and $\langle D \rangle_{\ell=0} = 32 \pm 12$ keV and $\langle D \rangle_{\ell=1} = 8 \pm 1$ keV.

*Abstract of paper to be presented at APS Meeting, Washington, D.C., April 24-27, 1978.

**State University of New York at Albany.

f. Parameters of the 203.4 eV Resonance in $^{59}\text{Ni} + n$
(J. A. Harvey, J. Halperin, N. W. Hill, R. L. Macklin and S. Raman)

Transmission, capture, (n, α) and (n,p) measurements have been re-analyzed to correct for a misunderstanding of the ^{59}Ni content in the low-enrichment sample of ^{59}Ni . The original mass analysis of the thin sample used for transmission and capture measurements was $2.96 \pm 0.03\%$ of mass 59 (the sample also contained 0.4% Co). However, a recent mass analysis of the sample after it had been purified to remove cobalt showed the mass 59 content to be only $2.65 \pm 0.02\%$. The initial analysis of the transmission data assumed the ^{59}Ni content was 2.96%. Hence, the value originally quoted for Γ_n from the sample is too low (by $\sim 13\%$). The revised values for the 203.4 eV resonance are $\Gamma_n = 9.6 \pm 0.3$ eV ($J = 1$), $\Gamma_\gamma = 3.0 \pm 0.3$ eV, $\Gamma_\alpha = 0.43 \pm 0.03$ eV and $\Gamma_p = 0.055 \pm 0.005$ eV. The sum of these partial widths (13.1 eV) is in good agreement (within experimental uncertainties) with the measured total width (13.3 ± 0.2 eV) from transmission measurements. The contribution of this resonance (E_0 in eV) to the thermal cross section can be computed from the equation

$$\sigma_{\text{th}}(n,x) \text{ barns} = \frac{0.6510 \times 10^6}{E_0^2} \frac{g \Gamma_n \Gamma_x}{\sqrt{0.0253 E_0}} \left(\frac{A+1}{A}\right)^2 =$$

$$2.690 \Gamma_n \text{ (in eV)} \Gamma_x \text{ (in eV)}.$$

The values obtained for the thermal capture, (n, α), (n,p) and absorption cross sections (at 0.0253 eV) are 78 ± 8 , 11.4 ± 0.8 , 1.43 ± 0.13 and 95 ± 9 barns. These are in good agreement with the experimental values for these thermal cross sections. Thus the contributions of higher energy resonances or a bound level are unimportant.

g. Neutron Resonance Parameters of ^{90}Zr below 300 keV*
(A. R. de L. Musgrove,** J. A. Harvey and W. M. Good)

Transmission data taken at both the 80 and 200 m stations of the Oak Ridge Electron Linear Accelerator have provided resonance parameters for ^{90}Zr to 300 keV bombarding energy. The average s-wave parameters obtained were: $\langle D \rangle = 8.6 \pm 1.6$ keV and $S_0 = (0.54 \pm 0.14) \times 10^{-4}$, while the average parameters for the two p-wave sequences were: for $p_{1/2}$, $\langle D \rangle = 8.6 \pm 1.6$ keV and $S_1 = (3.9 \pm 1.0) \times 10^{-4}$; for $p_{3/2}$, $\langle D \rangle = 4.3 \pm 0.5$ keV and $S_1 = (4.3 \pm 0.8) \times 10^{-4}$.

*Aust. J. Phys. 30, 379 (1977).

**AALC Research Establishment, Sutherland, N.S.W. 2232, Australia.

h. P-Wave Doorway States Correlated with M1 Radiation in $^{206}\text{Pb}+n$
(D. J. Horen and J. A. Harvey)

The neutron transmission of radiogenic lead (enriched to 88.3% ^{206}Pb) has been measured with an experimental energy resolution of $\Delta E/E \approx 0.07\%$. Resonance spin and parity assignments have been made based upon an R-matrix analysis of the data. In the energy interval $E_n = 80$ -400 keV structure is observed in the p-wave neutron strength function. A large doorway state, similar to that previously reported for $^{207}\text{Pb}+n$, is observed at $E_n \approx 140$ keV. Smaller fluctuations in the strength function at 200, 275 and 350 keV are seen. There is a strong correlation between these fluctuations and the M1 ground-state radiative strength as measured by Medsker and Jackson.*

i. Statistical Model Radiation Widths for $75 < A < 130$ and the Enhancement of P-Wave Neutron Capture for $A \approx 90$ ** (C.H. Johnson)

Statistical model calculations of radiation widths are made on the basis of the Axel-Brink hypothesis with two free parameters for the normalization and A dependence of the low-energy tail of the giant electric dipole resonance. The two parameters are adjusted to fit known radiation widths with a standard deviation of about $\pm 25\%$ for s-wave neutron resonance levels in nuclei with $75 < A < 130$. The resulting E1 strength functions are consistent with known values over a large mass region for transitions to low-lying states. The M1 transitions are included. The level densities or nuclear temperatures for the analysis are deduced by fitting the backshifted Fermi-gas model to the total number of states near the ground state and to the s-wave spacings at neutron binding. The low density of levels for $A \approx 90$ gives rise to statistical enhancement of p-wave relative to s-wave neutron radiative capture. The sum of calculated radiation widths for p-wave resonances plus calculated radiation widths for p-wave valency capture agree well with published experimental values.

4. Scattering and Reactions

a. Cross Sections for the $^7\text{Li}(n,xn)$ and $^7\text{Li}(n,n'\gamma)$ Reactions Between 1 and 20 MeV† (G. L. Morgan)

Differential cross sections for the production of secondary neutrons and gamma rays from neutron interactions in ^7Li have been measured at 50° and 126° (lab) for incident neutron energies in the range

*L.R. Medsker and H.E. Jackson, Phys. Rev. C 9, 709 (1974).

**Phys. Rev. C 16, 2238 (1977).

†Abstract of ORNL/TM-6247 (March 1978).

1 to 20 MeV. An electron linac was used as a white neutron source. Incident neutron energies were determined using time-of-flight techniques for a source-to-sample distance of 48 m. Secondary spectra were determined by analysis of the pulse-height distributions observed in a NE-213 scintillation counter. The results are compared to the current evaluated nuclear data file (ENDF/B-IV, MAT 1272).

b. The ${}^6\text{Li}(n,\alpha)$ Cross Section from 80-470 keV* (Cleide Renner,** J. A. Harvey, N. W. Hill, G. L. Morgan and K. Rush)

The ${}^6\text{Li}(n,\alpha)\text{T}$ cross section has been measured from 80-470 keV at 12 discrete neutron energies produced using 8 and 12 inch iron filters at ORELA. The ${}^6\text{Li}(n,\alpha)\text{T}$ events were detected with a 1 mm thick ${}^6\text{Li}$ glass scintillator whose ${}^6\text{Li}$ content was determined to <1% uncertainty from low energy neutron transmission measurements. The neutron flux was measured with an NE-110 detector 7.5 cm thick and 10 cm dia. Monte Carlo techniques were used to compute the efficiency of the NE-110 detector and to correct for multiple interactions in the ${}^6\text{Li}$ detector. Values obtained in the vicinity of the resonance are 2.86 ± 0.06 barns at 218.7 keV, 3.30 ± 0.08 barns at 243.7 and 2.46 ± 0.05 barns at 272.7. An R-matrix fit G. M. Hale (private communication, September 1977) to all our (n,α) data gives a peak cross section at ~ 240 keV of 3.36 ± 0.06 barns.

c. Angular Anisotropy in the ${}^6\text{Li}(n,\alpha){}^3\text{H}$ Reaction below 100 keV† (J. A. Harvey and I. G. Schröder‡)

The data on the differential (n,α) cross section of ${}^6\text{Li}$ has been reviewed below a neutron energy of 100 keV. Measurements in this region, compared to that above 100 keV, have been few. Only recently has interest increased as large and unsuspected anisotropies have been observed in this energy region. Thus, at 25 keV an anisotropy amounting to 67% in the forward-to-backward direction has been observed; while in the region between 1 eV and 10 keV measurements indicate that in the forward-to-backward 66° cone the asymmetry has an energy dependence, in the laboratory system, which can be expressed analytically as $1 + 0.0055 \sqrt{E_n(\text{eV})}$. These angular anisotropies seem to arise from interference between the large p-wave resonance at 247 keV and many s-wave resonances which account for the large $1/v$ (n,α) thermal cross section. New and detailed measurements of the differential (n,α) cross section are needed not only to be able to account analytically for these interference effects but also because it is necessary to consider these anisotropies when the ${}^6\text{Li}(n,\alpha){}^3\text{H}$ cross section is used as a standard.

*Abstract of paper to be presented at APS Meeting, Washington, D.C., April 24-27, 1978.

**Guest on assignment from Institute of Atomic Energy, Sao Paulo, Brazil.

†NBS SP 493, Proc. Int. Spec. Symp. Neutron Stds. and Applications, NBS, Gaithersburg, Md., March 28-31, 1977.

‡National Bureau of Standards, Washington, D.C. 20234.

- d. The Ti(n, γ) Reaction Cross Section for Incident Neutron Energies Between 0.3 and 20.0 MeV* (G. L. Morgan and D. C. Larson)

Differential cross sections for the neutron-induced gamma-ray production from natural titanium have been measured for incident neutron energies between 0.3 and 20.0 MeV. The Oak Ridge Electron Linear Accelerator was used to provide the neutrons and a NaI spectrometer to detect the gamma rays at 125°. The data presented are the double differential cross section, $d^2\sigma/d\Omega dE$, for gamma-ray energies between 0.3 and 10.6 MeV for coarse intervals in incident neutron energy. The integrated yield of gamma rays of energies greater than 300 keV with higher resolution in the neutron energy is also presented. The experimental results are compared with the Evaluated Nuclear Data Files (ENDF).

- e. Doorway States in s-, p- and d-wave Entrance Channels in $^{207}\text{Pb} + n$ Reaction (D. J. Horen, J. A. Harvey and N. W. Hill)

The $^{207}\text{Pb} + n$ reaction has been studied by means of high resolution neutron transmission and differential elastic scattering measurements. Information pertaining to resonance parameters, (E_n , ℓ , J and Γ_n) for some 118 resonances in the energy interval from 3 to 485 keV has been obtained. Distributions of neutron strengths have been determined for each value of J that can be formed by s-, p- and d-wave neutrons interacting with the ^{207}Pb ground state ($J^\pi = 1/2^-$). The existence of a doorway state in the $J^\pi = 1^-$, s-wave channel at ~ 500 keV is confirmed. Evidence is also found for the presence of doorway states in the p-wave ($J^\pi = 1^+$ and possibly 2^+) and d-wave ($J^\pi = 1^-$) channels. The doorway states in the p-wave channel are shown to be correlated with M1 ground-state radiative strength in ^{208}Pb . In the energy region above the doorway state, the "average" p-wave strength function for forming 1^+ resonances [$S^1(1^+) = (6.8 \pm 0.6) \times 10^{-5}$] is found to be equal to the sum of those for forming 0^+ , [$S^1(0^+) = (4.2 \pm 1.0) \times 10^{-5}$] and 2^+ , [$S^1(2^+) = (2.8 \pm 0.4) \times 10^{-5}$] resonances in agreement with predictions of the random phase assumption.

- f. On the Magnitude of M1 Strength Near 7.99-MeV in ^{208}Pb ** (D. J. Horen, G. F. Auchampaugh† and J. A. Harvey)

Recently, we reported that the resonance structure in the vicinity of $E_x = 7.99$ MeV in ^{208}Pb is complex. In particular, we noted it included a resonance with $J^\pi = 1^-$ which might indicate that not all of the observed $\Gamma_{\gamma 0}$ should be assigned as M1 radiation. To investigate this point we have analyzed high resolution neutron transmission and scattering measurements on ^{207}Pb in conjunction with published photo-neutron angular distribution and polarization results for ^{208}Pb .

*Abstract of ORNL/TM-6323 (to be published).

**Abstract of paper to be presented at Washington APS Meeting, April 1978.

†Los Alamos Scientific Laboratory, Los Alamos, NM 87545.

5. Capture Gamma Rays

a. The $^{59}\text{Ni}(n,\gamma)^{60}\text{Ni}$ Reaction with Thermal Neutrons* (S. Raman and E. T. Journey**)

We have investigated in great detail the energy levels of ^{60}Ni populated in the $^{59}\text{Ni}(n,\gamma)$ reaction at the Los Alamos thermal neutron capture γ -ray facility. The target consisted of ≈ 7 mg of metal enriched to 95% in ^{59}Ni . Over 250 γ -rays were identified, some with intensities as low as 0.02 photons/100 n-captures. Over 200 γ -rays have been incorporated into a ^{60}Ni level scheme with 60 excited states. The 44 primary γ -rays placed on the level scheme account for $\approx 85\%$ of the thermal-neutron capture cross section. The neutron separation energy was determined to be 11387.8 ± 1.0 keV.

b. Study of Neutron Resonances in ^{100}Mo † (H. Weigmann,‡ J. A. Harvey, R. L. Macklin, S. Raman and G. G. Slaughter)

Neutron resonance interactions with ^{100}Mo were studied at the Oak Ridge Electron Linear Accelerator time-of-flight facility. The transmission of two oxide samples (97.4% ^{100}Mo) was measured at an 80 m flight path and the neutron capture cross section was measured at 40 m. Resonance analysis yielded parameters of 124 resonances. Capture γ -ray spectra from 11 resolved resonances have been measured with a Ge(Li)-detector at a 10 m flight path. Contrary to neighboring nuclei, partial radiative widths of strong p-wave resonances are not in agreement with valence model predictions.

c. Resonance (n, γ) Measurements and Weak-coupling Model Calculations of Levels in ^{119}Sn , ^{117}Sn , and ^{115}Sn † (S. Raman, R. F. Carlton,‡ G. G. Slaughter and M. R. Meder§)

Neutron capture γ -ray measurements have been performed upon enriched samples of ^{118}Sn , ^{116}Sn and ^{114}Sn following resonance capture. The γ rays, measured with a Ge(Li) detector, have been incorporated in level schemes for ^{119}Sn , ^{117}Sn and ^{115}Sn . Spin and parity assignments have been made for many of the levels. Neutron separation energies for ^{119}Sn , ^{117}Sn and ^{115}Sn were determined to be 6484.6 ± 1.5 , 6942.9 ± 2.0 and 7545.3 ± 2.0 keV, respectively. The level schemes have been compared with those of heavier Sn isotopes to investigate systematic behavior. Various spectroscopic properties (level energies, electromagnetic moments

*Bull. Am. Phys. Soc. 22, 1023 (1977).

**Los Alamos Scientific Laboratory, Los Alamos, NM 87545.

†Abstract of paper submitted for publication in Physical Review C.

‡Central Bureau for Nuclear Measurements, Geel, Belgium.

¶Consultant from MTSU, Murfreesboro, Tennessee.

§Dept. of Physics, Georgia State University, Atlanta, Georgia 30303.

and transition rates) of ^{119}Sn , ^{117}Sn and ^{115}Sn were calculated on the basis of a model which pictures these nuclei as being formed by coupling the motion of the odd neutron quasiparticle to the states of the neighboring even-mass core. The effects on energies and electromagnetic properties in the core and the odd quasiparticle are taken into account through perturbation theory. The experimentally determined level properties of these Sn isotopes have been qualitatively reproduced by these calculations.

d. Resonance Neutron Capture Gamma-Ray Studies of Levels in ^{145}Nd * (D. A. McClure,** S. Raman and G. G. Slaughter)

Gamma-ray measurements have been performed on enriched ^{144}Nd targets following resonance neutron capture. The γ rays, measured with a Ge(Li) detector, have been incorporated in a level scheme for ^{145}Nd . The neutron separation energy for ^{145}Nd was determined to be 5756.9 ± 2.0 keV.

e. Study of the Neutron Resonance Reactions on ^{206}Pb † (Mizumoto,‡ Hamilton,¶ Raman, Macklin, Slaughter and Harvey)

The neutron resonance reactions on an enriched ^{206}Pb target have been studied below 45 keV neutron energy at ORELA. The neutron and radiation widths were obtained for 15 resonances from transmission and capture cross section measurements. J^π assignments for 5 resonances were made on the basis of transmission data and γ -ray decay patterns measured with a Ge(Li) detector. The γ -ray spectra are strikingly simple, being composed of less than five primary γ -rays. The M1 partial radiation widths show some enhancements.

f. Observation of Primary E2 Transitions in the $^{207}\text{Pb}(n,\gamma)$ Reaction† (Raman, Mizumoto,‡ Slaughter and Macklin)

Thirty-six high-energy, primary E2 transitions to the ^{208}Pb ground state have been identified and their radiation widths measured in a study of the $^{207}\text{Pb}(n,\gamma)$ reaction. The states in the (unbound) excitation energy region between 7.37 and 8.17 MeV studied in this experiment exhaust $\approx 9\%$ of the isoscalar EWSR strength. The measured E2 widths are reasonably consistent with those expected from the rising tails of isoscalar giant quadrupole resonances located at 8.9 and 10.9 MeV. The measured widths increased with higher excitation energy, but more rapidly than a Lorentzian.

*Phys. Rev. C 16, 1278 (1977).

**School of Physics, Georgia Institute of Technology, Atlanta, Georgia.

†Abstract of paper to be presented at Washington APS Meeting, April 1978.

‡Visitor from Japan Atomic Energy Institute, Tokai-mura, Japan.

¶Vanderbilt University, Nashville, Tennessee.

g. Fine Structure of the Magnetic Dipole Giant Resonance in ^{208}Pb * (S. Raman, M. Mizumoto,** and R. L. Macklin)

Eighteen M1 transitions to the ^{208}Pb ground state have been identified and their radiative widths measured in a study of the reaction $^{207}\text{Pb}(n,\gamma)$ combined with the results from recent neutron transmission and elastic scattering measurements. In the excitation region between 7.37 and 8.23 MeV, ~50% of the expected total M1 strength in ^{208}Pb has been located.

6. Actinides

a. Actinide Newsletter (S. Raman)

The first issue of the Actinide Newsletter was produced and mailed to 400 recipients in November, 1977. This newsletter was in response to General Recommendation 2 adopted at the Advisory Group Meeting on Transactinium Isotope Nuclear Data (Karlsruhe, Nov. 1975). Thirty-six contributions from fifteen countries were received. The next newsletter is planned for November, 1978.

b. Integral Measurements of Actinide Cross Sections (Raman, Stelson, Cooper, Carter, Williams and Weisbin)

On certain encapsulated actinide samples (^{232}Th , ^{233}U , ^{235}U , ^{238}U , ^{237}Np , ^{239}Pu , ^{240}Pu , ^{241}Pu) irradiated in EBR-II to an integrated dose of 10^{23} fast neutrons, we plan to establish the actinide profile employing various analytical techniques. The measured values will be compared with ORIGEN calculations. The ORIGEN program now incorporates preliminary ENDF/B-V data. Adjoint calculations will also be attempted.

c. Fission-Product Energy Release for Times Following Thermal-Neutron Fission of ^{235}U Between 2 and 14000 Seconds† (Dickens, Emery, Love, McConnell, Northcutt, Peelle and Weaver)

Fission-product decay energy-release rates have been measured for thermal-neutron fission of ^{235}U . Samples of mass 1 to 10 μgm were irradiated for 1 to 100 sec using the fast pneumatic-tube facility at the Oak Ridge Research Reactor. The resulting beta- and gamma-ray emissions were counted for times-after-fission between 2 and 14,000 secs. The data were obtained for beta and gamma rays separately as spectral distributions, $N(E_\gamma)$ vs E_γ and $N(E_\beta)$ vs E_β . For the gamma-ray data the spectra were

*Phys. Rev. Letters 39, 598 (1977).

**Visitor from Japan Atomic Energy Institute, Tokai-mura, Japan.

†Abstract of ORNL/NUREG-14.

obtained using an NE-110 detector with an anticoincidence mantle. The raw data were unfolded to provide spectral distributions of modest resolution. These were integrated over E_γ and E_β to provide total yield and energy integrals as a function of time after fission. Results are low compared to the present 1973 ANS decay-heat standard.

A complete description of the experimental apparatus and data-reduction techniques is presented. The final integral data are given in tabular and graphical form and are compared with published data.

- d. Note on $^{238}\text{U}+n$ Resolved Resonance Energies* (Olsen, de Saussure, Perez, Difilippo and Ingle)

ORELA neutron transmission measurements from 100 eV to 170 keV at 150 m through four ^{238}U samples are reported. The energy calibration is described and the resultant ^{238}U resolved resonance energies are found to be intermediate between those from other workers. In addition, some energies for sharp resonances in ^{23}Na , ^{27}Al , ^{32}S , and ^{206}Pb are given.

- e. Measurement at 150 m of Neutron Transmissions from 0.880 to 100.0 keV through Four Samples of ^{238}U **† (Olsen, de Saussure, Perez, Difilippo, Ingle and Weaver)

In order to study the $^{238}\text{U}+n$ total cross section, neutron transmissions through 0.076-, 0.254-, 1.080-, and 3.620-cm-thick samples of isotopically enriched ^{238}U have been measured from 0.880 to 100.0 keV using a time-of-flight technique over a path length of 150 meters with the ORELA pulsed source and a 13-mm-thick Li-glass detector. The measurement is described in detail and both a listing and figures of the resulting transmissions are given. An absolute energy scale accurate to 2 parts in 10,000 was established.

- f. Fission-Product Energy Release for Times Following Thermal-Neutron Fission of ^{239}Pu Between 2 and 14000 Seconds† (Dickens, Emery, Love, McConnell, Northcutt, Peelle and Weaver)

Fission-product decay energy-release rates have been measured for thermal-neutron fission of ^{239}Pu . Samples of mass 1 to 5 μg were irradiated for 1 to 100 sec using the fast pneumatic-tube facility at the Oak Ridge Research Reactor. The resulting beta- and gamma-ray

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**Abstract of ORNL/TM-5915 (October 1977).

†Relevant to request No. 69286.

‡Abstract of ORNL/NUREG-34.

emissions were counted for times-after-fission between 2 and 14000 secs. The data were obtained for beta and gamma rays separately as spectral distributions, $N(E_\gamma)$ vs E_γ and $N(E_\beta)$ vs E_β . For the gamma-ray data the spectra were obtained using a NaI detector, while for the beta-ray data the spectra were obtained using an NE-110 detector with an anticoincidence mantle. The raw data were unfolded to provide spectral distributions of modest resolution. These were integrated over E_γ and E_β to provide total yield and energy integrals as a function of time after fission. The final integral data are given in tabular and graphical forms, including a complete analysis of uncertainties.

Beta-ray energy emission rates fall somewhat below summation calculations based on the ENDF/B-IV fission product file except for times less than 15 seconds after fission and times near 2000 seconds after fission. Photon energy emission falls above the summation calculation for all measured time integrals, by amounts ranging from 1 to 25%.

g. Measurements of the Average Number of Prompt Neutrons
Emitted per Fission of ^{239}Pu and ^{235}U * (Gwin, Spencer,
Ingle, Weston, Todd and Weaver)

Measurements of $\bar{\nu}_p(E)$ for ^{235}U and ^{239}Pu relative to $\bar{\nu}_p$ for ^{252}Cf have been made over the neutron energy range from 0.005 eV to 10 MeV. The neutrons were generated in pulses by the ORELA with the neutron energy defined by time-of-flight methods. The samples were contained in fission chambers, and the neutrons from the fission process were detected by the large liquid scintillator. The present results for ^{239}Pu at 0.0253 eV agree with the value given in ENDF/B-IV, whereas the corresponding results for ^{235}U are about 0.7% larger than that given in ENDF/B-IV.

h. Neutron Total Cross Section Measurements of ^{239}Pu **
(R. Gwin, J. A. Harvey and K. Rush)

The neutron transmission of a 1.9 cm thick sample of ^{239}Pu was measured over the energy range from ~ 100 eV to 500 keV. A ^6Li glass detector 12.7 mm thick located ~ 78 m from the neutron source was used. An electron pulse width of 12 nsec was used with channel widths of 4 nsec for times up to 115 μsec after the neutron burst.

i. Neutron Capture Cross Section of ^{240}Pu †,‡ (L. W. Weston and
J. H. Todd)

The ^{240}Pu average capture cross section was measured from 200 eV to 350 keV. The cross section was normalized at thermal neutron

*Abstract of ORNL/TM-6246 (to be published).

**Relevant to request No. 74124.

†Nucl. Sci. Eng. 63, 143 (1977).

‡Relevant to request No. 69389.

energies (0.02 to 0.03 eV) and this normalization was confirmed at the 1.06 eV resonance by the black resonance technique. The Oak Ridge Electron Linear Accelerator (ORELA) was used as the source of pulsed neutrons. The capture gamma-ray detector used was the "total energy detector" which is a modification of the Moxon-Rae detector. The shape of the neutron flux was measured relative to the $^{10}\text{B}(n,\alpha)$ cross section up to 2 keV and the $^6\text{Li}(n,\alpha)$ at higher neutron energies. The results of the measurement define the average capture cross section of ^{240}Pu over a wide neutron energy range to an accuracy of about 8% which is significantly better than previously known. The results indicate that the ENDF/B-IV evaluation is about 25% low above 30 keV neutron energy. The cross section is important in fast Pu-fueled reactors.

j. Neutron Capture and Fission Cross Section of ^{241}Pu *,**
(L. W. Weston and J. H. Todd)

Neutron capture and fission cross sections of ^{241}Pu have been measured from 0.01 to 30 eV, and their ratio has been measured up to 250 keV. The cross sections were normalized at thermal-neutron energies (0.02 to 0.03 eV) to the ENDF/B-IV evaluation. The source of pulsed neutrons was the Oak Ridge Electron Linear Accelerator. The gamma-ray detector used to detect capture and fission events was the "total energy detector," which is a low-efficiency detector whose average efficiency is forced to be proportional to the energy of the interacting gamma rays by weighting these events according to their pulse height in the scintillator. Fast-neutron scintillation detectors with pulse-shape discrimination were used to detect fission events. The shape of the neutron flux was measured relative to the $^{10}\text{B}(n,\alpha)$ cross section. The measurements are unique in that absorption and fission were determined directly and simultaneously over a wide neutron energy range rather than indirectly by inferring capture from separate fission and total cross-section measurements. The results indicate that the neutron resonance region of the ENDF/B-IV evaluation underestimates capture by about a factor of two. Above the resonance region (~ 100 eV) there are no previous measurements of the differential capture cross section. These cross sections are important in Pu-fueled reactors.

k. Multilevel Resonance Parameters of Plutonium-241†
(L. W. Weston and J. H. Todd)

The data previously reported by the authors on the neutron fission and capture cross sections of ^{241}Pu have been simultaneously fit with the Adler formalism to obtain multilevel resonance parameters. The neutron energy range of the fit was 0.01 to 100 eV. The ^{241}Pu cross

*Nucl. Sci. Eng. 65, 454 (1978).

**Relevant to request Nos. 67132, 76042, 76094, and 76095.

†Proposed technical note to Nuclear Science and Engineering.

sections in the resonance region of neutron energies are complex and the Adler parameters present an efficient method of representing these cross sections which are important for Pu-fueled reactors. The parameters represent the data to an accuracy which is within the quoted experimental errors.

l. Neutron Resonance Parameters of ^{249}Bk and ^{249}Cf (R. W. Benjamin,* J. A. Harvey, N. W. Hill and M. S. Pandey**)

Transmission measurements of two ^{249}Bk samples (98% Bk and 2% Cf) and two ^{249}Cf samples (70% Cf and 30% Bk) have been analyzed to give parameters of the resonances up to ~ 100 eV. Radiation widths for the first 9 resonances in ^{249}Bk give an average radiation width of 35.7 ± 1.5 meV. Twelve resonances were observed in ^{249}Cf up to 20 eV which agree with resonances in the fission cross section; however, the total widths of many are considerably smaller than reported fission widths. Some details on this work have been reported in the Transactions of the ANS, San Francisco, Calif., Nov. 27-Dec. 2, 1977.

We have recently made additional transmission measurements on the samples, which are now $\sim 88\%$ ^{249}Cf and 12% ^{249}Bk , from 0.02 to 1000 eV.

m. Status Report on the ORNL Absolute Measurement of $\bar{\nu}_p$ for ^{252}Cf (R. R. Spencer, R. Gwin, R. Ingle and H. Weaver)

The average number of prompt neutrons emitted in spontaneous fission of ^{252}Cf , $\bar{\nu}_p$, has been measured using a gadolinium poisoned, liquid scintillator tank as neutron detector. The detector efficiency was determined absolutely as a function of energy by using "tagged" neutrons scattered from a liquid scintillator. A value of 3.789 ± 0.007 for $\bar{\nu}_p$ of ^{252}Cf was obtained from the first complete experiment. Work is continuing to discover and quantify systematic uncertainties and to replicate a result under changed experimental conditions.

7. Integral Measurements

a. A Measurement of the Neutron Streaming in a CRBR Prototypic Coolant Pipe Chaseway† (F. J. Muckenthaler and C. E. Clifford)

This report summarizes the measurements for a full scale mockup of the coolant pipe chaseway for the CRBR design. The chaseway contained two 90° bends and four chokes, all located in the same horizontal plane. The coolant pipe, 91.4 cm in diameter surrounded by 22.9 cm of Kaylo insulation, was divided into four separate sections of

*Savannah River Laboratory, Aiken, South Carolina 29801.

**College of William and Mary, Williamsburg, Virginia 23185.

†Abstract of ORNL/TM-5901 (August 1977).

unequal lengths. Measurements could then be made as a function of pipe length. The sodium coolant was simulated by sodium carbonate.

The TSR-II neutron energy spectrum was modified using 45.7 cm of stainless steel and 152.4 cm of sodium to resemble that of the CRBR chaseway. Measurements of the neutron flux, using a series of Bonner balls, indicated an attenuation of about 10^9 for the chaseway with all pipes present.

b. Experimental Studies of Radiation Heating in Iron and Stainless Steel Shields for the CRBR Project* (C. E. Clifford, et al.)

This report describes a series of radiation heating measurements in heavy-metal shield configurations performed at ORNL. Simultaneous measurements were made by personnel from ANL, MIT, and ORNL. The experimental techniques being evaluated involved the use of CaF_2 and ^7LiF thermoluminescent dosimeters (TLDs) and a high-pressure argon-krypton filled ion chamber designed and built by the ORNL Instrumentation and Controls Division. Intercomparison of the experimental results and comparison with calculation provides a meaningful evaluation of these experimental techniques for measuring the energy depositions.

It was shown that the ^7LiF -TLD measurements and the ion chamber results were about 14% higher than the CaF_2 -TLD measurements. The calculations were found to be about 2-5% lower than the CaF_2 -TLD measurements for the iron configuration and about 15-20% lower than the CaF_2 -TLD measurements for the stainless steel configuration. Even greater disparities were found between calculation and measurement for the ^7LiF -TLD and ion chamber dosimeters.

c. Secondary Gamma-Ray Production in Iron and Natural Thorium from Californium Fission Spectrum Neutrons**† (A. S. Makarious‡)

Measurement of the secondary gamma-ray spectra from the interaction of a Cf^{252} fission neutron spectrum with Fe samples of different thicknesses and a Th^{232} sample have been performed at the Tower Shielding Facility at ORNL. A 5-in. by 5-in.-diam NaI (Tl) scintillation spectrometer was used. The measured 0.846-MeV gamma ray from neutron inelastic scattering in Fe was compared with calculations using the differential values of cross sections as a function of incident neutron energy. This is an integral check for those differential cross sections.

*Abstract or ORNL-5161 (February 1977).

**Abstract of ORNL/TM-5675.

†Relevant to request No. 76078.

‡On assignment from the Atomic Energy Establishment of Egypt.

Thorium, as far as we know, had not been investigated before for this fast neutron energy range. Even though a peak at .184 MeV was found, it was felt that the resulting large cross section value obtained made it highly improbable that the gamma ray came from a fast neutron interaction. Search for other possible neutron-induced gamma rays was very difficult due to the high intensity of naturally radioactive gamma rays from thorium itself.

8. Experimental Techniques

- a. A Proton-Recoil Telescope for In-Line Absolute Neutron Fluence Measurements* (G. L. Morgan, D. K. Olsen and J. W. McConnell)

A proton recoil telescope has been designed for absolute neutron fluence monitoring at the Oak Ridge Electron Linear Accelerator. This telescope uses a combination radiator designed to provide usable efficiency over the energy range from 0.5 to 5.0 MeV. The telescope has greater than 99% transmission and can be used for in-line fluence measurements.

- b. An Assessment of the "Thermal Normalization Technique" for Measurement of Neutron Cross Sections vs Energy** (R. W. Peelle and G. de Saussure)

Refined knowledge of the thermal neutron cross sections of the fissile nuclides and of the (n, α) reaction standards, together with the reasonably well-known energy dependence of the latter, have permitted resonance-region and low-keV fissile nuclide cross sections to be based on these standards together with count-rate ratios observed as a function of energy using a pulsed "white" source. As one evaluates cross sections for energies above 20 keV, optimum results require combination of cross section shape measurements with all available absolute measurements. The assumptions of the "thermal normalization method" are reviewed and an opinion is given of the status of some of the standards required for its use. The complications which may limit the accuracy of results using the method are listed and examples are given.

For the $^{235}\text{U}(n,f)$ cross section, the option is discussed of defining resonance-region fission integrals as standards. The area of the ~ 9 eV resonances in this nuclide may be known to one percent accuracy, but at present the fission integral from 0.1 to 1.0 keV is known to no better than about two percent. This uncertainty is based on the scatter among independent results, and has not been reduced by the most recent measurements. This uncertainty now limits the accuracy attainable for the $^{235}\text{U}(n,f)$ cross section below about 50 keV.

*To be published.

**NBS SP 493, p. 174, Proc. Int. Specialists Symposium on Neutron Standards and Applications, Gaithersburg, Md., March 28-31, 1977.

c. Instruments for use of ^6Li as a Standard* (L. W. Weston)

A review is given of the instruments which use the $^6\text{Li}(n,\alpha)^3\text{H}$ reaction as a standard in the measurement of neutron flux. These instruments consist of scintillation detectors, gaseous ionization detectors, and external particle detectors. The Li glass scintillator is the most versatile because of minimized effects of the angular distribution of the reaction products and simplicity. The gaseous ionization detector has lower gamma-ray sensitivity than does the scintillation detector. Surface-barrier diodes may be used to detect the reaction products when a neutron spectrometer is desired. A choice of instruments to use this reaction must consider gamma-ray sensitivity, effects of the angular distribution of the reaction, and the range of the triton in the detector.

d. "Honeycomb" Fission Chamber for Intensely α -active Samples**
(J.W.T. Dabbs, H. W. Sang, Jr.,† K. Rush and H. Weigmann‡)

The problem of α -particle pulse pileup in fission chambers has been approached by introducing a separator constructed of thin phenolic plastic walls perpendicular to the large area parallel plates, forming hexagonal cells. The ratio of the cell dimension to the 3 mm plate spacing is $\sim 3:1$. Computer simulation of the behavior, based on Monte Carlo calculations of multiple pulse pileup, indicated that low fission rates ($< 1/\text{sec}$) could be measured in the presence of $10^8 \alpha/\text{sec}$. These expectations were confirmed using a 2 mg sample of ^{241}Am on a 7.5 cm dia. deposit. A fast current amplifier with Nowlin filters was used with pure CH_4 gas at 590 torr and 500 volts. A decrease in pulse height of 1.5%/week without a concomitant decrease in the d-c ion current (200 nA) is attributed to electron attachment to O_2 outgassed from the plastic grid.

*Abstract of paper presented at International Specialists Symposium on Neutron Standards and Applications, Gaithersburg, Maryland, March 28-31, 1977.

**Abstract of paper to be presented at APS Meeting, Washington, D.C., April 24-27, 1978.

†Summer graduate research participant from Massachusetts Institute of Technology, Cambridge, Massachusetts.

‡Visiting scientist from BCMN, Geel, Belgium.

B. DATA ANALYSES

1. Theoretical Calculations

a. Least-Squares Dosimetry Unfolding: The Program STAY'SL* (F. G. Perey)

A PDP-10 FORTRAN IV computer program STAY'SL, which solves the dosimetry unfolding problem by the method of least squares, is described. The solution (the output spectrum and its covariance matrix) is calculated by minimizing chi-square based on the input data (the activation data, the input spectrum, the dosimetry cross sections and their uncertainties given by covariance matrices). The solution reflects therefore the uncertainties in all of the input data and their correlations. The correlations among the various dosimetry cross sections are taken into account; however, the activation data, input spectrum and cross sections as classes are assumed to be uncorrelated with each other.

The code and sample problem are available from the Radiation Shielding Information Center (RSIC) at Oak Ridge National Laboratory.

b. Multi-Step Hauser-Feshbach Codes with Pre-Compound Effects: A Brief Review of Current and Required Developments and Applications up to 40 MeV** (C. Y. Fu)

Mainly for applications to fusion energy research, several multi-step Hauser-Feshbach codes with pre-compound effects were developed. An effort to intercompare these codes by their authors is in progress. Because extensive reviews on the relevant theories have recently become available, only a few points of interest with respect to the developments and applications of these codes will be discussed.

c. SIOB: A FORTRAN Code for Least-Squares Shape Fitting Several Neutron Transmission Measurements Using The Breit-Wigner Multilevel Formula† (G. de Saussure, D. K. Olsen and R. B. Perez)

The FORTRAN-IV code SIOB was developed to least-squares fit the shape of neutron transmission curves. Any number of measurements on a common energy scale for different sample thicknesses can be simultaneously fitted. The computed transmission curves can be broadened with either a Gaussian or a rectangular resolution function or both, with the resolution width a function of energy. The total cross section is expressed as a sum of single-level or multilevel Breit-Wigner terms and Doppler broadened using the fast interpolation routine QUICKW. The number of data points, resonance levels and variables which can be

*Abstract of ORNL/TM-6062, ENDF-254 (October 1977).

**BNL-NCS-50681, p. 453 (July 1977).

†Abstract of paper to be published as an ORNL report.

handled simultaneously is only limited by the overall dimensions of two arrays in the program and by the stability of the matrix inversion. In a test problem seven transmissions each with 3750 data points were simultaneously fitted using 74 resonances and 110 variable parameters. The problem took 47 minutes of CPU time on an IBM-91, for three iterations.

- d. A Perturbation Formalism for the Complex Poles and Widths of the Transition Matrix with an Application to Intermediate Structure Phenomena* (R. B. Perez, G. de Saussure, D. K. Olsen and F. C. Difilippo)

The complex poles and widths of the Transition T-matrix are determined by the trajectory equations which consist of a set of first order nonlinear differential equations. A hierarchy of approximate solutions to the trajectory equations is developed by iterative methods. The results of this formalism are compared to exact solutions for the case of some strongly interacting pairs of resonances in two iron isotopes. In the presence of intermediate structure the average neutron reaction cross section is interpreted in terms of a resonant strength function which exhibits peaks at neutron energies corresponding to "doorways" levels.

- e. The Effect of the Energy Dependence of the Neutron Widths on the Calculation of Average Reaction Cross Sections** (F. C. Difilippo and R. B. Perez)

We study the validity of neglecting the energy dependence of the neutron width in the calculation of average reaction cross sections.

- f. Neutronics and Radiation Damage Calculations for Fusion Reactors† (R. G. Alsmiller, Jr., T. A. Gabriel and R. T. Santoro)

In this paper some of the neutronics calculations that have been carried out at ORNL to aid in the conceptual design of fusion reactors are presented and discussed. The emphasis is on those calculations that have been done to assess the radiation damage in various reactor components. In Section II, the methods and cross section data used to carry out the calculations are briefly discussed. In Section III, the data base, RECOIL, that has been developed to assess radiation damage in various neutron environments is described and calculated results of displacement rates and gas production rates in several fusion reactors are presented and discussed. In Section IV, the effects of

*Abstract of paper to be submitted for publication in Physical Review.

**Abstract of ORNL/TM-5850 (December 1977).

†Proc. Second ASTM-Euratom Symposium on Reactor Dosimetry, Palo Alto, California, October 3-7, 1977.

reactor penetrations on the radiation damage in the toroidal field coils of a Tokamak experimental power reactor are studied.

- g. The Intranuclear-Cascade-Evaporation Model for Nonelastic Nuclear Collisions and Its Application in Biomedical and MFE Research* (T. A. Gabriel and R. G. Alsmiller, Jr.)

The intranuclear-cascade-evaporation model (ICEM) of nuclear reactions is a semiclassical approach used to describe in absolute terms continuum state transitions induced by a variety of incident particles including neutrons, protons, pions, heavy ions, etc. The emphasis here will be on incident protons and neutrons. The assumptions of the model are most applicable to high-energy ($\gtrsim 100$ -MeV) particle-induced nuclear reactions, but comparisons between calculated and experimental nonelastic total and differential cross section data at lower energies (~ 20 -100 MeV) has shown reasonable agreement. Due to this agreement and to the fact that above 20 MeV there is a lack of experimental data, this model has often been used to generate the differential nuclear reaction data for a variety of applications. For example, ICEM is currently incorporated into a Monte Carlo radiation transported code (HETC) that has been and is being used extensively and successfully for a variety of radiation transport problems, and data obtained from ICEM has often been used in the discrete ordinates codes ANISN and DOT.

In Section II, a brief description of ICEM is given and comparisons between results obtained with ICEM and experimental cross section data are presented. In Section III transport calculations carried out using differential cross section data obtained with ICEM are presented and compared with experimental data.

- h. High Energy ($E \leq 1000$ GeV) Intranuclear Cascade Model for Nucleons and Pions Incident on Nuclei and Comparisons with Experiments] Data** (H. W. Bertini, A. H. Culkowski, O. W. Hermann, N. B. Gove and M. P. Guthrie)

An intranuclear cascade model for reactions of pions and nucleons with complex nuclei that should cover the energy range from about 50 MeV to about 1000 GeV has been developed. The model includes the effect of a diffuse nuclear surface, the Fermi motion of the bound nucleons within the nucleus, the exclusion principle, a local potential for nucleons, a localized reduction in the density of the nucleus during the development of the cascade, and the sequencing of the events correctly with time. Theoretical results from the model are compared with experimental data over the energy range ~ 3 -1000 GeV. Within the

*Symposium on Neutron Cross Sections 10-40 MeV, BNL, Upton, NY, May 3-5, 1977, BNL-NCS-50681, p.515 (July 1977).

**Abstract of ORNL/TM-5710 (August 1977).

cascade model, the equations that are used to represent the pion multiplicity from the reactions of nucleons and pions with the individual nucleons of the nucleus underestimates the number of shower particles produced by these individual nucleon interactions. In spite of this the predicted number of shower particles escaping from the nucleus, for 100-GeV nuclear interactions, is overestimated by about 25% for light nuclei to about 60% for heavy nuclei. The agreement for the number of escapes from the nucleus is somewhat better at lower interaction energies (~ 10 -20 GeV). Some of the major trends in the observed high energy data are predicted quite well. These include the energy independence of (a) the number of black tracks produced at interaction energies above 5 GeV, (b) the number of shower particles produced above 100 GeV, and (c) the radionuclides produced above 10 GeV. Other trends that are predicted fairly well are the small mass dependence of the shower particle multiplicity (factor of 2 increase predicted from carbon to lead; factor of 1.5 measured), and the change in the angular dependence of the multiplicity with mass. In absolute comparisons, the predicted total reaction cross sections are in good agreement with experimental data, and the cross sections for the production of radionuclides are in fair agreement.

2. ENDF/B Related Evaluations

a. The Data Covariance Files for ENDF/B-V* (F. G. Perey)

In this report are presented the formats and procedures for the data covariances of ENDF/B-V.

b. R-Matrix Evaluation of Carbon as a Neutron Scattering Standard Below 2 MeV** (C. Y. Fu and F. G. Perey)

Cross-section and polarization data for neutron interaction with carbon below the inelastic threshold (4.81 MeV) were evaluated and analyzed by R-matrix theory. Six sets of total cross-section data below 2 MeV were partially smoothed and least-square fitted with non-diagonal weighting to obtain averages and their estimated uncertainties for use in the R-matrix search program. The resulting differential scattering cross sections below 2 MeV are recommended as standards. The good quality of the fits well above 2 MeV and a high-precision (0.1%) thermal value enhances the confidence in the recommended values below 2 MeV.

c. Ba-138 Evaluation (R. W. Roussin)

The Shielding Subcommittee of CSEWG recommended that the Ba-138 data set from the Livermore Evaluated Nuclear Data Library (LENDL) be submitted to NNDC for inclusion in ENDF/B-V.

*Abstract of ORNL/TM-5938, ENDF-249 (July 1977).

**To be submitted for publication in Atomic Data and Nuclear Data Tables.

Some minor adjustments to the original LENDL data were made at the Radiation Shielding Information Center to allow the Ba-138 evaluation to conform to ENDF/B-V format. These included extension of the lower energy region to $1.0\text{E-}5$ eV, the addition of an isotropic (c.m.) elastic scattering angular distribution at $1.0\text{E-}5$ eV, and the inclusion of isotropic (lab) distributions for nonelastic reactions.

d. Evaluation of the ^{232}Th Neutron Capture Cross Section above 3 keV* (G. de Saussure and R. L. Macklin)

This memo describes an evaluation of the ^{232}Th neutron capture cross section in the neutron energy range from 3 keV to 20 MeV. Most existing differential measurements are reviewed, and some data are renormalized to current values of the standards. Several experimentally determined sets of average resonance parameters are also discussed.

From 3 to 50 keV the evaluated cross section is described by a set of average statistical resonance parameters. Above 50 keV the evaluated capture cross section is a smooth curve which follows the trend of the most recent measurements.

The evaluated capture cross section is compared with many measurements and uncertainty estimates are given.

e. Review and Combination of Experimental Results for $\bar{\nu}(E)$ of ^{232}Th ** (R. Gwin)

An analysis of the existing experimental data for $\bar{\nu}(E)$ of ^{232}Th has been made. This analysis suggests that a single linear function of the neutron energy describes the data within the uncertainties of the data. The parameters of the linear function and their uncertainties are given.

f. Evaluation for $^{232}\text{Th}(n,n')$, $(n,2n)$ and $(n,3n)$ Cross Sections† (C. Y. Fu)

The techniques used for the evaluation of $^{232}\text{Th}(n,n')$, $(n,2n)$, and $(n,3n)$ cross sections are described. Because the presently used evaluation, ENDF/B-IV MAT 1296, was based on data taken ten years ago, a minor evaluation effort making use of more recent data and advanced computing technology is believed to result in substantial improvement. The recommended cross sections are tabulated in the appendix and are compared graphically with the available data and the ENDF/B-IV values.

*Abstract of ORNL/TM-6161 (December 1977).

**Abstract of ORNL/TM-6245 (to be published).

†Abstract of ORNL/TM-6316 (to be published).

- g. Evaluation of the ^{238}U Neutron Cross Sections for Incident Neutron Energies up to 4 keV* (G. de Saussure, D. K. Olsen, R. B. Perez and F. C. Difilippo)

This report describes an evaluation of the ^{238}U cross sections below 4 keV. Recent measurements and reanalyses of older data are discussed. Evaluated resonance parameters are obtained for 164 s-wave and 280 p-wave levels. The capture widths of the first three s-wave levels are significantly lower than in the ENDF/B-IV evaluation. The s-wave strength function above 1.5 keV is systematically larger than in ENDF/B-IV. Statistical and systematic uncertainties are evaluated for the resonance parameters and for the smooth backgrounds. The statistical distributions of the resonance parameters are compared with theoretically expected distributions.

- h. Compilation of Multigroup Cross-Section Covariance Matrices for Several Important Reactor Materials** (J. D. Drischler and C. R. Weisbin)

This report presents multigroup cross-section covariance matrices for fission in ^{235}U , ^{238}U , ^{239}Pu , and ^{241}Pu ; capture in ^{235}U , ^{238}U , ^{239}Pu , ^{240}Pu , and ^{241}Pu ; fission neutron yield ($\bar{\nu}$) for ^{235}U , ^{238}U , ^{239}Pu , and ^{240}Pu ; elastic scattering for Na and Fe; non-elastic reactions for Na and Fe; first-level inelastic scattering for ^{238}U ; and all reactions provided in the ENDF/B-IV covariance description of N, O, and C. Other data files generated are included for reference, but have not yet been tested. The report presents the multigroup data in six, ten, and fifteen energy group forms corresponding to weighting of the covariance data with fission (GODIVA), LMFBR (ZPR-6/7) and 1/E spectra, respectively. The data are illustrated and tabulated in an edited form for convenience. The multigroup covariance files are currently available from RSIC and NNDC in the COVERX format, a computer retrievable format designed for data uncertainty analysis and described herein. As new covariance files become available with subsequent issues of ENDF/B, this report will be added to or revised by the issuance of dated pages that can be incorporated in the report.

3. Validation of ENDF/B Evaluations Through Integral Measurements

- a. Propagation of Uncertainties in Fission Cross Section Standards in the Interpretation and Utilization of Critical Benchmark Measurements† (C. R. Weisbin and R. W. Peelle)

This work explores the constraints imposed on the $^{235}\text{U}(n,f)$ standard (proposed ENDF/B version V) by information deduced from clean

*Abstract of ORNL/TM-6152, ENDF-257 (January 1978).

**Abstract of ORNL-5318, ENDF-235 (October 1977).

†Int. Spec. Symp. Neutron Stds. and Appl., NBS, March 28-31, 1977.

integral measurements and demonstrates how uncertainties in fission cross section standards propagate in an uncertainty analysis and interpretation of those experiments. The question of what a significant improvement in the accuracy of the $^{235}\text{U}(n,f)$ standard would accomplish is addressed in the limited context of analyses of GODIVA and JEZEBEL measurements.

The CSEWG integral benchmark results and uncertainties were updated in accordance with more recent information. Sensitivity coefficients were developed and used to estimate calculated results which should be obtained using the subsequent release of $^{238}\text{U}(n,f)$, $^{235}\text{U}(n,f)$, and $^{239}\text{Pu}(n,f)$ at version V status. Covariance files were evaluated and processed for all important cross sections with the sole exception being inelastic scattering for all levels and the continuum. Uncertainties due to the $^{235}\text{U}(n,f)$ standard were estimated to comprise more than half of the calculated uncertainty for criticality and $\langle^{28}\sigma_f/^{25}\sigma_f\rangle_c$ spectral index in JEZEBEL as well as GODIVA; though the JEZEBEL assembly contained no ^{235}U . We are not able at this time to predict criticality or $\langle^{28}\sigma_c/^{28}\sigma_f\rangle_c$ to anywhere near the accuracy obtained by direct measurements, and therefore the integral results are significant to our analysis capability. Inclusion of integral information from GODIVA and JEZEBEL in an adjustment procedure was effective in reconciling all parameters other than $\langle^{28}\sigma_f/^{25}\sigma_f\rangle_c$ measurement in JEZEBEL for which current calculation and measurement are in disagreement. The adjustment procedure made changes of less than one standard deviation in the cross sections for $^{235}\text{U}(n,f)$, $^{235}\text{U}(n,\gamma)$, $^{238}\text{U}(n,f)$, $^{238}\text{U}(n,\gamma)$, and $^{239}\text{Pu}(n,f)$ including an increase of $\sim 1.5\%$ for the $^{235}\text{U}(n,f)$ cross section above 1.3 MeV. This specific adjustment result could change with inclusion of inelastic covariance files and must be viewed cautiously at this time.

b. Analyses of TSF Experiments on Radiation Heating in a Stainless Steel-Sodium CRBR Radial Shield Mockup Using a 32-in. Diameter Collimated Beam Source* (R. E. Maerker)

Analyses of the second phase of the radiation heating experiments performed at the Tower Shielding Facility have been made where the emphasis was placed on investigating the accuracy of TLD measurements in mockups of the CRBR radial shield. In particular, it is concluded that with the aid of flux calculations described in this report the corrections to both the Li^7F and CaF_2 TLD measurements are well enough understood that the TLD measurements can be brought into $\pm 3\%$ agreement with both ion chamber measurements and with each other. The accuracy of the gamma-ray calculations is limited by the accuracy of the 51 neutron group transport calculations; the production cross sections present in ENDF/B-IV are adequate for U^{238} , sodium, and stainless steel.

*Abstract of ORNL/TM-5992 (October 1977).

c. Measurement and Calculation of Secondary Gamma Rays
Resulting from Exposure of Fe, Pb, and H₂O to the ARERR-1
Spectrum* (A. S. Makarious,** W. E. Ford and K. R. Turnbull)

Integral experiments were performed to measure the angular distribution of secondary gamma rays produced when various thicknesses of Fe, Pb, and H₂O samples were exposed to bare and to B₄C-filtered neutron beams from the Research Reactor of Egypt. For selected experiments, multigroup coupled neutron-gamma cross sections and a discrete ordinates transport theory code (DOT4P1-M) were used to calculate the secondary gamma rays and the transport of primary gamma rays. Integral comparisons between the calculated and measured spectra were favorable.

Graphical comparisons of the measured flux for various angles of incidence of the neutron beams on the samples, for various angles of exit on the transmitted side of the samples, and for various sample thicknesses are shown. The comparisons show that the angular distribution of secondary gamma rays for the three materials changes slightly with a change in the angle of beam incident on the sample, but increasing the angle between the normal to the sample and the detector by 60° decreases the measured secondary gamma-ray flux up to a factor of two.

An investigation was made to determine the consequences of using single scatter Compton theory versus using discrete ordinates transport calculations to estimate the primary gamma-ray contribution to the measured photon spectra.

*Abstract of ORNL/TM-5678 (August 1977).

**On assignment from the International Atomic Energy Agency.

C. NUCLEAR DATA PROJECT ACTIVITIES — 1977

(R. L. Auble,* J. R. Beene,* F. E. Bertrand,* Y. A. Ellis,
W. B. Ewbank, M. L. Halbert,* J. Halperin,* B. Harmatz, M. J. Martin,
M. R. Schmorak, K. S. Toth,* and M. P. Webb*)

1. Evaluated Nuclear Structure Data File (ENSDF)

As of January 1978, ENSDF contains the following data sets:

1920	Adopted levels
1570	Decay schemes
2360	Other data sets (mostly nuclear reactions).

The details of ENSDF coverage are illustrated in the figures. Although the number of nuclei contained in the file has increased by only about 10%, the depth of coverage has been improved in two ways.

a) Adopted level properties for every nucleus are now included in ENSDF. For most nuclei, this information has been taken from the published *Nuclear Data Sheets*. For light nuclei, the evaluations published in *Nuclear Physics* have been used, and for $A = 117, 119, 147, 152,$ and 154 , the level properties have been taken from manuscripts prepared for the Seventh Edition of the *Table of Isotopes*.

b) Complete information on gamma-ray conversion and beta-neutrino energy partition has been added to over 200 decay schemes. Detailed radiation calculations can now be performed for about 500 decay schemes by the Nuclear Data Project program MEDLIST. This includes energy distribution over charged particles, photons, and neutrinos; comparison with available energy (Q-value); and preparation of tabular and computer-readable files of detailed radiation data.

The tabular output from MEDLIST has been used to prepare special collections of decay information for radiation protection¹ and for environmental monitoring.² A computer-readable collection of these data has been prepared by MEDLIST and is being distributed through the Radiation Shielding Information Center. The MEDLIST program is also used in response to requests for decay information and as a technique for checking the internal consistency of nuclear decay schemes.

The complete adopted level properties contained in ENSDF have been used to prepare systematic displays of level energies and energy ratios across the entire periodic table.

*Part-time assignment to Nuclear Data Project.

¹M. J. Martin, in *A Manual of Radioactivity Measurements Procedures*, National Council on Radiation Protection and Measurements, Washington, D.C., to be published.

²D. C. Kocher, Ed., *Nuclear Decay Data for Radionuclides Occurring in Routine Releases from Nuclear Fuel Cycle Facilities*, ORNL/NUREG/TM-102 (1977).

A tape copy of the complete contents of ENSDF is prepared twice each year for distribution as the "International File of Evaluated Nuclear Structure and Decay Data." Distribution of the tape (through the National Nuclear Data Center at Brookhaven) is made automatically to other data centers in the international data evaluation network and to other users on request.

2. Nuclear Structure References (NSR)

In 1977, over 2400 references from primary sources (journals) and 2700 references from secondary sources (reports, conference abstracts) were indexed and added to the Nuclear Data Project master file. New entries into the NSR file are collected and published three times each year in "Recent References" issues of *Nuclear Data Sheets*. All entries since 1969 are also available for remote search through the RECON network.

Agreement has been reached with the Nuclear Data Centers at Gatchina (Leningrad Institute) and Moscow (Kurchatov Institute) on the format and content of computer-readable nuclear structure reference information. These conventions will provide a simpler channel for USSR literature to enter the NSR file.

Magnetic-tape copies of the NSR file are made available to other data centers on a schedule matching the cutoff for "Recent References."

3. International Network for Nuclear Structure Data Evaluation

Commitments to data evaluation by other US and non-US centers were formalized at the Oak Ridge meeting of the IAEA Advisory Group on Nuclear Structure and Decay Data. The stated goal of the network is to provide a four-year cycle for incorporation of new experimental results into ENSDF. The Nuclear Data Project provides data listings and reference printouts for network data evaluators. Standards for data evaluation and content of ENSDF data sets are monitored by the Nuclear Data Project. Each new evaluation will be reviewed for completeness and correctness before being added to ENSDF. Programs for preparing drawings, formatted tables, and reference lists from ENSDF data sets are in regular use at the Nuclear Data Project.

ENSDF Decay Data

02-05-78

ENSDF Data Bank Inventory

02-05-78

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