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Status Report to the DOE Nuclear Data Committee

F. G. Perey
J. C. Gentry

OAK RIDGE NATIONAL LABORATORY
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Engineering Physics Division

STATUS REPORT TO THE DOE NUCLEAR DATA COMMITTEE

Compiled and edited by:

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final report.

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ABSTRACT

This report was prepared for the DOE Nuclear Data Committee and covers work performed at ORNL since April 1978 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 $O(n,\gamma)$ Reaction Cross Section for Incident Neutron Energies Between 6.5 and 20.0 MeV* (G. L. Morgan and G. T. Chapman)

Differential cross sections for the neutron-induced gamma-ray production from oxygen have been measured for incident neutron energies between 6.5 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 1.6 and 10.6 MeV for coarse intervals in incident neutron energy. The integrated yield of gamma rays of energies greater than 1.6 MeV with higher resolution in the neutron energy is also presented. The experimental results are compared with the Evaluated Nuclear Data File (ENDF).

- b. The $^{23}\text{Na}(n,\gamma)$ Reaction Cross Section** (D. C. Larson and G. L. Morgan)

Differential cross sections for neutron-induced gamma-ray production from sodium have been measured for incident neutron energies between 0.2 and 20.0 MeV. Gamma rays with energies $0.35 \leq E_\gamma \leq 10.6$ MeV were detected with a sodium iodide spectrometer at 125° . The data presented are the double-differential cross section $d^2\sigma/d\Omega dE$, for coarse intervals in incident neutron energy, the measured results are compared with calculations based on multistep Hauser-Feshbach theory, and with a benchmark gamma-ray production measurement performed at the Oak Ridge Tower Shielding Facility.

- c. The $\text{Th}(n,\gamma)$ Reaction Cross Section for Incident Neutron Energies Between 0.3 and 20.0 MeV† (G. L. Morgan)

Differential cross sections for the neutron-induced gamma-ray production from thorium have been measured for incident neutron energies between 0.3 and 20.0 MeV. 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 0.3 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.

* Abstract of ORNL-5545 (to be published).

** Abstract of note to be submitted for publication in Nucl. Sci. Eng.

† Abstract of ORNL/TM-6758 (to be published).

d. Measurement of $^{238}\text{U}(n,n'\gamma)$ and $^7\text{Li}(n,n'\gamma)$ Gamma-Ray Production Cross Sections* (D. K. Olsen, G. L. Morgan, and J. W. McConnell)

Employing a 95-cm³ Ge(Li) detector, positioned 20 m from the ORELA white neutron source, 125° cross sections for gamma-ray production from 0.48 to 5.0 MeV incident neutrons on ^{238}U and ^7Li samples were measured by time-of-flight techniques. The incident neutron flux was determined with a proton-recoil telescope which used a solid-state, recoil-proton detector. Altogether, 28 cross sections for ^{238}U transitions from levels with 680 to 1224 keV of excitation were measured. In addition, seven branching ratios for weak ^{238}U transitions and the $^7\text{Li}(n,n'\gamma)^7\text{Li}^*$ (478-keV) cross section were measured. From these data and other level-decay information, neutron inelastic scattering cross sections from the 680-, 732-, and 827-keV levels and the 965-, 1045-, and 1170-keV pseudo-levels of ^{238}U were constructed and compared with those of the proposed ENDF/B-V evaluation.

2. Capture Cross Sections

a. Neutron Cross Sections of the Os Isotopes and Nucleosynthesis (R. R. Winters, J. Halperin, J. A. Harvey, N. W. Hill, and R. L. Macklin)

The neutron capture cross sections of the osmium isotopes 186, 187, and 188 were measured in the keV energy because of their interest to nucleosynthesis. The total cross sections of these three isotopes have also been measured from ~200 eV to 300 keV. The duration of nucleosynthesis prior to the formation of the solar system is calculated from the natural abundance of ^{187}Os , produced from the decay of the long-lived ^{187}Re , and the capture cross sections of ^{186}Os and ^{187}Os . A preliminary estimate of $\sim 12 \times 10^9$ years agrees well with that of Browne and Berman,¹ but is significantly larger than estimates from uranium-thorium dating. However, the neutron inelastic scattering of ~30-keV neutrons to the 10-keV level in ^{187}Os is an important input in the calculation. An experimental measurement of this cross section using 24-keV Fe window neutrons combined with the time-of-flight technique is planned.

b. Capture Cross Section Measurements of Fission Product Poisons (R. L. Macklin, J. Halperin, and R. R. Winters)

Isotopes of Pd and Ru, produced from fission, account for a considerable fraction of the poisoning in a fast reactor. Capture cross section measurements have been made in the keV energy region on five isotopes of Pd (including the important fission product 105) and four isotopes of Ru (including the important isotope 101). Parameters for individual Pd resonances (~100 in each isotope) were obtained up to ~10

* Abstract of ORNL/TM-6832 (to be published).

¹ Nature 262, 197 (1976).

keV and the average cross sections were analyzed at the higher energies to obtain strength functions Γ_γ/D_0 , S^1 , S^2 , and S^0 (the last only for ^{105}Pd). A similar analysis on the data for the isotopes of Ru is in progress.

3. Total Cross Sections

a. Neutron Total Cross Sections for H, C, O, and Fe from 0.5 to 50 MeV (D. C. Larson, J. A. Harvey, and N. W. Hill)

We have measured the transmission of neutrons through samples of CH_2 ($n_H=0.822$ at/b), C ($n=0.412$ at/b), O ($n=0.548$ at/b), and Fe ($n=0.430$ at/b). The Be block target of ORELA provided the neutrons, which were detected by a NE110 proton recoil detector located 80 m from the source. The data were corrected for deadtime losses and background effects, and converted to cross sections. Our measured hydrogen cross section is in good agreement over the complete energy range with the results from the various extensive phase shift analyses of this cross section. Data for C, O, and Fe are needed for shield design of the Fusion Material Irradiation Test Facility (FMIT).

b. Measurement of the Neutron Total Cross Section of Natural Magnesium from 9 keV to 39 MeV* (D. C. Larson, J. A. Harvey, N. W. Hill, and H. Weigmann**)†

The neutron transmission through a 5.09-cm sample of natural magnesium has been measured for neutron energies between 9 keV and 39 MeV. The Oak Ridge Electron Linear Accelerator (ORELA) was used to provide the neutrons, which were detected at the 200-m flight path by a NE-110 proton recoil detector. The experimental results are tabulated and compared with the total cross section in the ENDF/B-IV file for magnesium.

c. Neutron Transmission Measurements of the Thick Neutron Filters (J. A. Harvey, N. W. Hill, and J. R. Harvey†)

Transmission measurements have been made upon thick samples of ^{58}Ni (99.93%), ^{60}Ni (99.68%), ^{64}Zn (97.87%) to assess their usefulness as neutron filters to produce neutron beams of ~ 14 , ~ 4 , and ~ 2 keV energy, respectively. This window neutron technique is presently used at several reactors to produce beams of 2, 24, and 120 keV using thick filters of Sc, Fe, and Si. Windows at 160 eV in ^{184}W (94.51%) and 7.5 keV in natural copper are also being investigated. These "monoenergetic" neutron beams can be used for basic nuclear physics, instrument calibrations, fundamental radiobiology, and for radiotherapy of brain tumors.

* Abstract of ORNL/TM-6420 (to be published).

** Visiting scientist from the Central Bureau of Nuclear Measurement, Geel, Belgium.

† Berkeley Nuclear Laboratories, UK.

- d. Recent Results for ^{58}Ni and ^{56}Fe at ORELA* (F. G. Perey, G. T. Chapman, W. E. Kinney, and C. M. Perey)

Transmission and capture data from ^{58}Ni have been analyzed up to 120 keV and are reported. High resolution scattering measurements for Fe are discussed and the determination of the J^π value for most resonances seen in transmission data up to 400 keV is given including an attempt at evaluation of the resonances of ^{56}Fe on the basis of recently published data.

- e. $^6\text{Li}(n,\alpha)\text{T}$ Cross Section from 70 to 3000 keV via $^{235}\text{U}(n,f)$ Calibration of a Thin Glass Scintillator (R. L. Macklin, R. W. Ingle, and J. Halperin)

The efficiency of a 0.5 mm ^6Li glass scintillation monitor was determined above the "1/v" region by comparison with the counting rate of a 10 plate ^{235}U fission ionization chamber in a neutron beam from the Oak Ridge Electron Linear Accelerator (ORELA). The chief difference in derived $^6\text{Li}(n,\alpha)$ cross sections from the ENDF/B-V evaluation is a slightly greater width ($\sim 8\%$) of the prominent resonance peaking near 240 keV and a higher cross section in the wings. The peak value, 3.37 barns, is slightly higher than ENDF/B-V, 3.3087 barns, but is in good agreement with the value of 3.36 ± 0.06 barns obtained from an R-matrix fit to the absolute measurements by Renner *et al.*¹ The steep rise in efficiency from 3500 to 5000 keV is attributed primarily to the $^{16}\text{O}(n,\alpha)$ reaction.

- f. Measurement of the 2.35-MeV Window in $^{16}\text{O} + n$ (J. L. Fowler, C. H. Johnson, N. W. Hill, and J. M. Ortolf)

Stelson and Barnett have suggested² that the transmission of a thick oxygen scatterer can be used to measure the temperature of a d-d plasma. For a thick oxygen scatterer, neutrons are transmitted only near the 2.35-MeV minimum in the total cross section. The relative number of plasma neutrons near this minimum depends on the ion temperature. Accurate transmission measurements have been made on a 1.5-m liquid oxygen sample using the 200-meter flight path at ORELA. After correcting for the 0.17% impurities of N_2 and A, a value of 114.0 ± 1.7 mb at the minimum was obtained. The cross sections on the sides of the minimum were also measured using thinner matched samples of BeO and Be. Calculations show that the transmission of d-d neutrons will increase up to an ion temperature of about 6 keV.

* Proc. Specialists' Meeting on Neutron Data of Structural Materials for Fast Reactors, ed. K. H. Böckhoff, Pergamon Press Ltd. (1978).

¹ INDC(USA)-79/U, p. 233.

² Bull. Am. Phys. Soc. 23, 882 (1978).

4. Scattering and Reactions

a. Cross Sections for the $^{14}\text{N}(n,p_0)$, (n,α_0) , and (n,α_1) Reactions from 0.5 to 15 MeV* (G. L. Morgan)

Cross sections have been measured for the $^{14}\text{N}(n,p_0)$ reaction from 0.5 to 7.0 MeV and for the (n,α_0) and (n,α_1) reactions from 1 to 15 MeV and 4 to 15 MeV, respectively. The data were obtained using a gaseous scintillator containing N_2 and Xe mixtures. A linac was used as a pulsed, white neutron source with a 29-m flight path. The results of the measurement are compared to the current evaluated file for nitrogen; agreement is good for neutron energies below 8 MeV, but the measurement is substantially higher than the evaluation for neutron energies near 10 MeV.

b. Cross Sections for the $\text{Ti}(n,xn)$ and $\text{Ti}(n,x\gamma)$ 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 natural titanium have been measured at 130 deg. (lab) for incident neutron energies in the range 1 to 20 MeV. An electron linac was used as a pulsed, 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 unfolding 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 1286).

c. Cross Sections for the $\text{Cu}(n,xn)$ and $\text{Cu}(n,x\gamma)$ 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 natural copper have been measured at 130 deg. (lab) for incident neutron energies in the range 1 to 20 MeV. An electron linac was used as a pulsed, 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 unfolding 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 1295).

* Abstract of ORNL/TM-6528 (November 1978).

** Abstract of ORNL-5544 (to be published).

† Abstract of ORNL-5499, ENDF-273 (February 1979).

d. High Resolution Neutron Transmission and Scattering Measurements on ^{206}Pb (D. J. Horen, J. A. Harvey, and N. W. Hill)

High resolution neutron transmission and differential measurements have been made with ^{206}Pb samples. The data have been analyzed to obtain the E_0 , J , ℓ , and neutron widths of ~ 200 resonances up to ~ 600 keV. Doorway states are observed in the s-, p-, and d-wave neutron channels. Resonances in both the $p_{1/2}$ and $p_{3/2}$ channels are evident and are consistent with observations in the $^{207}\text{Pb} + n$ system. These doorways probably arise from a $d_{5/2}$ particle, 3^- core excitation. A major fraction of the resonances assigned from photonuclear work as p-wave are found to be s- or d-wave. In the interval from 3 to 600 keV we can deduce a value of < 24 eV for the M1 ground-state radiation $\Sigma \gamma \Gamma_{\gamma 0} \Gamma_n / \Gamma$. The average level density of the s-wave resonance shows an increase of about 12% per 100 keV up to 800 keV. The s-wave data (up to 800 keV) can be fitted by a constant temperature model with $T = 0.9$ MeV. The d-wave level density is consistent with a $(2J+1)$ dependence, but the number of p-wave resonances is greater than expected. The data also indicate that the level density for $J = 1/2$ is not parity independent.

5. Actinides

a. Actinide Neutron Cross Sections Program (J. W. T. Dabbs, L. W. Weston, J. A. Harvey, S. Raman, C. E. Bemis, R. L. Macklin, J. Halperin, K. Rush, N. W. Hill, J. H. Todd, C. H. Johnson, and M. L. Williams)

Fission - Development of a new type (honeycomb) fission chamber for $> 10^8$ α /sec samples was completed. Together with specially developed ultrafast amplifiers and a new Xe gas scintillator $^6\text{Li}(n, \alpha)$ neutron beam monitor of large area, this chamber permitted the measurement of the fission cross section of ^{241}Am over the energy range thermal to 20 MeV at ORELA. The ^{241}Am fission cross section in the 1 to 100 keV energy region is much lower than was obtained with earlier underground explosion measurements. Other laboratories have also confirmed the strikingly lower fission cross section in this energy range. Papers on fission of ^{234}U and ^{235}U were completed and published. In the latter paper, a collaboration between LASL and ORNL, the spins of some 375 resonances and structures below 300 eV were definitively established.

Capture - Results of capture cross section measurements on ^{240}Pu were published. Measurements of the capture cross section of ^{241}Pu with a simultaneous fission cross section determination were completed and published. Multilevel resonance parameters for this nuclide (Adler formalism) were derived and published. The $^{232}\text{Th}(n, \gamma)$ cross section from 2.6 to 800 keV has been revised and updated. Additional data have been

taken on ^{237}Np capture to extend the neutron energy range from 0.01 eV to 400 keV. Data reduction and analysis are in progress. Below 8 eV the data are in only fair agreement with ENDF/B-IV and resonance parameters will be derived for the new data. Agreement of the average capture cross section with optical model calculations within about 15% above 200 eV is found; these calculations have been used for ENDF/B-IV in the absence of differential data.

Total - Analysis of transmission data on 98% ^{249}Bk was completed and reported. The sample was permitted to decay to ^{249}Cf (330 day half-life) and remeasured twice. A preliminary analysis of data from the 70% ^{249}Cf was made and data have been taken on 86% ^{249}Cf and converted to cross section. A resonance analysis is in progress.

Integral Cross Section Determinations - Several separated actinide samples ranging from ^{232}Th to ^{241}Pu were irradiated for four years in EBR-II at Idaho Falls. A new program of measuring the present composition of these samples has been initiated in conjunction with the Analytical Chemistry Division of ORNL. First results, for a ^{239}Pu sample, have been published recently.

Actinide Newsletter - The second actinide newsletter detailing worldwide developments in actinide research (edited by S. Raman) was published by ORNL in February 1979.

- b. Measurement and Analysis of the Fission Cross Section and the Fission Fragment Anisotropy in the MeV-Neutron Induced Fission of ^{232}Th * (S. Plattard,** G. F. Auchampaugh,† N. W. Hill, R. B. Perez, and G. de Saussure)

The $^{232}\text{Th}(n,f)$ to $^{235}\text{U}(n,f)$ fission ratio and the fission fragment anisotropy in the $^{232}\text{Th}(n,f)$ -reaction have been measured at ORELA with a nominal resolution of 0.10 ns/m and for incident neutron energies from 0.6 to 10 MeV.

As far as the gross structures of the fission cross section are concerned, our data are in very good agreement with ENDF/B-V and with the results of the recent measurements of Blons *et al.*,¹ but our data do not reproduce the fine structure reported by Blons *et al.*

K-quantum numbers have been assigned to all major broad resonances from 0.9 to 2.5 MeV. None of these resonances can be described by a single K-quantum number. The two resonances at 920 and 1015 keV have predominantly $K=1/2$, with weaker contribution with $K=5/2$.

* IAEA Symposium on Physics and Chemistry of Fission, Jülich, Germany, May 14-18, 1979.

** Centre d'Etudes de Bruyères-le-Châtel, France.

† Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

¹ J. Blons, C. Mazur, and D. Paya, Phys. Rev. Lett. 35, 1749 (1975).

Using a code¹ based on the statistical model, calculations of the fission cross section and of the fission fragment angular distribution have been performed in the range 1.4 to 1.7 MeV, within the framework of the double humped fission barrier.

- c. Delayed Beta- and Gamma-Ray Production Due to Thermal-Neutron Fission of ^{235}U , Spectral Distributions for Times After Fission Between 2 and 14000 sec: Tabular and Graphical Data*
(J. K. Dickens, T. A. Love, J. W. McConnell, J. F. Emery, K. J. Northcutt, R. W. Peelle, and H. Weaver)

Fission-product decay energy-release rates have been measured for thermal-neutron fission of ^{235}U . Samples of mass 1 to 10 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 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 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 moderate resolution. These distributions are given in graphical and tabular form as differential cross-section values of $d\sigma/dE/\text{fission}$ for gamma-ray energy intervals ranging from 10 keV for $E_\gamma < 0.18$ MeV to 100 keV for $E_\gamma > 6.8$ MeV, and beta-ray energy intervals ranging from 20 keV for $E_\beta < 0.25$ MeV to 160 keV for $E_\beta > 6.4$ MeV. Counting-time intervals range from 1 sec for times-after-fission (t_w) < 6 sec to 4000 sec for $t_w = 10^4$ sec. The graphical representations also include calculated spectra using summation methods and the ENDF/B-IV fission yield and decay scheme data base.

- d. Measurement of the ^{238}U to ^{235}U Fission Cross Section Ratio for Neutron Energies Between 0.1 and 25 MeV** (F. C. Difilippo,† R. B. Perez, G. de Saussure, D. K. Olsen, and R. W. Ingle)

The ^{238}U to ^{235}U fission cross-section ratio has been measured for incident neutrons from 0.1 to 25.0 MeV. A ratio shape measurement was normalized by the threshold cross-section method. A fission cross-section ratio $.436 \pm .004$ was found averaged over neutron energies from 2.35 to 2.95 MeV.

¹ J. Trochon, H. Abou Yehia, J. Jary, and Y. Pranal, "Propriétés dynamiques de la fission de ^{233}Th ," to be presented at IAEA Symposium on Physics and Chemistry of Fission, Jülich, Germany, May 14-18, 1979.

* Abstract of ORNL/NUREG-39 (June 1978).

** Nucl. Sci. Eng. 68, 43 (1978).

† IAEA Fellow from the Comisión Nacional de Energia Atomica, Argentina.

- e. The Neutron Induced ^{238}U Subthreshold Fission Cross Section for Neutron Energies Between 5 eV and 3.5 MeV* (R. B. Perez, F. C. Difilippo, G. de Saussure, and R. W. Ingle)

A measurement of the ^{238}U neutron-induced fission cross section has been performed at the ORELA Linac facility in the neutron energy range between 5 eV and 3.5 MeV. The favorable signal-to-background ratio and high resolution of this experiment resulted in the identification of 85 subthreshold fission resonances or clusters of resonances in the neutron energy region between 5 eV and 200 keV. The fission data below 100 keV are characteristic of a weak coupling situation between Class I and Class II levels. The structure of the fission levels at the 720 eV and 1210 eV fission clusters is discussed. There is an apparent enhancement of the fission cross section at the opening of the 2^+ neutron inelastic channel in U-238 at 45 keV. An enhancement of the subthreshold fission cross section between 100 keV and 200 keV has been tentatively interpreted in terms of the presence of a Class II, partially damped vibrational level. There is a marked structure in the fission cross section above 200 keV up to and including the plateau between 2 and 3.5 MeV.

- f. Statistical Tests for the Detection of Intermediate Structure: Application to the Structure of the ^{238}U Neutron Capture Cross Section Between 5 keV and .1 MeV** (R. B. Perez, G. de Saussure, R. L. Macklin, and J. Halperin)

Recent measurements of the ^{238}U neutron capture cross section show a considerable amount of fluctuation between 5 and 100 keV.

Statistical tests performed on the measured cross section suggest that the fluctuations are not compatible with the statistical model of nuclear reactions and imply the existence of intermediate structure, which is interpreted in terms of doorway states. The validity of the statistical tests used here is confirmed by numerical experiments with simulated cross sections generated by the Monte Carlo method, in accordance with the statistical method.

The behavior of the capture cross section is compared to those of the subthreshold fission cross section and of the inelastic scattering cross section. The threshold anomaly at the opening of the inelastic channel at 45 keV is seen in the form of a rounded step.

- g. Fission-Product Yields for Thermal-Neutron Fission of ^{239}Pu † (J. K. Dickens and J. W. McConnell)

Absolute yields have been determined for 49 fission products representing 36 mass chains created during thermal-neutron fission of

* Abstract of ORNL/TM-6788 (March 1979).

** Submitted for publication in Physical Review.

† To be submitted for publication in Nuclear Science and Engineering.

^{239}Pu , including three mass chains for which no prior data exist. Using Ge(Li) spectroscopy spectra were obtained of gamma rays due to decay of fission products between 1550 sec and 31 days after a 100-sec irradiation. Data were obtained for all fission products simultaneously. Gamma rays were assigned to the responsible fission products by matching gamma-ray energies and half lives. The resulting fission-product yields are compared with previous measurements and with recommended yields given in two recent (and independent) evaluations. The present results are significantly larger for mass chains between 101 and 107, somewhat smaller for mass chains 87 and 151, and in reasonable agreement with the remaining mass chains. Uncertainties assigned to the present results range between 2.5 and 25%, and are smaller than or comparable to uncertainties assigned to other experimental or evaluated yields for 14 mass chains.

h. Fission-Product Energy Release for Times Following Thermal-Neutron Fission of ^{241}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 ^{241}Pu . Samples of mass 1 and 5 μg were irradiated for 1 to 50 sec using the fast pneumatic-tube facility at the Oak Ridge Research Reactor. The resulting beta- and gamma-ray emission spectra were recorded 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 spectra distributions of modest resolution. Total yield and energy integrals as a function of time after fission were obtained from integration over E_γ and E_β . The final differential spectral and integral data are given in tabular and graphical form.

The total integral energy-release data are compared with similar data previously obtained for ^{235}U and ^{239}Pu . Following a pulse of fissions the total decay-heat power for ^{241}Pu fission is greater by $\sim 5\%$ than that for ^{235}U for times after a fission pulse < 2500 sec, and greater by up to 40% than that for ^{239}Pu . For times after a fission pulse greater than 5000 sec the decay-heat power for ^{241}Pu asymptotically approaches that for ^{239}Pu , and is less than that for ^{235}U by $\sim 25\%$ at 14000 sec.

On an infinite irradiation basis, the decay-heat power for ^{241}Pu is equal to that for ^{235}U for times after shutdown less than 100 sec, less than that for ^{235}U for times after shutdown greater than 300 sec. The decay-heat power for ^{241}Pu is greater than that for ^{239}Pu for times after shutdown less than 50 sec, asymptotically approaching and becoming equal to the ^{239}Pu decay-heat power for longer times after fission.

* Abstract of NUREG/CR-0171, ORNL/NUREG-47 (August 1978).

i. Fission Yields for Thermal-Neutron Fission of ^{241}Pu *
(J. K. Dickens)

Cumulative fission yields for seventeen fission products (sixteen mass chains) created by thermal-neutron fission of ^{241}Pu were determined from analysis of gross fission-product gamma-ray spectra obtained using a large volume Ge(Li) detector. Uncertainties assigned to nine of the measured yields are smaller than existing evaluated uncertainties.

j. Interim Report on the ORNL Absolute Measurements of $\bar{\nu}$ for ^{252}Cf ** (R. R. Spencer, R. Gwin, R. Ingle, and H. Weaver)

An initial effort has been made to measure absolutely the average number of neutrons, $\bar{\nu}$, emitted in spontaneous fission of ^{252}Cf to an unprecedented accuracy of $\pm 0.25\%$. Fission neutrons were counted with a large, gadolinium poisoned, liquid scintillator. A "white source" of neutrons from the ORELA was used to calibrate the detector efficiency as a function of neutron energy. Source neutrons were scattered into the large scintillator by a thin NE-213 proton-recoil detector which employed pulse shape discrimination to eliminate unwanted γ -ray background. The resulting neutron energy- and scattering angle-dependent efficiencies were used to normalize a Monte Carlo calculation of the scintillator efficiency for fission neutrons. Under the assumptions that the effects of parasitic charged particle reactions and multiple neutron scattering in the proton-recoil counter have negligible influence on the energy calibration, the value of the average number of prompt neutrons emitted per ^{252}Cf fission was found to be 3.783 ± 0.010 . This report is intended as a documentary and guide for future measurements incorporating improvements suggested by the analysis of this first determination.

6. Experimental Techniques

a. Scintillation Detectors for Neutron Physics Research†
(J. A. Harvey and N. W. Hill)

The characteristics of scintillation detectors for neutron physics such as efficiency, timing, resolution, size, pulse height resolution, backgrounds, are reviewed. Solid and liquid organic scintillation detectors are now widely used for neutrons from 10 keV to 200 MeV. Detailed calculations and measurements of the pulse height distributions and efficiencies for several organic scintillation detectors are presented. ^6Li glass scintillation detectors are valuable as neutron flux monitors and as efficient neutron detectors below 10 keV. Problems associated with these ^6Li glass scintillation detectors are discussed. Examples of many scintillation detectors in use today are described.

* Submitted for publication in Nuclear Science and Engineering.

** Abstract of ORNL/TM-6805.

† Abstract of a Review Article for a Special Volume on Detectors in Nuclear Science, Nucl. Instr. Methods.

B. DATA ANALYSES

1. Theoretical Calculations

a. Contributions to Few-Channel Spectrum Unfolding* (F. G. Perey)

In this report are two papers dealing with the subject of spectrum unfolding. These papers are closely related and will appear in the proceedings of two different conferences. Although they deal with analysis of dosimetry data, the method presented in these two papers is very general and applicable to any few-channel unfolding problem.

b. A Consistent Nuclear Model for Compound and Precompound Reactions with Conservation of Angular Momentum** (C. Y. Fu)

An attempt is made to develop a multi-step Hauser-Feshbach model capable of calculating the compound and precompound cross sections consistently and conserving angular momentum in both compound and pre-compound reactions.

The model is coded into a computer program, TNG. Results calculated with pre-fixed parameters are compared with experimental data for 14-MeV (n,xn), (n,xp), and (n,x α) cross sections and spectra for 13 isotopes ranging from Al to Nb. Agreements between the calculations and experiments are reasonably good for 90% of the (n,xn) and (n,xp) spectra, but are good for only 50% of the (n,x α) spectra. Calculations with another set of optical-model parameters did not improve the agreement.

c. Comparison of One- and Two-Dimensional Cross-Section Sensitivity Calculations for a Fusion Reactor Shielding Experiment† (Y. Seki,‡ R. T. Santoro, E. M. Oblow, and J. L. Lucius)

Cross-section sensitivities calculated with one- and two-dimensional models of a fusion reactor shielding experiment are compared. The effectiveness of the 2-D calculation in accurately modeling the experiment and detector configurations is demonstrated. At the same time the validity of a 1-D sensitivity study is also demonstrated.

d. Cross Section Sensitivity Analysis of a Proposed Neutron Streaming Experiment with a Two-Dimensional Model†† (Y. Seki,‡ R. T. Santoro, E. M. Oblow, J. M. Barnes, and J. L. Lucius)

Cross section sensitivity analysis of a proposed streaming experiment for a typical penetration in a fusion reactor shield has been

* Abstract of ORNL/TM-6267 (February 1978).

** To be submitted for publication in Physical Review.

† Abstract of ORNL/TM-6667 (January 1979).

‡ Visiting scientist from Tokai Research Establishment, Japan.

†† Abstract of ORNL/TM-6588 (February 1979).

performed using a two-dimensional sensitivity method. The neutron streaming was shown to be determined mostly by the 4.5-cm-thick duct liner made of iron and the concrete structure immediately surrounding the liner. The neutrons scattered near the surface of the liner were found to be very important. A recommendation is made to move the proposed detector position to improve spatial resolution in the measurements without changing the sensitivity of the measurement to the nuclear characteristics of the duct materials.

2. ENDF/B Related Evaluations

a. Evaluations Performed for ENDF/B-V (C. Y. Fu, D. C. Larson, and L. W. Weston)

Evaluations of neutron-induced reactions and gamma-ray production were performed for carbon, fluorine, sodium, magnesium, silicon, calcium, iron, copper, lead, and $^{240-241}\text{Pu}$. Updates were based on recent experimental data combined with results of advanced model calculations. Uncertainty files were given for all materials except magnesium and copper. Evaluations of special purpose activation, dosimetry, and gas production cross sections are underway for the requested reactions and materials.

b. Status of ENDF/B-V Neutron Emission Spectra Induced by 14-MeV Neutrons* (D. M. Hetrick, D. C. Larson, and C. Y. Fu)

ENDF/B-V neutron emission spectra induced by 14.6-MeV incident neutrons are graphically compared with experimental data. The elements selected for the comparisons include Na, Mg, Al, Si, Ca, Ti, V, Cr, Fe, Ni, Cu, Nb, W, and Pb. Partial as well as total spectra from the ENDF/B-V evaluations are shown in each graph, while experimental data were available only for the total. Energy distribution laws utilized for the reaction types in each element are explained. Agreement between evaluated and experimental data is discussed, and recommendations for improvements are made. In general, evaluations which utilized advanced nuclear model codes, including precompound effects, agree well with measured spectra.

c. Expectations for ENDF/B-V Covariance Files: Coverage, Strength and Limitations** (F. G. Perey)

The concept of the estimated data covariance files of ENDF/B is explored in detail. The relationship between uncertainties and "possible mistakes" is discussed in order to avoid likely misunderstanding concerning the use of the data covariance files. Some perceived strengths and weaknesses of the ENDF/B-V data covariance files are mentioned.

* Abstract of ORNL/TM-6637 (to be published).

** Abstract of paper presented at Workshop on Theory and Application of Sensitivity and Uncertainty Analysis, Oak Ridge, August 22-24, 1978.

d. Covariance Matrices of Experimental Data* (F. G. Perey)

A complete statement of the uncertainties in data is given by its covariance matrix. It is shown how the covariance matrix of data can be generated using the information available to obtain their standard deviations. Determination of resonance energies by the time-of-flight method is used as an example. The procedure for combining data when the covariance matrix is non-diagonal is given. The method is illustrated by means of examples taken from the recent literature to obtain an estimate of the energy of the first resonance in carbon and for five resonances of ^{238}U .

e. Evaluation of Resonance Parameters for Iron** (C. M. Perey and F. G. Perey)

A new evaluation of the resonance parameters of the iron isotopes is necessary for ENDF/B-V, and is justified by new high resolution measurements made at ORELA. For the first time this version of ENDF gives an estimate of the errors of the resonance parameters.

Since the publication of ENDF/B-IV, Ribon and Le Coq¹ have made an evaluation of the iron resonance parameters which was based on data up to the end of 1973 to which they added many resonances obtained from plots of ORELA raw data. Since 1973 ORELA data were reduced and published. These new data gave information on many resonances previously unresolved for ^{54}Fe and ^{56}Fe .

f. Review of Cross Section Data Important to the Uranium Plutonium Fuel Cycle in Thermal Reactors† (L. W. Weston)

Since there are hundreds of cross sections involved in the design of a thermal reactor, this paper will be limited to the important fissile and fertile nuclide cross sections with emphasis on the problems and discrepancies in these cross sections. Before considering such problems it should be noted that the overall data base and the evaluations of this data base have improved markedly in recent years — even with a dramatic reduction in experimental measurements. The fact that discrepancies still exist should not overshadow the fact that experimenters and evaluators have made progress in providing an increasingly reliable differential cross section data base for reactors.

* Abstract of paper presented at Int. Conf. on Neutron Physics Data for Reactors and other Applied Purposes, Harwell, England, 25-29 Sept. 1978.

** Abstract of ORNL/TM-6405. (to be published).

¹ "Notes sur l'évaluation des paramètres de résonance et de la section efficace de capture du fer," unpublished (1975).

† Abstract of paper presented at Seminar on "Nuclear Data Problems for Thermal Reactor Applications," BNL, New York, 22-24 May 1978.

g. Review of Microscopic Neutron Cross Section Data for the Higher Plutonium Isotopes in the Resonance Region*
(L. W. Weston)

The microscopic neutron cross section data for plutonium-240, -241, and -242 in the resonance region are reviewed. In the context of importance to reactors the data on plutonium-240 are acceptable except for the resonance parameters of the 1-eV resonance. Plutonium-241 has discrepancies in the cross sections from thermal to 3 eV and to a lesser extent in the fission and capture cross section in the unresolved resonance region. The plutonium-242 cross sections appear to be known with sufficient accuracy as compared with the other plutonium isotopes.

3. Validation of ENDF/B Evaluations Through Integral Measurements

a. Sensitivity Coefficient Compilation for CSEWG Data Testing Benchmarks** (C. R. Weisbin, J. H. Marable, J. Hardy, Jr.,† and R. D. McKnight‡)

This report compiles and documents sensitivity coefficients generated by member laboratories of the Cross Section Evaluation Working Group (CSEWG) in the course of ENDF/B data testing. The work will be continuously updated as new benchmarks and new types of data are developed. The scope of this effort is sensitivities to many cross section data types for fast reactors, thermal reactors, shielding, etc. Detailed tabulations of the energy-integrated sensitivity coefficient (i.e., the change in response due to a uniform one percent change in cross section over the entire energy domain), sensitivities to changes in individual resonance parameters, and illustrative examples of energy dependent sensitivity profiles are given. The entire compilation of energy dependent coefficients is available in a computer-retrievable format along with programs for editing, mode changing, folding with projected changes to the reference data file, and performance parameter uncertainty estimation.

* Abstract of paper presented at the Specialist Meeting on the Nuclear Data of Higher Plutonium and Americium Isotopes for Reactor Applications, BNL, New York, 20-22 November 1978.

** Abstract of BNL-NCS-24853 (ENDF-265) (August 1978).

† Bettis Atomic Power Laboratory, Pittsburgh, Pennsylvania.

‡ Argonne National Laboratory, Argonne, Illinois.

C. NUCLEAR DATA PROJECT ACTIVITIES — 1978

(R. L. Auble,* S. J. Ball,** J. R. Beene,* F. E. Bertrand,*
S. H. Dockery,** Y. A. Ellis, W. B. Ewbank, R. L. Haese,
M. L. Halbert,* J. Halperin,* B. Harmatz, F. W. Hurley,**
M. J. Martin, M. R. McGinnis,** J. T. Miller,** S. Ramavataram,*
M. R. Schmorak, K. S. Toth,* and M. P. Webb*)

The Nuclear Data Project (NDP) is a comprehensive information analysis center which provides the basic research community with indexed references and collections of critically evaluated nuclear structure data. The systematic publication in *Nuclear Data Sheets* of new evaluations provides nuclear structure physics with an information service far in advance of what is available to most areas of science. The computer files of evaluated data developed by the NDP also present the basic research scientist with a valuable tool for looking at extensive nuclear level information in order to make comparison with new measurements or new theoretical calculations.

These computer files of nuclear data also are being used as a means of making the results of basic research quickly and easily available to a broader audience. Radioactivity information, in particular, has wide application in fields such as nuclear medicine, reactor engineering, environmental impact assessment, and nuclear waste management. Often the specialists in these areas have neither the time nor the training to make effective use of the data generated by basic nuclear research. The NDP has made important progress during the last few years toward providing a channel through which the results of new nuclear measurements can be transferred to any engineer or scientist who needs evaluated data to factor into his or her own work.

1. Data Evaluation

As part of the international network for nuclear structure data evaluation, the Nuclear Data Project has continuing responsibility for approximately 100 mass chains in three regions: $A=45-69$, $101-118$, and 195 -up. A total of 20 new mass chains was prepared and published during 1978, and six more from temporary or former NDP evaluators are nearly complete as of the beginning of 1979. Figure 1 gives the publication status of the mass chains for which NDP is responsible. For comparison, the status of all published mass chains is shown in Fig. 2.

In addition to its evaluation responsibility, NDP is committed to maintaining uniform, high standards for ENSDF (and consequently for *Nuclear Data Sheets*) by providing training for new evaluators, followed by a thorough review of the first few mass chains prepared by each new evaluator. The NDP staff members have organized training seminars for 28 new data evaluators in order to introduce them to NDP evaluation techniques, analysis programs, and conventions used in ENSDF and *Nuclear Data Sheets*.

* Part-time assignment to Nuclear Data Project.

** Technical support staff.

During 1977-1978, NDP staff have reviewed 14 mass chains prepared by new evaluators from six other data evaluation centers. About half of these have already been published in *Nuclear Data Sheets* or accepted for publication. Others are undergoing final revisions before acceptance.

2. Evaluated Nuclear Structure Data File

The Evaluated Nuclear Structure Data File (ENSDF), developed and implemented by the NDP, contains a documented summary of the current status of nuclear measurements. The ENSDF now contains 6600 distinct sets of evaluated nuclear information. This includes:

- 1950 sets of adopted level properties
- 1850 decay schemes
- 3020 nuclear reaction data collections, including
 - 230 (n, γ) reactions
 - 225 (d,p) reactions
 - 500 (charged-particle,xn γ) reactions.

All decay scheme information in ENSDF is now at least as complete as the most recent *Nuclear Data Sheets* warrant. Normalization information is included wherever available, and details of electron capture and internal conversion have been added systematically, so that complete tables of atomic and nuclear radiations can be assembled for more than 1200 decay schemes. This information is being assembled for distribution in microfiche form.

The ENSDF computer format has been adopted as an international standard for the systematic storage and exchange of nuclear structure data. At six-month intervals, beginning in 1977, NDP has prepared complete copies of ENSDF on magnetic tape for distribution through an international network of data centers.

3. Nuclear Structure References

Nuclear Data Project's Nuclear Structure References (NSR) file contains $\approx 65,000$ entries. Approximately 5000 indexed new research works are added each year. About half of the additions are journal publications; the other half consists of reports, conference abstracts, preprints, etc. The keyword indexing system used in the NSR file since 1964 has been shown¹ to allow more complete retrievals from the nuclear structure literature than the much larger INIS system (extended from the former *Nuclear Science Abstracts*).

The NSR file is used routinely to direct interested users to the nuclear structure literature. Special reference collections are assembled in partial response to most of the 100 information requests processed each year. A shorter version of the NSR file (1969 to present) is available for interactive search through the remote terminals of the DOE/RECON network. This file is queried an average of two times every working day.

¹ H. Behrens and J. W. Tepel, *Comparison of the International Nuclear Information System (INIS) and Recent References (RR) (Mass Chains A=27 and A=86)*, ZAED-M-13, Zentralstelle für Atomkernenergie-Kodokumentation, Karlsruhe, West Germany (October 1977).

Each month an SDI (selective dissemination of information) service is provided from new entries to the NSR file. The service is used by data evaluators from the international network and by other extensive users of new nuclear structure data.

An index to the new literature is published three times per year as "Recent References" includes both isotope and reaction indexes for both journal and non-journal literature. A second indexed cumulation of journal literature was published in 1978.¹

The NSR file is used as an international standard for the systematic computer storage and exchange of indexed reference information. Two copies of the complete indexed file have been distributed to the international network of data evaluation centers. The regular distribution of computer-readable copies of the new literature summarized in "Recent References" will begin in 1979.

4. Publications

The Nuclear Data Project is the editorial and publications office for the journal *Nuclear Data Sheets*. The NDP prepares camera-ready copy which is sent to Academic Press for publication and distribution. Implementation of the ENSDF system, with computer programs to select information from the data file, organize it into tables or drawings, and assemble the tables or drawings onto pages, has revolutionized the preparation of copy for *Nuclear Data Sheets*. The principal advantage of the computer system is the elimination of much redundant data copying and most proofreading. Although the same data item may appear in several places in the data sheets and drawings, it is usually contained only once in ENSDF, and must therefore be correctly entered only one time. Tables or drawings are also prepared in a precisely reproducible way. The computer programs have helped to establish and maintain greater uniformity among manuscripts from different evaluators, so that the user needs to adjust to fewer style variations.

Manuscripts are now being received from several data evaluation centers other than NDP. Twenty percent of the new evaluations published during 1978 were prepared by non-NDP evaluators. The distribution of mass-chain responsibility requires that this fraction increase to more than fifty percent. Maintaining tolerant limits on the style variations used by many different evaluators has added to the editorial work for *Nuclear Data Sheets*. The ENSDF system has avoided a much more substantial problem in the production of manuscripts.

¹ W. B. Ewbank, R. L. Haese, F. W. Hurley, and M. R. McGinnis, *Nucl. Data Sheets* 24, 445 (1978).

Fig. 1. Status of mass-chain evaluations in NDP's regions of responsibility.

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