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REPORT TO THE U. S. NUCLEAR DATA COMMITTEE

F. G. Perey

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Neutron Physics Division

REPORT TO THE U. S. NUCLEAR DATA COMMITTEE

F. G. Perey

JUNE 1974

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
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ABSTRACT

This is a collection of recent, not generally publicized, cross-section work done at ORNL and recent papers which have been submitted for publication. This report is prepared for the USNDC and only includes material which the author thinks might be of interest to the USNDC Subcommittee members. The memo covers the period of time since the last USNDC meeting.

OAK RIDGE NATIONAL LABORATORY

A. NEUTRON DATA APPLICATIONS SUBCOMMITTEE

A.1. Gamma-Ray Production Measurements

1. $^{28}Si(n,n'\gamma)$ Photon Production Cross Sections for E_γ = 1.78 MeV, $5.0 \leq E_n \leq 9.5$ MeV* (J. K. Dickens and G. L. Morgan)

The excitation function for the production of the 1.78-MeV gamma ray due to neutron interactions with ^{28}Si has been measured for incident neutron energies between 5 and 9.5 MeV with neutron energy resolution ~35 keV for E_n = 5 MeV to ~80 keV for E_n = 9.5 MeV. These data are compared with previously reported values and with the current ENDF/B evaluation.

*To be published in Physical Review C.

2. Gamma-Ray Production Due to Neutron Interactions with Tin for Incident Neutron Energies Between 0.75 and 20 MeV: Tabulated Differential Cross Sections* (J. K. Dickens, T. A. Love and G. L. Morgan)

Numerical values of differential cross sections for gamma rays produced by neutron reactions with tin have been obtained for neutron energies between 0.75 and 20 MeV for θ_γ = 125 deg. The $d^2\sigma/d\omega dE$ values were obtained using a NaI spectrometer. These data consist of neutron and gamma-ray production group cross-section values of $d^2\sigma/d\omega dE$ for $0.7 \leq E_\gamma \leq 10.5$ MeV, with gamma-ray intervals ranging from 20 keV for $E_\gamma \leq 1$ MeV to 160 keV for E_γ ~ 9 MeV. Neutron energy intervals varied from 0.25 MeV for E_n = 0.75 to 2 MeV to 3 MeV for E_n = 14 to 20 MeV.

*Abstract of ORNL-TM-4406

3. Gamma-Ray Production Due to Neutron Interactions with Zinc for Incident Neutron Energies Between 0.85 and 20 MeV: Tabulated Differential Cross Sections*,** (J. K. Dickens, T. A. Love and G. L. Morgan)

Numerical values of differential cross sections for gamma rays produced by neutron reactions with zinc have been obtained for neutron

ORNL-DWG 74-588

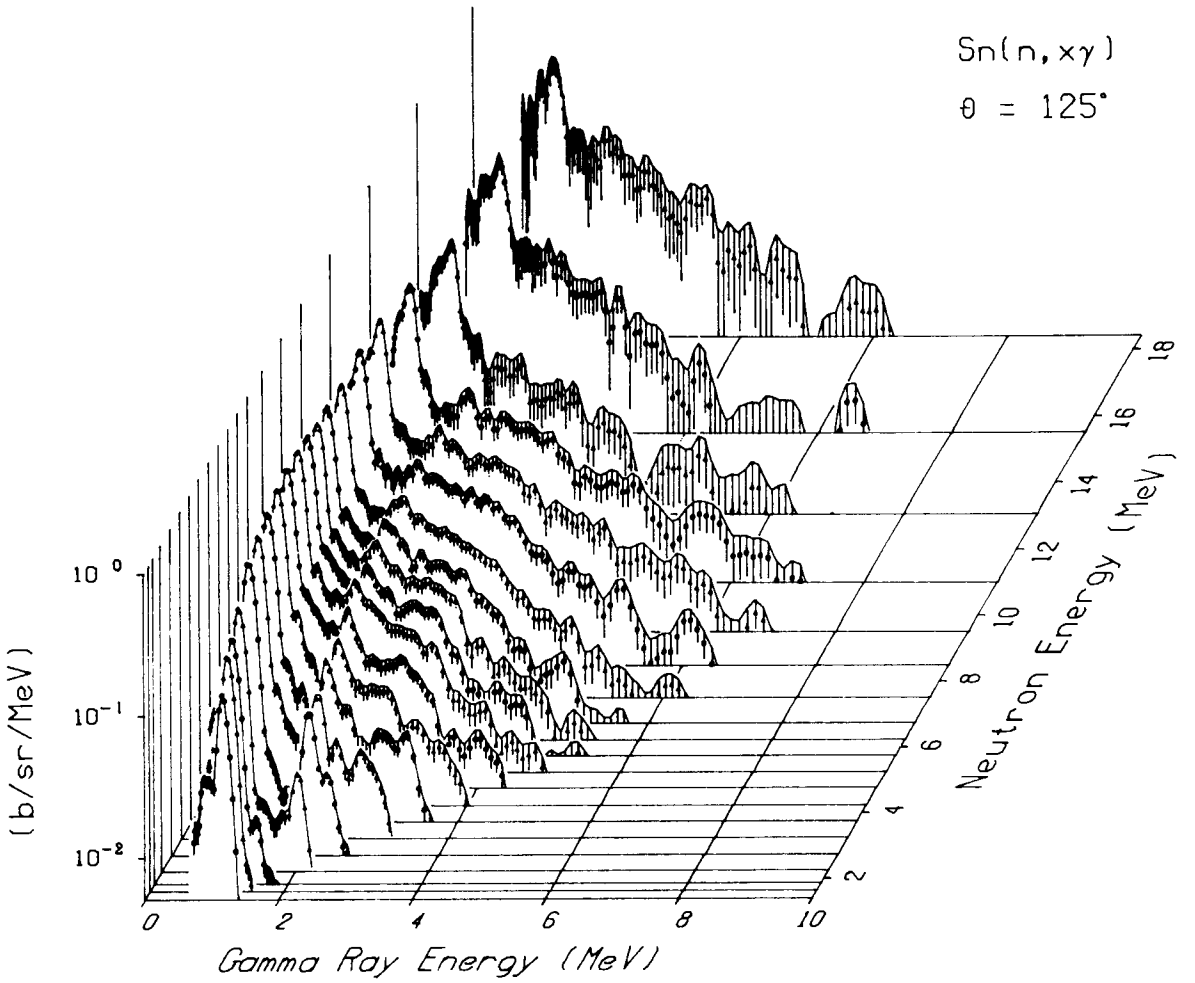

Figure 1

ORNL-DWG 74-585

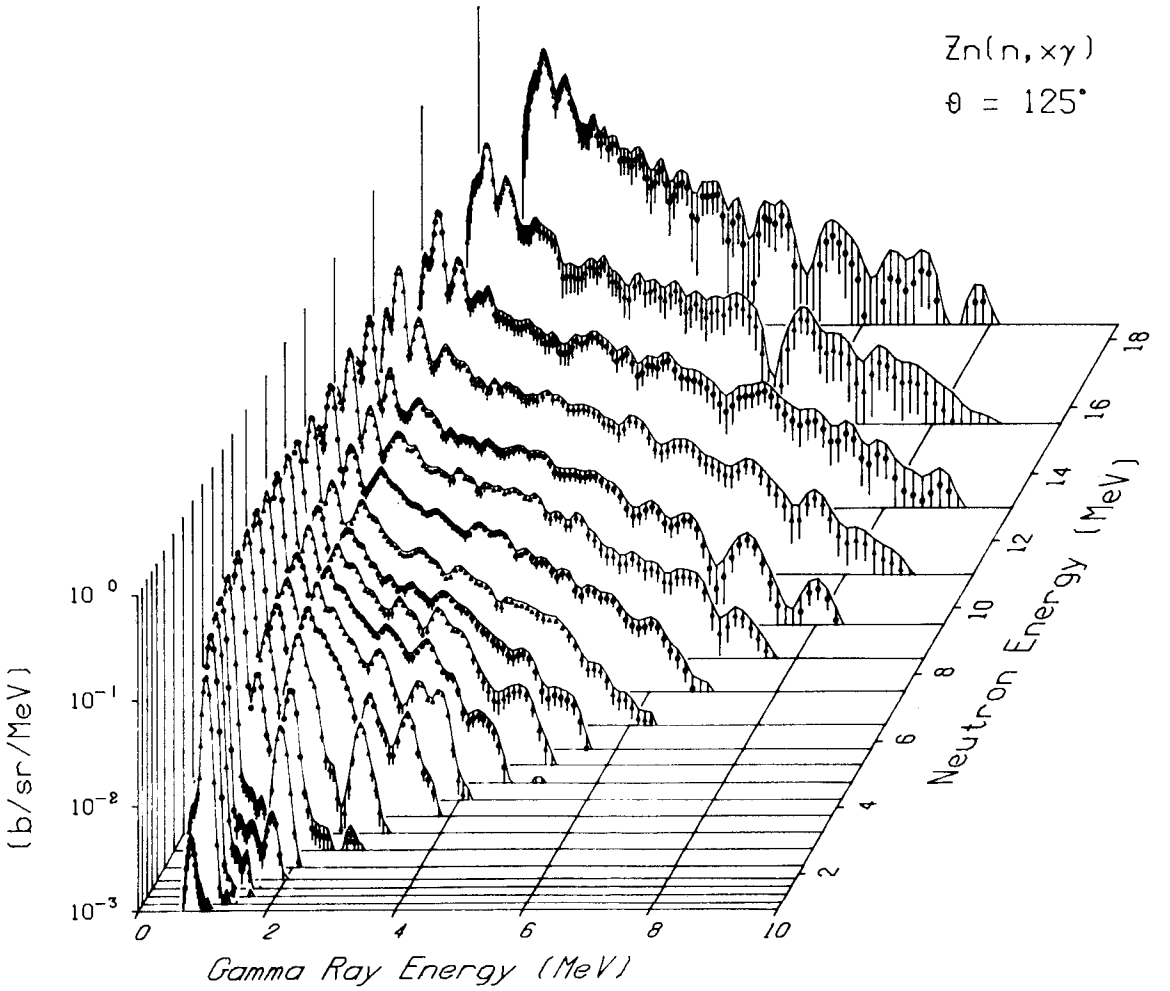

Figure 2

energies between 0.85 and 20 MeV for θ_γ = 125 deg. The $d^2\sigma/d\omega dE$ values were obtained using a NaI spectrometer. These data are presented as gamma-ray production group cross-section values of $d^2\sigma/d\omega dE$ for $0.7 \leq E_\gamma \leq 10.5$ MeV, with gamma-ray intervals ranging from 20 keV for $E_\gamma \leq 1$ MeV to 160 keV for $E_\gamma \sim 9$ MeV. Neutron energy intervals varied from 0.15 MeV for E_n = 0.85 to 1 MeV to 3 MeV for E_n = 14 to 20 MeV.

---

*Abstract of ORNL-TM-4464.

**Relevant to request No. 216.

4. Gamma-Ray Production Due to Neutron Interactions with Fluorine and Lithium for Incident Neutron Energies Between 0.55 and 20 MeV: Tabulated Differential Cross Sections*,** (J. K. Dickens, T. A. Love and G. L. Morgan)

Numerical values of differential cross sections for gamma rays produced by neutron reactions with lithium fluoride have been obtained for neutron energies between 0.55 and 20 MeV for θ_γ = 125 deg. The cross-section values were obtained using a NaI photon spectrometer and the Oak Ridge Electron Linear Accelerator as the neutron source. The data for neutron interactions with fluorine are presented as gamma-ray production group corss-section values of $d^2\sigma/d\omega dE$ for $0.7 \leq E_\gamma \leq 10.5$ MeV, with gamma-ray intervals ranging from 20 keV for $E_\gamma \leq 1$ MeV to 160 keV for $E_\gamma \sim 9$ MeV; for these data neutron energy intervals varied from 0.25 MeV for $1.25 \leq E_\gamma \leq 2$ MeV to 3 MeV for $14 \leq E_n \leq 20$ MeV. The data for neutron interactions with lithium are presented as gamma-ray production cross-section values of $d\sigma/d\omega$ for the 0.478-MeV gamma ray; for the data the neutron energy intervals varied between 10 keV at threshold and 1 MeV for $E_n \geq 14$ MeV.

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*Abstract of ORNL-TM-4538.

**Relevant to request No. 11.

5. Gamma-Ray Production Due to Neutron Interactions with Magnesium for Incident Neutron Energies Between 0.8 and 20 MeV: Tabulated Differential Cross Sections* (J. K. Dickens, T. A. Love and G. L. Morgan)

Numerical values of differential cross sections for gamma rays produced by neutron reactions with magnesium have been obtained for neutron energies between 0.76 and 20 MeV. The cross-section values were obtained using a NaI spectrometer. These data consist of (a) the production of gamma rays by neutron reactions with values of $d^2\sigma/d\omega dE$ for θ_γ = 125 and 90 deg and for $0.7 \leq E_\gamma \leq 10.5$ MeV, with gamma-ray intervals ranging from 20 keV for $E_\gamma \leq 1$ MeV to 160 keV for $E_\gamma \approx 9$ MeV and with neutron energy intervals varying from ~0.25 MeV for E_n = 0.76 to 1.5 MeV to 3 MeV for E_n = 14 to 20 MeV; and (b) values of $d\sigma/d\omega$ for E_n = 1.37 MeV for θ_γ = 125 deg and for

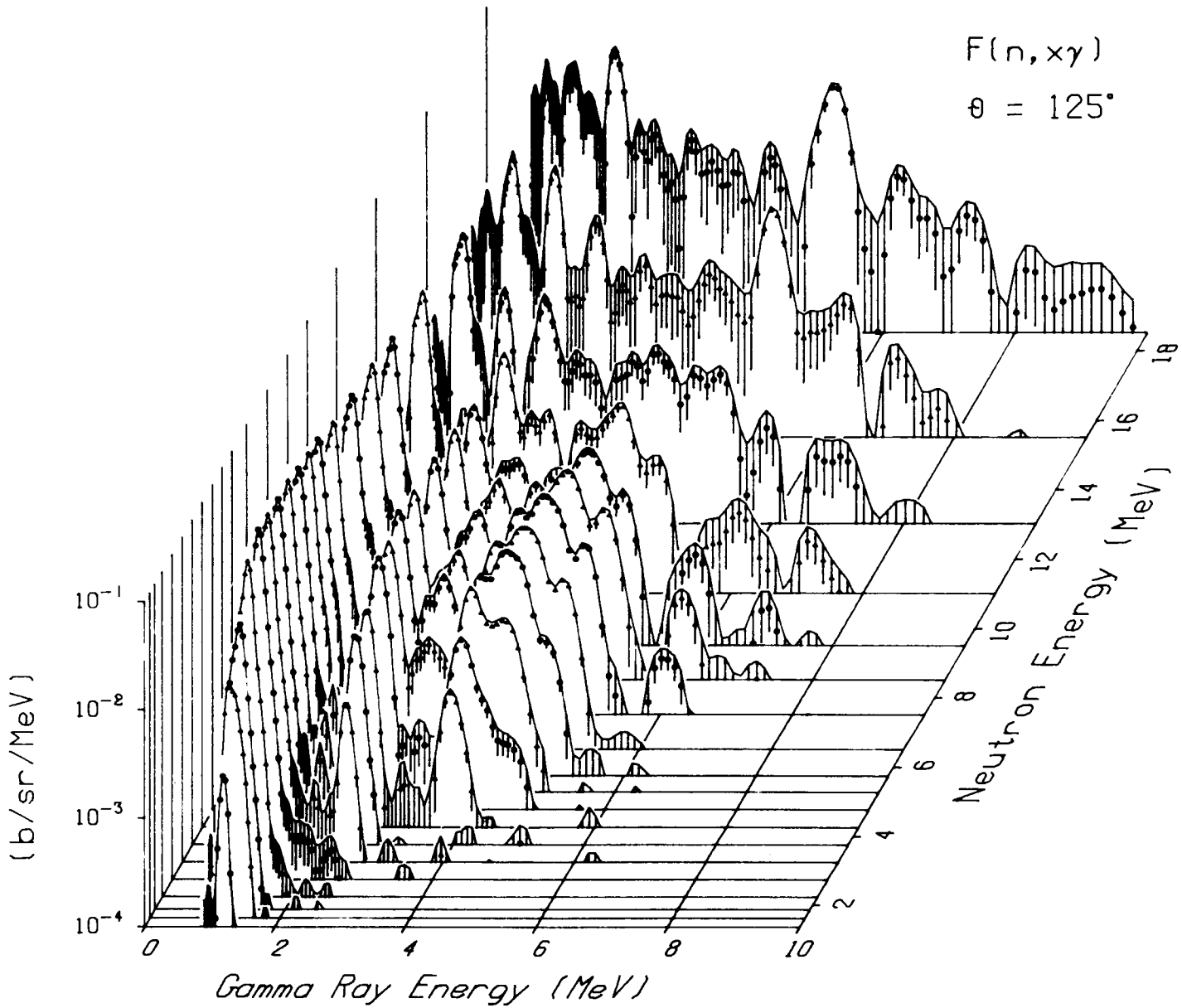
F(n,xγ)
θ = 125°
(b/sr/MeV)
10⁻¹
10⁻²
10⁻³
10⁻⁴
0
2
4
6
8
10
Gamma Ray Energy (MeV)
2
4
6
8
10
12
14
16
18
Neutron Energy (MeV)

Figure 3

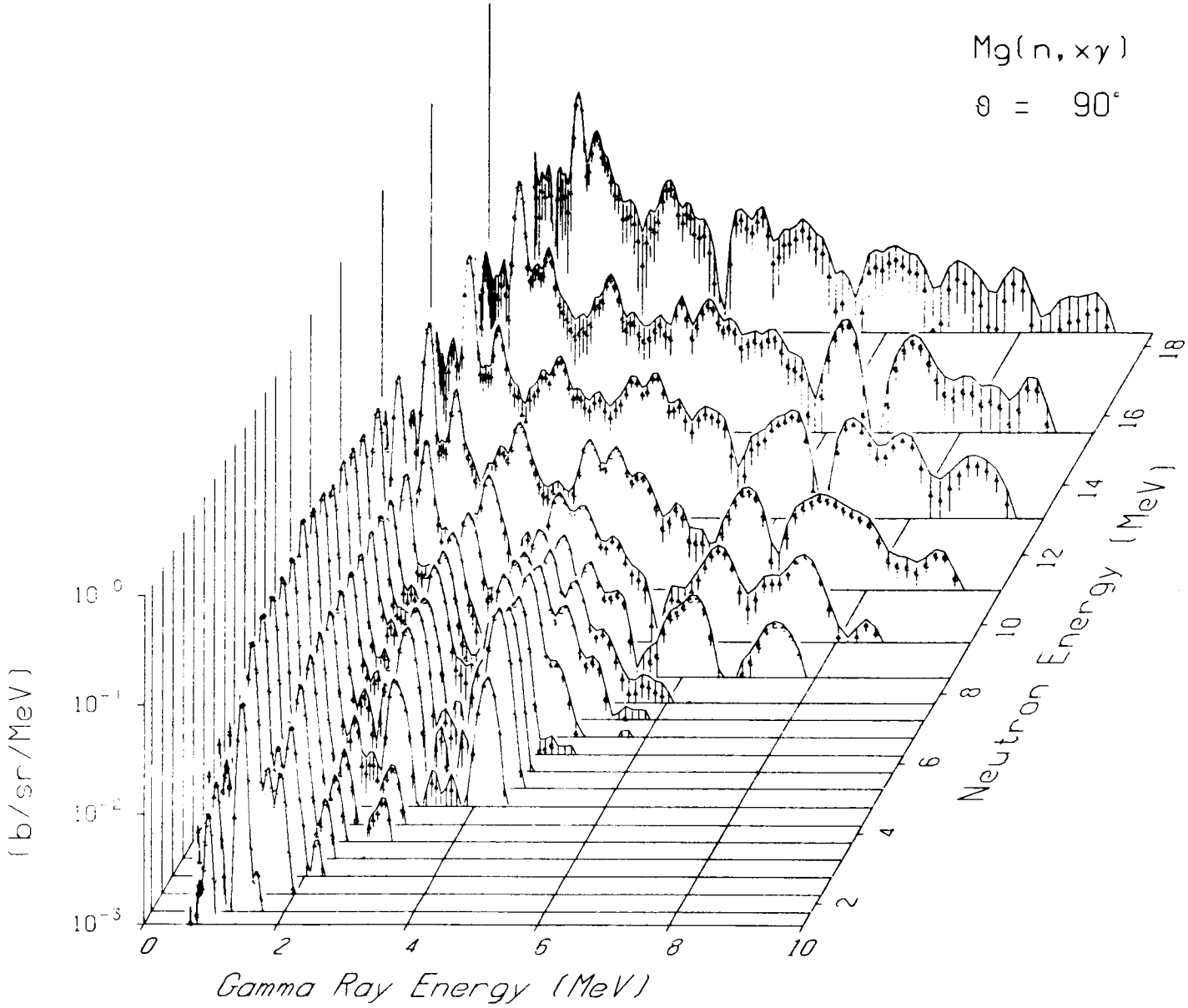
Mg(n,xγ)
θ = 90°
(b/sr/MeV)
10⁰
10⁻¹
10⁻²
10⁻³
0
2
4
6
8
10
Gamma Ray Energy (MeV)
2
4
6
8
10
12
14
16
18
Neutron Energy (MeV)

Figure 4

E_n between threshold and 6.0 MeV and for E_γ = 1.81 MeV for θ_γ = 125 deg and for E_n between threshold and 3.2 MeV.

*Abstract of ORNL-TM-4544.

6. Gamma-Ray Production Due to Neutron Interactions with Zinc. Tabulated Differential Cross Sections for 31 Gamma Rays for Incident Neutron Energies Between 0.9 and 6 MeV*,** (G. G. Slaughter and J. K. Dickens)

Numerical values of differential cross section for gamma rays produced by neutron interactions with zinc have been measured for neutron energies between 0.9 and 6 MeV for σ_γ = 120 deg. The $d\sigma/d\omega$ data were obtained using a 35 cm^3 Ge(Li) detector. The data consist of cross section values for 31 gamma rays having E_γ between 300 and 2780 keV. Neutron energy intervals varied between a minimum of ~50 keV at E_n ~ 900 keV and a maximum of ~1.5 MeV for E_n ~ 5.8 MeV.

*Abstract of ORNL-TM-4523

**Relevant to request No. 216.

7. Direct-Interaction Interpretation for $^{40}Ca(n,np\gamma)^{39}K$ Reactions at E_n = 17 - 20 MeV* (J. K. Dickens)

Gamma-ray production cross sections measured for the $^{40}Ca(n,np)^{39}K$ reactions are interpreted using a model based upon the 2-particle-2-hole configuration mixing in the ground-state wave function of ^{40}Ca and a direct knock-out reaction mechanism.

*Submitted to Physical Review C for publication.

A.2. Neutron Scattering

1. ^{206}Pb, ^{207}Pb and ^{208}Pb Neutron Elastic- and Inelastic-Scattering Cross Sections from 5.50 to 8.50 MeV*

(W. E. Kinney and F. G. Perey)

Measured neutron ^{208}Pb differential elastic scattering cross sections at 5.50, 7.00, and 8.50 MeV are given and compared with previous results. Measured ^{206}Pb, ^{207}Pb, and ^{208}Pb neutron inelastic-scattering cross sections are given at roughly 0.5 MeV intervals from 5.50 to 8.50 MeV and also compared with previous results. ENDF/B III Mat 1136 elastic angular distributions, angle integrated elastic-and inelastic-scattering cross sections, and nuclear temperatures are in generally good agreement with experiment over this energy range.

*Abstract of ORNL-4909.

A.3. Neutron Total Cross Sections

1. The Total Neutron Cross Sections of the Isotopes of Zr

(W. M. Good, J. A. Harvey and N. W. Hill)

Measurements have been completed on the total cross sections of the isotopes of Zr. The results for ^{90}Zr, obtained for a metallic sample, were presented earlier. Fig. 5 is a representation of the results for $^{92,94,96}Zr$ in which the earlier results for ^{90}Zr are given for comparison. The measurements were performed using both the ^{6}Li glass and the NE-110 plastic detectors at 80 meters, but only the results with the ^{6}Li glass detector are shown here. The ^{96}Zr was only 58-42 percent enriched; Table I below summarizes the isotopic computation of the $^{92,94,96}Zr$ targets.

Table I

	Composition				
Target	90	91	92	94	96
92	1.65	0.98	96.68	0.70	<0.10
94	1.95	0.576	0.878	96.35	0.258
96	22.70	4.33	6.42	8.20	58.42

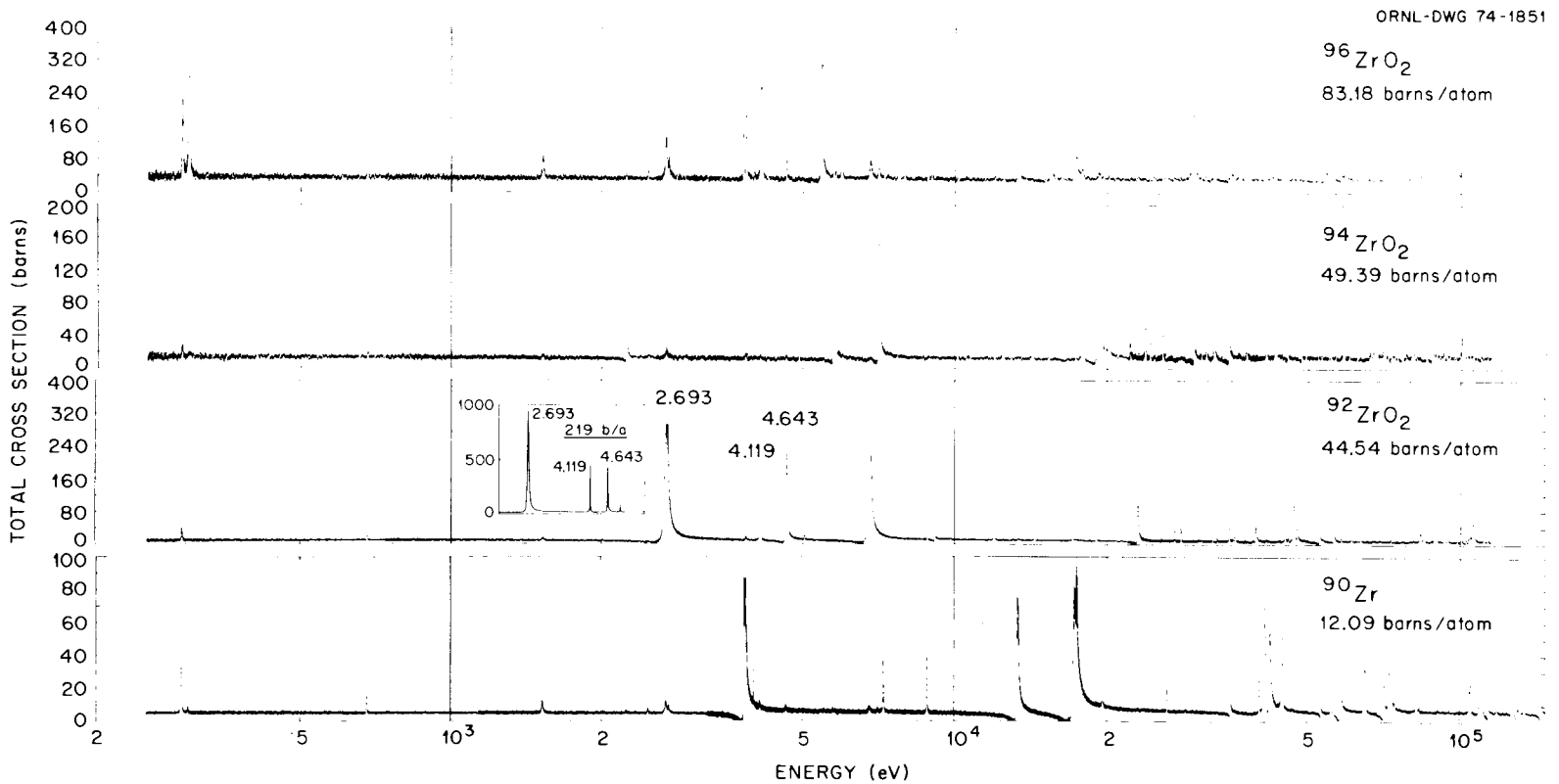
ORNL-DWG 74-1851
$^{96}ZrO_2$
83.18 barns/atom
$^{94}ZrO_2$
49.39 barns/atom
$^{92}ZrO_2$
44.54 barns/atom
^{90}Zr
12.09 barns/atom
2.693
4.643
4.119
1000
500
0
2.693
219 b/a
4.119
4.643
TOTAL CROSS SECTION (barns)
ENERGY (eV)
400
320
240
160
80
0
200
160
120
80
40
0
400
320
240
160
80
0
100
80
60
40
20
0
2
5
10^3
2
5
10^4
2
5
10^5

Figure 5

2. The Neutron Total Cross Section of ^{243}Am*,** (O. D. Simpson,† F. B. Simpson,† J. A. Harvey, G. G. Slaughter, R. W. Benjamin,†† and C. E. Ahlfeld††)

Neutron transmission measurements have been made on two high-purity samples of ^{243}Am, having inverse thicknesses of 1288.2 and 279.3 b/a, respectively. Data were collected from 0.5-1000 eV using the Oak Ridge Electron Linear Accelerator. High resolution data were taken using 10-nsec and 30-nsec bursts of 140-MeV electrons, 10-nsec channel widths, and a flight path of 18.576 meters. An average value of Γ_γ of 39 $\pm$ 1 MeV was determined from shape analysis of 24 resonances below 18 eV. Single level Breit-Wigner resonance parameters were obtained from area analysis up to 250 eV. The average level spacing between resonances was found to be 0.68 $\pm$ 0.06 eV. An s-wave neutron strength function of (0.96 $\pm$ 0.10) x 10^{-4} was determined from the resonance parameters. The resonance-absorption integral for neutrons with energies above 0.625 eV was determined to be 1810 $\pm$ 70 b from the resonance.

---

*Submitted to Nucl. Sci. Eng.

**Relevant to request No. 548.

†Present address: Aerojet Nuclear Company, Idaho Falls, ID.

††Present address: Savannah River Laboratory, E. I. du Pont de Nemours & Co., Aiken, SC.

3. Neutron Total Cross Section of ^{248}Cm* (R. W. Benjamin,† C. E. Ahlfeld,† J. A. Harvey and N. W. Hill)

The neutron total cross section for ^{248}Cm has been measured from 0.5 to 3000 eV using the Oak Ridge LINAC, ORELA, as a pulsed neutron source. The small diameter (1.6 to 4.0 mm) cylindrical samples contained up to 13 mg of 97% ^{248}Cm and 3% ^{246}Cm in the oxide form. Samples were cooled with liquid nitrogen to reduce Doppler broadening. The thickest sample had an inverse thickness for curium isotopes of 625 barns/atom which made possible the identification of forty-seven resonances attributable to ^{248}Cm and five resonances attributable to ^{246}Cm. The cross-section data have been analyzed to obtain single-level, Breit-Wigner resonance parameters for all observed resonances. An average level spacing 40 $\pm$ 5 eV and an

average s-wave neutron strength function of $(1.2 \pm 0.2) \times 10^{-4}$ were determined for ^{248}cm. The resonance contributions to the thermal capture cross sections and the resonance integrals determined from the resonance parameters are: ^{248}Cm - $\sigma_{n\gamma}^{2000} = 2.51 \pm 0.26$ b, $I_{n\gamma} = 259 \pm 12$ b; ^{246}Cm - $\sigma_{n\gamma}^{2000} = 1.2 \pm 0.4$ b, $I_{n\gamma} = 101 \pm 11$ b. These values compare well with the results of integral measurements.

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*Submitted to Nucl. Sci. Eng.

**Relevant to request No. 568.

†Present address: Savannah River Laboratory, E. I. du Pont de Nemours and Co., Aiken, SC.

4. Neutron Total Cross Section of ^{6}Li from 100 eV to 1 MeV (J. A. Harvey and N. W. Hill)

Transmission measurements were made upon two samples of ^{6}Li (98.75%) with inverse thicknesses of 11.84 and 2.585 barns/atom. Data were obtained with a Li glass scintillator and an NE-110 proton recoil detector 78.203 meters from the neutron target at ORELA. The neutron energy resolution $\Delta E/E$ was $\sim$0.1% or 0.2 keV at 247 keV. Since no fine structure was observed, the data with the thin sample using the NE-110 detector shown in Figure 6 have been averaged to give $\sim$2-keV resolution. The statistical accuracy on these averaged points is $\sim$0.05 barns. The backgrounds (room and 2.23-MeV gamma rays from neutron capture in the water of the moderator) were < 1% in this energy region. Other systematic errors arising from uncertainties in the neutron monitor are estimated to produce << 0.1 barn uncertainty. The observed peak cross section is 11.0 ± 0.1 barns in good agreement with values reported in references 1 and 2. The data obtained with the thin sample and the ^{6}Li glass detector are in excellent agreement (within 0.1 barns and 0.5 keV) with the data shown in Figure 1. The energy scale is accurate to $\lesssim$ 0.1%. The resonance energy obtained by the method of diameters is 246 ± 1 keV, in good agreement with the time of flight measurements of Uttley[1] (247 keV). Energy values from Van de Graaff measurements on this nuclide are $\sim$5 keV too high. In the energy region from 300 to 10000 eV the data from the thin sample are in excellent agreement (within $\sim$0.05 barns or $\sim$1%) with the formula proposed by Uttley[1] namely $\sigma_T = 0.70 + 149.5/\sqrt{E}$.

---

[1] C. A. Uttley, M. G. Sowerby, B. H. Patrick, and E. R. Rae, Proceedings of Conference on Neutron Standards and Flux Normalization, AEC Symposium Series 23, (1971), p. 80.

[2] J. W. Meadows and J. F. Whalen, Nucl. Sci. Eng. 48, 221 (1972).

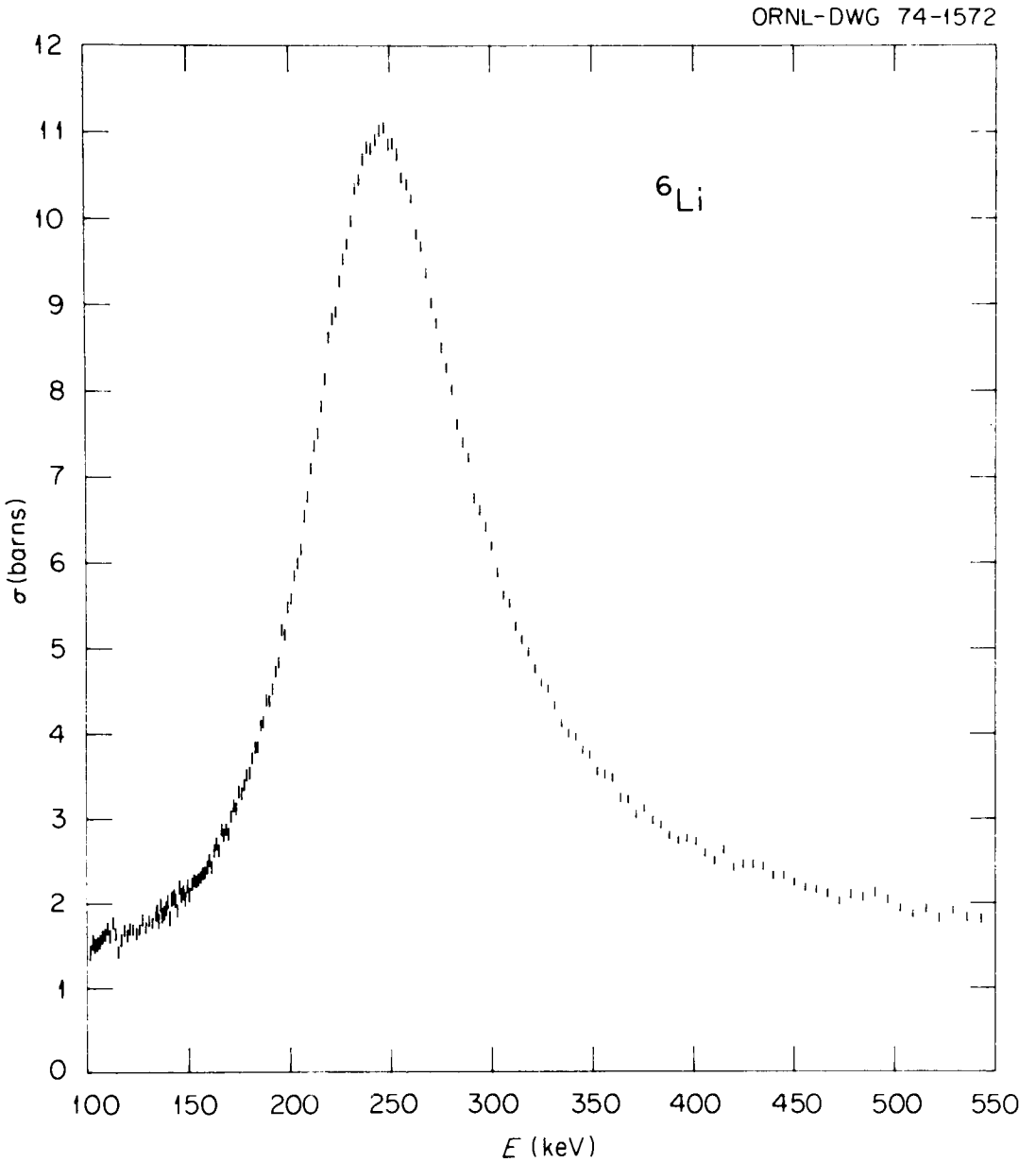
ORNL-DWG 74-1572
^{6}Li
σ (barns)
E (keV)
0
1
2
3
4
5
6
7
8
9
10
11
12
100
150
200
250
300
350
400
450
500
550

Figure 6

A.4. Neutron Capture

1. Comments on the Doorway State in ^{206}Pb* (B. J. Allen,† R. L. Macklin, C. Y. Fu and R. R. Winters††)

The neutron capture cross section of $^{206}Pb(n,\gamma)$ has been measured with high resolution at the Oak Ridge Electron Linear Accelerator. The capture results show that the reported $s_{1/2}$ doorway in ^{206}Pb is not observed in the photon channel.

---

*Phys. Rev. C, 7, No. 6 (1973) p. 2598.

†Present address: Australian Atomic Energy Commission, Lucas Heights, Australia.

††Present address: Denison University, Granville, Ohio.

2. Neutron Capture Gamma-Ray Yields in Iron* (J. E. White and C. Y. Fu)

Gamma-ray yields as a function of neutron energy from thermal to 1 MeV for iron have been generated with a combined experimental and theoretical approach. The theoretical part is to a large extent statistical; however, parameters are introduced to compensate for the nonstatistical behavior. Experimental information used to evaluate these parameters are the branching ratios among discrete levels and the gamma-ray primary transitions from thermal and available resonance capture. A discussion of the implications of additional resonance capture yield data, which was made available after the completion of the calculation, is included. The results have been compared with integral experiments, and the agreement is favorable. Considerable variations in the capture gamma-ray yields as a function of incident neutron energy are noticed.

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*Nucl. Sci. Eng. 51, 496-508 (1973).

3. Gold Neutron Capture Cross Section from 3 to 550 keV* (R. L. Macklin, J. Halperin and R. R. Winters†)

A careful remeasurement of this standard cross section at ORELA using the pulse height weighting technique in small scintillators has been completed. The 4.9 eV resonance was used for calibration and the $^{6}Li(n,\alpha)$ cross section for flux shape. Estimated errors range from 1.4% near 30 keV to 3.3% at 550 keV. Individual resonance parameters

were deduced in the 2.6-4.9 keV range and the fluctuations over tens of resonances were analyzed below 90 keV. The fluctuations are larger than expected, limiting the precision attainable with monoenergetic sources using this standard. The fluctuation intensity appears to indicate intermediate resonance structure in the compound nucleus with 10 keV width and 50 keV spacing.

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*Submitted to Physical Review C.

†Present address: Denison University, Granville, Ohio.

4. A Study of $^{205}T\ell(n,\gamma)^{206}T\ell$ Resonance Parameters* (E. D. Earle,† R. R. Winters,†† and R. L. Macklin)

We have repeated with improved resolution and statistics a $^{205}T\ell(n,\gamma)^{206}T\ell$ cross-section measurement[1] for $E_n < 400$ keV using the total energy gamma-ray detector at the ORELA 40 m station.[2] The energy resolution was 0.2% and, since the level spacing is about 1 keV, most resonances below 250 keV were resolved. The relative magnitude of the 5.5 MeV gamma-ray anomaly[1] for each resonance is determined and where possible values of the resonance parameters Γ_n and $g\Gamma_\gamma$ are deduced from the measured widths and capture areas.

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*Presented at the APS Meeting, Washington, D. C., April 23-26, 1974; published in the Bulletin of American Physical Society 19, 574 (April 1974).

†Present address: Chalk River Nuclear Laboratories, AECL, Chalk River, Ont., Canada.

††Present address: Denison University, Granville, Ohio.

[1]E. D. Earle, M. A. Lone, G. A. Bartholomew, B. J. Allen, G. G. Slaughter and J. A. Harvey, "Statistical Properties of Nuclei" (J. B. Garg, Ed.) Plenum Press, New York (1972) p. 263.

[2]R. L. Macklin and B. J. Allen, Nucl. Instr. Meth. 91 (1971) 565.

5. The $^{57}Fe(n,\gamma)^{58}Fe$ Reaction and Shell Model Calculations of ^{58}Fe Levels* (G. G. Slaughter, S. Raman, W. M. Good, J. A. Harvey, J. B. McGrory and D. Larson)

We have studied 14 neutron resonances below 30 keV in the $^{57}Fe+n$ system via both transmission and capture gamma-ray studies. A level scheme for ^{58}Fe was constructed with 23 excited states below 5.3 MeV. We have collected together all available information on ^{58}Fe levels

in order to make a rigorous comparison with the results of a shell model calculation. The calculated energy levels correlate very well with observed ones. The agreement is less satisfactory in the case of gamma-ray branchings, partly due to the uncertainty concerning the effective M1 operator.

---

*Presented at the APS Meeting, Washington, D. C., April 22-25, 1974; published in the Bulletin of American Physical Society 19, 430 (April 1974).

6. The ^{143}Nd(n,γ) Reaction*,** (D. A. McClure,† S. Raman, G. G. Slaughter, J. A. Harvey, J. C. Wells, Jr.,†† Jung Lin,††† and E. T. Jurney,†††)

Continuing our investigations of levels in ^{144}Nd (Ref. 1), we have carried out Ge(Li)-Ge(Li) coincidence measurements with a natural Nd target bombarded with thermal neutrons. The two-parameter (4096 x 4096 channel) measurements involved ≈ 16 x 10^6 coincidence events collected in 120 h. The level scheme now contains ≈ 60 levels (a third of these confirmed by coincidence measurements) below 3.5 MeV and incorporates ≈ 225 gamma rays (half of the total observed). The coincidence measurements were invaluable in avoiding (and in some cases confirming) multiple placements of gamma rays.

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*Presented at the APS Meeting, Washington, D. C., April 22-25, 1974; published in the Bulletin of American Physical Society 19, 500 (April 1974).

**Relevant to request No. 318.

†Present address: Georgia Institute of Technology, Atlanta, GA.

††Present address: Tennessee Technological University, Cookeville, TN.

†††Present address: Los Alamos Scientific Laboratory, Los Alamos, NM.

A.5. Charged Particle Induced Reactions

1. Differential Cross Sections for the Production of Neutrons from the Bombardment of ^{12}C, ^{27}Al, ^{54}Fe, and ^{208}Pb by 40-MeV Protons*,** (J. W. Wachter, R. T. Santoro, T. A. Love and W. Zobel†)

Differential cross sections in energy and angle have been obtained using time-of-flight spectroscopy for secondary neutrons produced in the reactions of 39.3- and 40.8-MeV protons with ^{12}C, ^{27}Al, ^{54}Fe, and ^{208}Pb. Neutron energy spectra are given for laboratory angles of 0°, 20°, 45°, 60°, 90°, and 135° for energies ≥ 6 MeV. The NE-213 efficiency was calculated using the O5S Monte Carlo code. Comparisons with the predictions of the intranuclear-cascade model of Bertini show good agreement at

medium angles. As with the earlier 63-MeV measurements, the data do not show the predicted quasifree scattering peak at small angles. The calculated cross sections at 135° are low by factors of 3 to 6.

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*Presented at the 1973 Winter APS Meeting, Berkeley, CA, December 27-29, 1973.

**Relevant to request No. 630.

†Present address: Tennessee Valley Authority, Knoxville, TN.

2. Coulomb Excitation of Vibrational-Like States in the Even-A Actinide Nuclei* (F. K. McGowan, C. E. Bemis, Jr., W. T. Milner, J. L. C. Ford, Jr., R. L. Robinson and P. H. Stelson)

Coulomb excitation of vibrational-like states in the even-A actinide nuclei ($230 \leq A \leq 248$) was measured using ^{4}He ions in order to test nuclear models describing these states. In particular, the one-phonon octupole vibrational interpretation of the low-lying negative parity states provides an interesting theoretical framework with which to compare the experimental information. The excitation probabilities were determined relative to the elastic scattering by the observation of elastically and inelastically scattered ^{4}He ions using a split-pole magnetic spectrometer equipped with a position-sensitive proportional detector. The values of $B(E\lambda, 0 \rightarrow J = \lambda)$ range from 0.5 to 4 single-particle units for $\lambda = 2$ and from 10 to 30 single-particle units for $\lambda = 3$. For those cases, where the K, $J\pi$ assignments are known, the agreement between the experimental results and the microscopic calculations by Neegard and Vogel of the $B(E3,0 \rightarrow 3)$ for the 3^{-} members of the one-phonon octupole quadruplet is good when the Coriolis coupling between the states with K and $K \pm 1$ is taken into account. The magnitudes of the reduced E0 nuclear matrix element, $\rho(E0, 2' \rightarrow 2)$, extracted from the E0 transition probabilities $T(E0,2' \rightarrow 2)$ for decay of the β-vibrational-like $2'^{+}$ state are 0.37 ± 0.06 and 0.43 ± 0.06 for ^{232}Th and ^{238}U, respectively. Several 2^{+} states observed in this Coulomb excitation reaction survey are presumed to be 2^{+} members of rotational bands based on 0^{+} excited states which are strongly populated in the (p,t) reaction.

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*To be published in Physical Review C.

A.6. Benchmark Measurements

1. Final Report on a Benchmark Experiment for Neutron Transport in Thick Sodium* (R. E. Maerker, F. J. Muckenthaler, R. L. Childs and M. L. Gritzner†)

An experiment concerning deep neutron penetration in sodium is described, and experimental results are presented which provide a basis for verification of the accuracy of sodium cross sections to be used in transport calculations. The experiment was performed at the Tower Shielding Facility of ORNL and included measurements of both the neutron fluence and neutron spectra through a large diameter sample of sodium up to 15 ft thick. Calculated results for the experiment are presented for comparison with the experimental measurements. These results were obtained using the multigroup Monte Carlo code, MORSE, and a two-dimensional discrete ordinates code, DOT III. One-hundred group data sets were developed from both a preliminary and the final version of the ENDF/III set (MAT=1156) for sodium for use in the calculations. Comparisons of the calculations with experiment indicate that the preliminary version is slightly superior to the final version and that using the preliminary set the total neutron leakage above thermal energies penetrating up through 15 ft of sodium can be calculated to within ~15% and the absolute spectra penetrating up through 12.5 ft of sodium can be calculated to within 20%. Using the final set, the corresponding comparisons are 30% and 60%.

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*Abstract of ORNL-4880.

†Present address: Science Applications, Inc., Huntsville, AL.

2. Final Report on a Benchmark Experiment for Neutron Transport Through Iron and Stainless Steel* (R. E. Maerker and F. J. Muckenthaler)

An experiment concerning neutron penetration in iron and stainless steel is described, and experimental results are presented which provide a basis for verification of the accuracy of iron cross sections to be used in transport calculations. The experiment was performed at the Tower Shielding Facility of ORNL and included measurements of both the neutron fluence and neutron spectra through samples of iron up to 3 ft thick and of stainless steel up to 18 in. thick. Calculations of the experiment were performed with a special version of the MORSE multigroup Monte Carlo code which uses point total cross sections. Comparison of the calculations with experiment indicates that the recently evaluated MAT 4180-Mod. 1 iron cross-section set is superior to the older MAT 1101 and MAT 1124 sets. Calculations using this newest set result in total neutron leakages above thermal energies penetrating up to 3 ft of iron or 18 in. of stainless steel that agree with experiment to within about 20%. The calculated leakage spectra above 90 keV arising from scattering through up to 1 ft of iron or 18 in.

of stainless steel also agree with experiment to within about 20%. Using any of the three sets, the calculated unscattered component through 1 ft of iron or stainless steel above 1 MeV is only accurate to within about 40%.

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*Abstract of ORNL-4892.

A.7. Cross-Section Sensitivity Work

1. Estimated Uncertainties in Evaluated Data* (F. G. Perey)

During the last decade large efforts have gone into preparing microscopic neutron cross section data files, called evaluated data files, to serve as basic input data for various neutron transport applications. A prime example of such evaluated microscopic cross sections is the ENDF/B set, a cooperative effort of the Cross Section Evaluation Working Group (CSEWG). The ENDF/B cross-section reference set is updated periodically to provide increased coverage of nuclides, energy range, reaction types, ...etc., and generally to upgrade the data files to reflect our improved knowledge of the cross sections due to new measurements or theoretical calculations and also to remove deficiencies discovered in the analysis of integral experiments (Phase II data testing). The data files are intended to represent as accurately as possible our knowledge of the microscopic cross sections and, therefore, should be application independent. However, because this evaluation work has been funded almost exclusively out of various applied programs, invariably the content of the ENDF/B set has been influenced by the applications for which the different evaluations were needed. The most efficient use of limited financial resources devoted to this aspect of nuclear technologies, the different stages of development of these technologies with respect to nuclear data needs, and the varying importance of the nuclei of the set in different applications have caused the 'intrinsic quality' of the data in the files to vary widely as a function of nuclei, reaction types and energy ranges. The fact that an evaluated file exists for a nuclei in the official CSEWG reference set at a given time is not a proof of its adequacy for any specific application, but only represents the collective judgement of the CSEWG members that it was the best overall evaluation available in this format at that time and it meets a minimum of procedural requirements (Phase I review).

At the moment possibly only one evaluation, the one for hydrogen, is generally thought to exceed the accuracy requirements in the microscopic data for most present, or contemplated, applied uses. For most important neutron transport applications, it is generally conceded that many of the neutron cross sections will not be known, for a long time, to such a high degree of accuracy that uncertainties in the basic microscopic data can be ignored. Several studies have been made, for a few applications, of the cost and design penalties associated with nuclear data uncertainties and yielded what we could call 'target accuracies' in the various microscopic data as acceptable for these applications. These studies have had to

assume what were acceptable design parameter uncertainties and on the basis of the then known cross sections make assumptions on what would be the 'correlations on the uncertainties' in the final acceptable data set. At present it is thought that for some applications a few of the very important partial cross sections may be known to within a factor of two of the 'target accuracies' of these studies. There is, however, no consensus on the question of whether the present estimated uncertainties are sufficiently uncorrelated or not.

In order to answer in a credible manner most of the questions regarding the adequacy of nuclear data for different applications, we require a knowledge of the estimated uncertainties, and their correlations, in the evaluated data. This information at the present time is sometimes to be found in the documentation of the evaluations, is very incomplete, difficult to extract and sufficiently ill-defined as to the nature of the correlations in the data so as to prevent very credible quantitative statements to be made regarding the adequacy of the data. With ENDF/B-IV a start has been made toward the implementation of the complete description of the estimated covariances of the microscopic data on the tape. We will present the concepts and major features of the ENDF/B-IV format for representing the covariance matrices of the pointwise microscopic cross sections as a function of energies, of different partial cross sections for a given nuclei and of cross sections for different nuclei. We will show how the method of representation chosen allows the computation of covariance matrices of group cross sections as a straightforward additional step to most present group cross-section processing codes. The problems of representing these covariances and their handling by processing codes for the resolved and unresolved resonance regions are under active investigation and will be alluded to.

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*To be presented at the June ANS Meeting, Philadelphia, PA.

2. The Formalism for Data Covariance Representation in ENDF/B*
(F. G. Perey)

In many transport calculations a significant fraction of the uncertainties in the calculated results comes from the uncertainties in the basic cross-section data used as input. The implications of such uncertainties for the design of reactors and their significant economic impacts have been discussed by Greebler, Bane, Usachev, and others. Evaluated microscopic neutron cross-section files used to generate the input data for such calculations have not in the past attempted to represent in the files the estimated covariances of the microscopic cross sections for the purpose of propagating these estimated uncertainties to the final results of transport calculations. CSEWG decided for ENDF/B-IV to adopt formats to allow a precise representation of estimated covariances in some of the microscopic data.

It is the purpose of this paper to present in some detail how estimated uncertainties and correlations in the evaluated data, the covariances

of the cross sections, can be represented in the ENDF/B files. The basic concept used in the formalism is the expansion of the covariances of the energy dependent cross sections into elements which are fully correlated over a stated energy range.

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*To be presented at the ANS Topical Meeting on "Advanced Reactors; Physics, Design and Economics," Atlanta, GA, Sept. 8-11, 1974.

3. Radiation Transport Cross-Section Sensitivity Analysis - A General Approach Illustrated for a Thermonuclear Source in Air* (D. E. Bartine, E. M. Oblow and F. R. Mynatt)

A general approach to radiation transport cross-section sensitivity analysis is introduced and its applicability demonstrated for a problem involving neutron and gamma-ray transport in air. The basis for the method is generalized perturbation theory using flux solutions to the transport equation and its adjoint. Both an analytical aspect of the technique, designed for surveying the sensitivity of a result to the entire cross-section data field, and a predictive aspect, designed for predicting the effect of changes in the data field, are presented. The analytic procedure is demonstrated by results that include a determination of important energy regions in the total, partial, and gamma-ray-production cross sections of nitrogen and oxygen for deep-penetration calculations of tissue dose in air. The predictive capability is illustrated for specific cross-section perturbations in the system and the effects of truncating the Legendre expansion of the scattering kernel. In addition, the applicability of the method for predicting variances in a calculated result arising from cross-section data uncertainties is demonstrated. In the sample case, the variance in the total neutron-gamma tissue dose is estimated from preliminary cross-section error files given in the evaluations of the nitrogen and oxygen cross sections.

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*Abstract of ORNL-TM-4335.

4. Effects of Highly Anisotropic Scattering on Monoenergetic Neutron Transport at Deep Penetrations* (E. Oblow, K. Kin,† H. Goldstein,†† and J. J. Wagshal††)

The sensitivity of the flux in deep-penetration problems to anisotropic scattering was studied within the framework of monoenergetic transport theory. Several parameterized, anisotropic scattering kernels were used to represent a general class of anisotropies. The representation of these kernels in Legendre polynomial series of various orders was explored to determine their effect on calculated discrete eigenspectra and infinite medium fluxes. Eigenspectra for several kernels are presented as a function of the kernel parameter. Conclusions were drawn about the

order of the Legendre expansion of the kernels required for accurate deep-penetration calculations, and the possible existence of multiple diffusion decay modes in realistic problems. In general, rather low order Legendre expansion was found to be adequate for problems in which the scalar flux was the primary quantity of interest.

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*Abstract of ORNL-TM-4408.

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††Present address: Columbia University, New York, NY.

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5. Effects of Air-Density Perturbations on the Transport of Gamma Rays Produced by Point Gamma-Ray Sources*
(B. J. McGregor† and F. R. Mynatt)

A series of MORSE Monte Carlo calculations have been performed to determine the effect that changes in the air density produced by one weapon detonation would have on the transport of gamma-ray radiation produced by a second weapon detonated about one second later. The response of interest was the ionization that would be induced in silicon by gamma rays in the vicinity of and beyond the first burst. A gamma-ray emission spectrum was used for the second weapon and four burst separation distances were considered. The medium was assumed to be infinite air, and spherical geometry was employed with the origin at the center of the second detonation. The changes in density about the first detonation were handled with a pseudo-collision technique. Boundary-crossing estimators were used at two radii from the second detonation and within nine solid angles measured from an axis passing through both detonations. Total, uncollided, and time-dependent gamma-ray ionization responses were calculated at each detector position. Total responses calculated for a position in the perturbed air immediately beyond the first burst were about 50% higher than those obtained in air; an even greater increase was calculated for the uncollided response, which is a significant portion of the total response at detector positions between 1000 and 1500 m from the source.

The changes in the total ionization due to the perturbations were very similar to the changes in the neutron displacement calculated for a 14-MeV neutron source in a previous study. Changes in the peak ionization rate followed changes in the total ionization for large separation distances but were less for small separations.

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*Abstract of ORNL-TM-4266.

†Present address: Australian Atomic Energy Commission, Lucas Heights, Australia.

6. Cross-Section Sensitivity of Breeding Ratio in a Fusion-Reactor Blanket* (D. E. Bartine, R. G. Alsmiller, Jr., E. M. Oblow, and F. R. Mynatt)

For a particular fusion-reactor-blanket configuration, the changes in the tritium breeding ratio, i.e., in the number of tritium nuclei produced in the blanket per incident neutron, due to changes in nuclear cross-section data are calculated on the basis of linear perturbation theory. Results are presented for the changes in the breeding ratio due to changes in specific energy ranges of various partial cross sections of ^{6}Li, ^{7}Li, Nb, and C. The breeding ratio is found to be most sensitive to changes in the ^{7}Li(n,n')α,t cross section, but the sensitivity to changes in this cross section is not large.

*Nucl. Sci. Eng. 53, 304-318 (1974).

7. Reactor Cross-Section Sensitivity Studies Using Transport Theory* (E. M. Oblow)

An approach to making reactor sensitivity studies and reactor parameter uncertainty analysis using transport theory is developed. Sensitivity functions based on variational principles are reviewed and compared with an alternate approach using generalized perturbation theory. The computational implementation of the method using transport codes is also discussed. Finally, the use of cross-section error files in conjunction with sensitivity coefficients in estimating uncertainties in reactor parameters is described.

*Abstract of ORNL-TM-4437.

8. Generalized Reactor Sensitivity Analysis Program at ORNL* (E. G. Silver, E. M. Oblow, J. M. Kallfelz,† C. R. Weisbin, D. E. Bartine, G. F. Flanagan and F. R. Mynatt)

The shielding sensitivity analysis program at ORNL based on one-dimensional transport calculations is currently being expanded to include core physics sensitivity analysis capability. Major development items associated with this task lie in the areas of applying generalized perturbation theory to transport calculations of reactor core problems and generating and utilizing correlated cross-section uncertainty data in estimating uncertainties in reactor design parameters. The problems associated with applying generalized perturbations theory are numerical in nature and particular to the use of finite-difference methods in solving the transport equation; they do not occur in using the diffusion approximation. As a result, restrictions are placed on the type of reactor models which can be analyzed with transport methods. Estimation of uncertainties in reactor

paremeters presents major problems in the areas of evaluating the uncertainties in the cross-section data used in a reactor calculation with particular attention to correlations between the data. Computer formats suitable for storing the correlated uncertainty data and codes for processing such data into multigroup data files must be developed. The effort at ORNL is directed towards automating in a single computer code system the procedure for solving generaled perturbation theory equations to generate sensitivity coefficients and linking this data with processed cross-section uncertainty files to generate and analyze reactor design parameter uncertainties.

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*To be presented at the ANS Summer Meeting, Philadelphia, PA, June 23-26, 1974.

†Present address: Georgia Institute of Technology, Atlanta, GA.

A.8. Theoretical Analysis

1. Compilation of Phenomenological Optical-Model Parameters 1969-1972* (C. M. Perey and F. G. Perey)

A little over a year ago, we published a pilot compilation of phenomenological optical-model parameters obtained by fitting elastic-scattering data. This compilation covered only two years of publication 1969 and 1970, but we have been led to believe that it is more widely used than we had anticipated. Encouraged by this result, we continued collecting optical-model parameters and have now added the years 1971 and 1972 to our compilation.

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*To be published in Nuclear Data Tables.

2. Calculated Secondary-Particle Spectra from Alpha-Particle and Carbon-Induced Nuclear Reactions* (T. A. Gabriel, R. T. Santoro, N. W. Bertini, and N. M. Larson)

A newly developed calculational model for nucleus-nucleus collisions has been applied to obtain secondary-neutron spectra from 100-MeV/nucleon alpha particles incident on C and from 100-MeV/nucleon C incident on C. These data can be used in estimating shielding requirements for medium-energy heavy-ion machines. Also included is a comparison between a previous model used only for calculating secondary-particle spectra from alpha-particle nuclear reactions and the new, more general nucleus-nucleus collision model.

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*Nucl. Sci. Eng. 53, 3 (1974).

3. Treatment of Large Perturbations of the Hamiltonian and the Foundary Conditions of a Quantum Mechanical System as an Initial Value Problem* (R. B. Perez and G. de Saussure)

On the basis of an integrodifferential equation satisfied by the transition T-matrix, together with its associated initial conditions, we have developed a general formalism to treat large perturbations in both the Hamiltonian and the boundary conditions of a quantum mechanical system. As a result of this formalism, a set of first order differential equations, in terms of any of the physical parameters of the system, is given for the widths and poles of the collision U-matrix.

The technique is illustrated by the coversion of a set of R-matrix resonance parameters into its equivalent set of U-matrix widths and poles, which corresponds to the passage from the R-matrix boundary conditions to the complex, momentum-dependent boundary conditions associated with the Kapur-Peierls reaction formalism.

The case of large perturbations of the Hamiltonian is illustrated by the calculation of the elastic- and inelastic-scattering cross sections in a strongly coupled two-channel system which was proposed by Tobocman and has been widely used as testing grounds for reaction theorites.

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*To be published in Physical Review C.

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