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Volume 19

**An Integrated System for Production of Neutronics
and Photonics Computational Constants
Volume 19**

MASTER

**NEUTRON-INDUCED ANGULAR
AND ENERGY DISTRIBUTIONS:
GRAPHICAL EXPERIMENTAL DATA**

D. E. Cullen, R. J. Howerton, M. H. MacGregor,
and S. T. Perkins

April 1, 1977

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UCRL-50400 Volume 19

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Foreword

The UCRL-50400 series describes an integrated and computer-oriented system for the production and application of neutronics and photonics calculational constants.

The system must supply reliable up-to-date data, select specific types of data on request, provide output in a variety of forms — ultimately in the form of input to other computer codes — and function rapidly and efficiently. The system has now been developed to a point where these goals are being realized.

The UCRL-50400 series, *An Integrated System for Production of Neutronics and Photonics Calculational Constants*, comprises the following volumes:

- Vol. 1 Rev. 3, *ECSII, A System for Storage, Retrieval and Display of Experimental Neutron Data*, to be published in September 1976.
- Vol. 2 Rev. 2, *Neutron-Induced Interactions: Bibliography of Experimental Data*, July 1976.
- Vol. 3 Rev. 2, *Neutron-Induced Interactions: Index of Experimental Data*, July 1976.
- Vol. 4, *Evaluated Nuclear Cross-Section Library*, April 1971.
- Vol. 5, Rev. 1, *CLYDE: A Code for the Production of Calculational Constants from Nuclear Data*, September 1975.
- Vol. 6, Rev. 1, *Tables and Graphs of Photon Interaction Cross Sections from 1.0 keV to 100 MeV Derived from the LLL Evaluated Nuclear Data Library*, October 1975.
- Vol. 7 Part A Rev. 1, *Major Neutron-Induced Interactions ($Z \leq 55$): Graphical, Experimental Data*, July 1976.
- Vol. 7 Part B Rev. 1, *Major Neutron-Induced Interactions ($Z > 55$): Graphical, Experimental Data*, July 1976.
- Vol. 8 Rev. 1 Part A, *Supplemental Neutron-Induced Interactions ($Z \leq 35$): Graphical, Experimental Data*, July 1976.
- Vol. 8 Rev. 1 Part B, *Supplemental Neutron-Induced Interactions ($Z > 35$): Graphical, Experimental Data*, July 1976.
- Vol. 9, *Thresholds of Nuclear Reactions Induced by Neutrons, Photons, Deuterons, Tritons, and Alpha Particles*, September 1970.
- Vol. 10, *Tabulated Experimental Data for Neutron-Induced Interactions*, July 1976.
- Vol. 11, *Experimental Data, Indexes and Techniques of Obtaining a Selected Set of*

- Neutron Resonance Parameters*, May 1972.
- Vol. 12, *An Atlas of Resolved Neutron Resonance Parameters*, July 1972.
 - Vol. 13, *An Atlas of Unresolved Neutron Resonance Parameters*, September 1972.
 - Vol. 14, *TARTNP: A Coupled Neutron-Photon Monte Carlo Transport Code*, July 1976.
 - Vol. 15, Part A, *The LLL Evaluated Nuclear Data Library (ENDL): Evaluation Techniques, Reaction Index, and Descriptions of Individual Evaluations*, September 1975.
 - Vol. 15, Part B, *The LLL Evaluated Nuclear Data Library (ENDL): Graphs of Cross Sections from the Library*, April 1976.
 - Vol. 15, Part C, *The LLL Evaluated Nuclear Data Library (ENDL): Translation of ENDL Neutron-Induced Interaction Data into the ENDF/B Format*, April 1976.
 - Vol. 16, *Tabular and Graphical Presentation of 175 Neutron Group Constants Derived from the LLL Evaluated Neutron Data Library (ENDL)*, April 1976.
 - Vol. 17, *Utility Codes for the Processing of Evaluated Data*.
 - Vol. 18, *ACTL-Evaluated Neutron Activation Cross Section Library (1977)*.
 - Vol. 19, *Neutron Induced Angular and Energy Distributions: Graphical Experimental Data*, April 1977.

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NEUTRON-INDUCED ANGULAR AND ENERGY DISTRIBUTIONS: GRAPHICAL AND EXPERIMENTAL DATA

Abstract

We have generated graphs of neutron-induced distributions based on the data found in the Experimental Cross Section Information Library (ECSIL) as of April 1, 1977. Angular and energy distributions as well as

Legendre coefficients have been presented for all secondary particles emitted from the nucleus (e.g., neutrons, protons, deuterons, etc). We have plotted the data with error bars when they have been available.

Introduction

In 1958, Lawrence Livermore Laboratory (LLL) installed a computer system to store and retrieve experimental neutron interaction data. This system, the Experimental Cross Section Information Library (ECSIL), has developed gradually and is still being improved.

The present ECSIL system¹ comprises two separate reference files: a numerical data file and bibliographic information file. The two files are linked through the use of a four-digit number uniquely assigned to each reference.

In 1959 and 1960, LLL published tabulations of integrated and differ-

ential neutron cross sections below 15 MeV. Since that time, the number of entries in the system has increased by more than an order of magnitude. Consequently, the current library contains too much data (over 1.6 million data points) to publish tabulations; the resulting volumes would be prohibitively expensive and bulky. However, by presenting the data in graphs^{2,3} and on microfiche,⁴ we can significantly reduce expense and bulk. Moreover, bulk reduction means that indexes⁵ and bibliographies⁶ can be added to help in data manipulation.

Graphical Data

The present ECSIL system contains 136 048 angular distribution data points (C = 101-149),^{*} 12 684 Legendre coefficients (C = 451-499), and 11 678 energy distribution data points (C = 201-249). Since it takes almost 10 000 plots to graph these data, they have been put on microfiche. Users at Livermore may obtain printed copies of all or any portion of these data by contacting M. MacGregor of the Theoretical Physics Dept.

In this volume each data set[†] is plotted separately. The plots are presented in three separate sections:

- Angular distributions
- Legendre coefficients
- Energy distributions

Within each section the plots are ordered by ascending atomic number and weight. (See "ECSIL Conventions" for compounds and special material.)

Within each material the reactions are ordered by ECSIL C number. Within a given reaction the plots are ordered by incident neutron energy. Reference number and year of reference appear to the left of the plot (e.g., ECSIL-3327 (68) indicates ECSIL reference number 3327 and reference data from 1968).

^{*}C numbers refer to ECSIL C numbers: see ECSIL Conventions.

[†]A data set in this context includes the data from a given reference for a single target and reaction.

An angular distribution, energy distribution, or set of Legendre coefficients containing four or more points is plotted. Data sets with fewer points are listed at the end of each material (ZA) in ECSIL C order.

In general each plot represents a fixed incident neutron energy, and the abscissa is either the

- Cosine of the scattering angle (see ECSIL conventions for the laboratory or center-of-mass systems)
- Legendre order
- Secondary energy

However, when appropriate, the incident neutron energy may be plotted along the abscissa for either a fixed cosine, fixed Legendre order, or fixed secondary energy. This convention is more appropriate for the representation of certain experimental data; for example:

- Measurement at a fixed angle
- Derivation of an average scattering cosine $\bar{\mu}$
- Measurement of excitation functions

In most cases the distributions describe secondary neutrons. However, in the case where there is no neutron in the exit channel the distribution will be for another particle [e.g. (n, α) - α particle; (n,x) γ - photon, etc.].

Relationship to Other Volumes

This volume is closely related to other volumes in the UCRL-50400 series and can be used to determine whether experimental data are available for a given target and reaction. The following volumes provide other paths to the information:

- *Volume 1* describes the format and conventions associated with the library as well as the supporting system of programs. It also gives the forms (e.g., plots and listings) and the order in which data and bibliographic information may be obtained.
 - *Volume 2* contains bibliographic indexes that can be used to determine whether a specific reference is included in the ECSIL system and which experimental data are associated with the reference.
 - *Volume 3* lists data indexes that may be used to determine the data in the library for a given isotope or reaction.
 - *Volume 7* presents graphs of all total, elastic, capture, and fission integral cross sections. It also supplies data on $\bar{\nu}$ (neutrons/fission), α (capture/fission ratio), and η (neutrons/nonelastic event).
 - *Volume 8* presents graphs of all other integrated (as opposed to angular distribution) cross sections, including (n,n') , (n,α) , etc.
 - *Volume 10* contains the ECSIL library contents tabulated on microfiche.
 - *Volume 11* lists the indexes and tabulated resonance parameters in ECSIL.
 - *Volume 12* lists selected tabulated resolved resonance parameters.
 - *Volume 13* lists selected tabulated unresolved resonance parameters.
- See this volume's foreword for a list of associated volumes on evaluated data.

Production of Graphs

The computer program ECSPLT¹ produced all of the graphs in this volume. The program required three noninteractive passes through the

ECSIL data library to produce microfiche of all the plots correctly ordered. These passes used 16 min of CDC-7600 time.

Corrections and Suggestions

Users of these volumes have been a major aid in detecting and reporting erroneous data that have crept into ECSIL. They have also suggested improvements in the format and scope of these volumes. Please continue to

communicate all corrections and suggestions to:

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data collected at the four centers.

Many experimenters have furnished us with their data before publication. To them, especially, we offer our grateful thanks. Finally, we would like to express our sincere gratitude to Violet Gamble and Sally Mooney for their efforts in maintaining the bibliographic file and to Kenneth Hill for ensuring that the numerous computer runs were satisfactorily completed.

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Appendix A

ECSIL Conventions

The ECSIL data system describes experimental neutron-induced cross sections and related information by indicating:

- *Target.* The ZA number describes the target. There are several special conventions. For example, A is set at zero for elemental mixtures. For compounds, the Z of the element that appears first in the molecular formula is used, and A is defined as 300 plus the molecular weight (e.g., H_2O is assigned $Z = 1$ and $A = 318$). For unstable targets, the longest-lived isomer is assigned the ZA number of the target. Short-lived isomers are assigned the Z of the target, and A is defined as 600 plus the atomic weight of the target (e.g., $^{242}G_{Am}$ is assigned $Z = 95$ and $A = 842$). See Table A1 for a complete list of compounds and special isotopes.

- *Interaction.* A numerical equivalent is used to designate the type of interaction: total, elastic, capture, etc. In ECSIL, this numerical equivalent becomes the basic C number. Table A2 gives a com-

plete list of all basic C numbers.

- *Interaction Property.* A numerical equivalent designates the interaction properties that are measured, such as cross section, angular distribution, or energy distribution. In ECSIL, this numerical equivalent becomes the C-increment number. The total C number used to describe the interaction and its property is the sum of the C-number increment and the basic C number (e.g., 11 indicates the total '(n,n') cross section, while 311 indicates the (n,n') secondary neutron energy spectrum). Table A3 gives a complete list of all C-number increments. Table A4 lists miscellaneous quantities not included in the basic C-number/C-number-increment scheme.
- *Interaction Modifier.* A numerical equivalent is used to further qualify or describe the interaction. This quantity indicates conditions such as target temperature, the cross section for excitation of one or more levels of the residual nucleus, and the cross section

for production of one or more photons. In ECSIL, this numerical equivalent becomes

the S number. Table A5 gives a complete list of all S numbers.

Table A1. Compounds and special isotopes (assigned ZA's).

Assigned ZA number	Material	Assigned ZA number	Material
1302	H ₂ (gas)	14360	SiO ₂
1308	H ₂ O	16364	SO ₂
1320	D ₂ O	22349	TiH _{0.6}
5370	B ₂ O ₃	22350	TiH _{1.9}
6328	C ₂ H ₄	26460	Fe ₂ O ₃
6331	CH ₃ OH	27660	60mCo
6376	C ₆ H ₆	40391	ZrH _{0.63}
6384	C ₆ H ₁₂	40392	ZrH _{0.98}
6386	C ₆ H ₁₄	40393	ZrH _{1.5}
6392	C ₃ H ₈ O ₃	40394	ZrH _{1.98}
6404	C ₈ H ₈	40395	Zircaloy-2
6492	C ₁₀ H ₈ O ₄	40423	ZrO ₂
6652	C ₂₅ H ₅₂	52723	123mTe
7328	N ₂ (gas)	60636	Nd ₂ O ₃
7353	NH ₄ Cl	61748	148BPm
7398	NH ₄ Br	82999	RADIO-Pb
7445	NH ₄ I	92570	UO ₂
8332	O ₂ (gas)	95842	242gAm
12340	MgO	95844	244gAm
13402	Al ₂ O ₃	99854	254mEs

Table A2. Basic reaction designator (basic C).

Basic C number	Cross-section type	Basic C number	Cross-section type
1	Total	25	(n,X) charged-particle emission
2	Elastic	26	(n,p)
3	Nonelastic	27	(n,Xp)
4	Neutron emission (elastic + nonelastic)	28	(n,d)
5	Total scattering (inelastic + elastic)	29	(n,Xd)
6	Neutron nonelastic emission	30	(n,t)
7	Removal	31	(n,Xt)
8	—	32	(n, ³ He)
9	—	33	(n,X ³ He)
10	—	34	(n, α)
11	(n,n')	35	(n,X α)
12	(n,2n)	36	Activation
13	(n,3n)	37	(n,2 α)
14	(n,n'p)	38	—
15	(n,n'd)	39	—
16	(n,n't)	40	—
17	(n,n', ³ He)	41	Bound atom
18	(n,n', α)	42	Free atom
19	(n,4n)	43	Coherent scattering
20	—	44	Incoherent scattering
21	Absorption	45	Potential scattering
22	(n,fission)	46	$\bar{\nu}_p$, prompt neutrons per fission (average)
23	(n, γ)	47	$\bar{\nu}_d$, delayed neutrons per fission (average)
24	(n,X γ) gamma-ray production	48	η , neutrons produced per nonelastic
		49	α , capture-to-fission ratio

Table A3. Reaction designator increments (C increment).

C increment number	Reaction property (units)	Definition
0	Integrated cross sections (b) or related parameters	σ
50	Spectrum-averaged cross sections (b)	$\bar{\sigma}$
100 ^a	Angular distributions (b/sr)	$\sigma(E, \theta)$
200	Energy distributions (b/MeV)	$\sigma(E, E')$
250 ^a	Angular distributions integrated between fixed angular limits (b)	$\sigma(E, \theta_{\min}, \theta_{\max})_{\text{lab}}$
300 ^a	Differential energy distributions (b/sr MeV)	$\sigma(E, E', \theta)_{\text{lab}}$
350 ^a	Partial distributions integrated between fixed energy and angular limits (b)	$\sigma(E, E'_{\min}, E'_{\max}, \theta_{\min}, \theta_{\max})_{\text{lab}}$
400	Energy distributions integrated between fixed energy limits (b)	$\sigma(E, E'_{\min}, E'_{\max})$
450 ^a	Legendre expansion of angular distributions - $g_{\ell}(E)$ (dimensionless)	$\sigma(E, \theta) = \sigma(E) \sum_{\ell=0}^{\infty} \frac{2}{4\pi} \frac{+1}{\ell} g_{\ell}(E) P_{\ell}(\cos \theta)$
500	Resonance integrals (b)	$R.I. = \int_{E_{\min}}^{E_{\max}} \sigma(E) \frac{dE}{E}$
550 ^a	Polarization (dimensionless)	$P(E, \theta)$
600 ^a	Partial distributions integrated between fixed-energy limits (b/sr)	$\sigma(E, E'_{\min}, E'_{\max}, \theta)_{\text{lab}}$
650 ^a	Partial distributions integrated between fixed angular limits (b/MeV)	$\sigma(E, E', \theta_{\min}, \theta_{\max})_{\text{lab}}$
850	C/S ratios (dimensionless)	
900	Miscellaneous quantities	See Table 4

^aAngular distributions for all unique *two-body* reactions are expressed in the center-of-mass system. Multibody reactions are expressed in the laboratory frame of reference.

Table A4. Reaction designator for miscellaneous quantities.

C	Spectra parameters				
901	Nuclear temperature, nonelastic (excluding fission)				
902	Nuclear temperature, total nonelastic				
903	Nuclear temperature, fission				
904	Nuclear temperature, inelastic (first neutron)				
905	Nuclear temperature (second neutron)				
Thermal parameters					
911	Thermal scattering law, $S(\alpha, \beta)$				
Average resonance parameters					
941	$\bar{D}_{\text{observed}}$	944	$\bar{\Gamma}_n^{\ell}$		
942	$\bar{\Gamma}_{\gamma}$	945	$\bar{D}_{\ell}$		
943	$\bar{\Gamma}_f$	946	$\bar{S}_{\ell}$		
Resolved resonance parameters					
951	E_o (energy only)	966	$g\Gamma_n$	981	$\sigma_o \Gamma_f / \Gamma_t$
952	J, π	967	$g\Gamma_n^o$	982	$\sigma_o \Gamma_{\gamma} / \Gamma_t$
953	ℓ	968	$g\Gamma_{\gamma}$	983	$\sigma_o \Gamma_a / \Gamma_t$
954	g	969	Γ_n / Γ_t	984	$\sigma_o \Gamma_{\gamma} \Gamma_f / \Gamma_t$
955	σ_o	970	Γ_a / Γ_t	985	$\sigma_o \Gamma_f^2 / \Gamma_t$
956	Γ_t	971	$\Gamma_{\gamma} / \Gamma_t$	986	$g\Gamma_{\gamma} \Gamma_n / \Gamma_t$
957	Γ_n	972	Γ_n / Γ_a	987	$2g\Gamma_n^2 / \Gamma_t$
958	Γ_n^o	973	Γ_f / Γ_t	988	$\Gamma_t^2 \sigma_o$
959	Γ_{γ}	974	Γ_f / Γ_a	989	$g\Gamma_n^o \Gamma_f$
960	Γ_f	975	$\Gamma_{\gamma} / \Gamma_f$	990	$g\Gamma_f \Gamma_n / \Gamma_t$
961	Γ_a	976	$\Gamma_t \sigma_o$	991	$\sigma_o \Gamma_f \Gamma_t$
962	Γ_{α}	977	$\Gamma_f \sigma_o$	992	$\Gamma_n^o \Gamma_f / \Gamma_t$
963	Γ_p	978	$\Gamma_{\gamma} \sigma_o$	993	$g(\Gamma_n)^2$
964	$g\Gamma_n^1$	979	$\Gamma_n \sigma_o$	994	$g\Gamma_n \Gamma_{\gamma}$
965	$g\Gamma_n^2$	980	$\sigma_o \Gamma_n / \Gamma_t$		

Table A5. Reaction designator modifier^a (S number).

S number	Modification (units)
1	Level excitation (MeV)
2	Isomer production (sec)
3	Isomer production (min)
4	Isomer production (hr)
5	Isomer production (d)
6	Isomer production (yr)
7	Photon production (MeV)
8	Unresolved level excitation (MeV)
9	Material temperature (K)
10	Unresolved photon production (MeV)
11	Spin state (dimensionless)
12	Isotope bound in material (dimensionless)
13	Oriented crystal (Miller number)
14	Electron production (MeV)
20	Transmission measurement (b/atom)

^aS + 80 indicates relative distribution.