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THE LLL EVALUATED-NUCLEAR-DATA LIBRARY (ENDL): GRAPHS OF CROSS SECTIONS FROM THE LIBRARY

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

October 31, 1978

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LAWRENCE LIVERMORE LABORATORY

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UCRL-50400

Volume 15, Part B, Rev. 1

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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 we are achieving these goals.

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

- Vol. 1, Part A, Rev. 3, *ESCIL: A System for storage, Retrieval and Display of Experimental Neutron Data*, September 1976.
- Vol. 1, Part B, Program *ECSK4 (Version 78-1): Conversion of Experimentally Measured Cross Section Data from the Four Center Exchange (X-4) Format to the Livermore ECSIL Format*, 1979.
- Vol. 2, Rev. 2, *A Bibliography of the Experimental Data of Neutron-Induced Interactions*, July 1976.
- Vol. 3, Rev. 2, *An Index of the Experimental Data of Neutron-Induced Interactions*, July 1976.
- Vol. 4, *Evaluated-Nuclear-Cross-Section Library*, April 1971.
- Vol. 5, Part A, Rev. 1, *CLYDE: A Code for the Production of Calculational Constants from Nuclear Data*, September 1975.
- Vol. 5, Part B, Rev. 1, *Relativistic Transformations between Center-of-Mass and Laboratory Systems for Two-Body Nuclear Reactions*, April 1978.
- 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, Part A, Rev. 1, *Supplemental Neutron-Induced Interactions ($Z \leq 35$): Graphical, Experimental Data*, July 1976.

- Vol. 8, Part B, Rev. 1, *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.
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- 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*, February 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, Rev. 1, *The LLL Evaluated-Nuclear-Data Library (ENDL): Graphs of Cross Sections from the Library*, October 1978.
- 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. 15, Part D, *The LLL Evaluated-Nuclear-Data Library (ENDL): Descriptions of Individual Evaluations for $Z = 90-98$* , June 1977.
- Vol. 15, Part E, *The LLL Evaluated-Nuclear-Data Library (ENDL): Descriptions of Individual Evaluations for $Z = 0-23$* , 1978.
- Vol. 15, Part F, *The LLL Evaluated-Nuclear-Data Library (ENDL): Descriptions of Individual Evaluations for $Z = 24-89$* , 1978.
- Vol. 16, Rev. 2, *Tabular and Graphical Presentation of 175 Neutron-Group Constants Derived from the LLL Evaluated-Nuclear-Data Library (ENDL)*, October 1978.
- Vol. 17, Part A, *Program LINEAR (Version 77-1): Linearize Data in the Evaluated-Nuclear-Data File/Version B (ENDF/B) Format*, January 1977.

- Vol. 17, Part B, Program
*SIGMA1 (Version 77-1): Doppler
Broaden Evaluated Cross Sec-
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Format, January 1977.*
- Vol. 18, *ACTL-Evaluated Neutron
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- Vol. 19, *Neutron-Induced
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tions: Graphical Experimental
Data, April 1977.*
- Vol. 20, *Bonderenko Self-
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THE LLL EVALUATED-NUCLEAR-DATA LIBRARY (ENDL): GRAPHS OF CROSS SECTIONS FROM THE LIBRARY

Abstract

We present graphs of neutron cross sections and related parameters as of October 31, 1978, for the Lawrence Livermore Laboratory Evaluated-Nuclear-Data Library (ENDL).

Introduction

The Lawrence Livermore Laboratory (LLL) and others extensively use the evaluated nuclear data¹ given here for neutron transport and related calculations. This document presents data contained in the Evaluated-Nuclear-Data Library (ENDL) as of October 31, 1978. Other volumes of the UCRL-50400 series have related information:

- Volumes 2, 3, 7, and 8 present the experimental neutron cross-section data used to define the ENDL.
- Volume 6 presents photon interaction data.
- Volume 16 presents 175 group constants from ENDL for neutron interaction and photon production.

1978 Edition

Since the 1976 edition of this volume, the following evaluations have been modified:

6 _{Li}	31 _P	nat _{Ni}	nat _{Eu}	233 _{Th}	240 _{Pu}	247 _{Cm}
9 _{Be}	32 _S	58 _{Ni}	nat _{Gd}	233 _U	241 _{Pu}	248 _{Cm}
10 _B	nat _{Cl}	nat _{Cu}	165 _{Ho}	234 _U	242 _{Pu}	249 _{Bk}
11 _B	nat _{Ar}	nat _{Ga}	181 _{Ta}	235 _U	243 _{Pu}	249 _{Cf}
12 _C	nat _K	nat _{Zr}	nat _W	236 _U	241 _{Am}	250 _{Cf}
14 _N	nat _{Ca}	93 _{Nb}	185 _{Re}	237 _U	242 _{mAm}	251 _{Cf}
16 _O	nat _{Ti}	nat _{Mo}	187 _{Re}	238 _U	243 _{Am}	252 _{Cf}
19 _F	51 _V	107 _{Ag}	nat _{Pt}	239 _U	242 _{Cm}	
23 _{Na}	nat _{Cr}	109 _{Ag}	197 _{Au}	240 _U	243 _{Cm}	
nat _{Mg}	55 _{Mn}	nat _{Cd}	nat _{Pb}	237 _{Np}	244 _{Cm}	
27 _{Al}	nat _{Fe}	nat _{Sn}	231 _{Th}	238 _{Pu}	245 _{Cm}	
nat _{Si}	59 _{Co}	138 _{Ba}	232 _{Th}	239 _{Pu}	246 _{Cm}	

For details on how any individual evaluation has been modified, contact R. J. Howerton.

Cross Sections and Parameters

This volume contains graphs of all neutron cross sections for all complete ENDL evaluations. We also present the average number of neutrons per fission ($\bar{\nu}$ - total and delayed) and the following parameters, as defined, for elastic scattering:

• Average Laboratory Cosine (μ_{lab})

$$\bar{\mu}_{lab}(E_0) = \int_{-1}^{+1} \mu_{lab} \times P(E_0, \mu_{lab}) d\mu_{lab},$$

where E_0 is the incident-neutron energy and P is the normalized angular distribution for elastic scattering in the laboratory system.

• Average Logarithmic Energy Decrement (ξ)

$$\begin{aligned}\bar{\xi}(E_0) &= \left\langle \ln \left(\frac{E_0}{E} \right) \right\rangle \\ &= \int_{\alpha E_0}^{E_0} \ln \left(\frac{E_0}{E} \right) P(E_0, E) dE,\end{aligned}$$

where E is the secondary-neutron energy.

• Greuling-Gertzel Coefficient (γ)

$$\begin{aligned}\bar{\gamma}(E_0) &= \frac{\left\langle \ln^2 \left(\frac{E_0}{E} \right) \right\rangle}{2 \left\langle \ln \left(\frac{E_0}{E} \right) \right\rangle} \\ &= \frac{1}{2 \bar{\xi}(E_0)} \int_{\alpha E_0}^{E_0} \ln^2 \left(\frac{E_0}{E} \right) \\ &\quad \times P(E_0, E) dE.\end{aligned}$$

We omitted angular and energy distribution from this volume.

Grouping of Data

We grouped our data into the following major cross-section and parameter categories:

1. Total, elastic, capture, fission, and total inelastic.
2. Total inelastic, discrete inelastic levels, and/or continuum.
3. $(n, 2n)$, $(n, 3n)$, $(n, 4n)$, $(n, n')p$, $(n, n')d$, $(n, n')t$, etc. (i.e., reactions between neutrons and multiple particles in which at least one neutron is emitted).
4. (n, p) , (n, d) , (n, t) , etc. (i.e., reactions between neutrons and particles in which no neutrons are emitted).
5. Parameters $\bar{\nu}$, $\bar{\mu}$, $\bar{\xi}$, and $\bar{\gamma}$.

We expanded any plot that contains sufficient cross-section structure and presented cross sections individually over compatible energy ranges. For category 1, we plotted only those cross sections that are at least 0.1%

of the total cross sections. Although this convention eliminates the capture cross section over some energy ranges for light isotopes, it greatly clarifies the resulting plots. (See Appendix A for a tabulation of ENDL conventions.)

Availability of Data

For the convenience of those outside LLL who need the data, we translated the ENDL into the ENDF/B format.² Those interested can get data tapes from the Radiation Shielding Information Center (Oak Ridge

National Laboratory), the National Neutron Cross-Section Center (Brookhaven National Laboratory), and the Nuclear Data Section of the International Atomic Energy Agency, Vienna, Austria.

Production of the Graphs

We used Program EVALPLOT to produce the graphs.³ This program required a single noninteractive pass through a ZA-ordered copy of the ENDL data in the ENDF/B format.⁴ Such a pass,

using 4.7 min of CDC 7600 time, produced a single roll of 35-mm film. This film contained all graphs in correct order, ready for photo-offset printing.

References

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3. D. E. Cullen, *Program EVALPLOT*, Lawrence Livermore Laboratory, Rept. UCRL-50400, Vol. 17, Part E (to be published).
4. M. K. Drake, *Data Formats and Procedures for the ENDF Neutron-Cross-Section Library*, Brookhaven National Laboratory, Upton, New York, Rept. BNL-50274 (T-601), (TID-4500), ENDF-102, Vol. 1 (1970).

Appendix A: ENDL Conventions

This appendix tabulates the ENDL convention discussed in Vol. 4 of this series. Table A1 lists the particle designators, which identify the incident and outgoing particles. Table A2 lists the reaction-property designators, which specify the properties

of the reaction being defined. Tables A3 and A4 list the reaction descriptor (C number), which identifies the reaction when taken with the incident-particle designator. Table A5 lists reaction modifiers, which provide additional specific descriptions.

Table A1. Particle designator,^a y.

y	Particle
0	"not applicable" or none ^b
1	n
2	p
3	d
4	t
5	³ He
6	α
7	γ
8	β

^aUsed to identify the incident particle, y_1 , and/or the outgoing particle, y_0 , to which any distribution data (e.g., energy, angle) pertains.

^bIf no property (e.g., energy distribution) is given, the y_0 is defined to be zero.

Table A2. Reaction-property designator (I number).

I	Reaction property	Definition
0	Integrated cross sections (barns; also related parameters)	$\sigma(E)$
1 ^a	Angular distributions, normalized probabilities (per unit cosine)	$p(E\mu)$
2 ^a	Angular distributions, normalized Legendre coefficients; i.e., $g^0(E) \equiv 1.0$	$g^{l'}(E)$
3	Energy-angle distributions, normalized probabilities (per MeV cosine)	$p(E \rightarrow \mu, E')$
4	Energy-angle distributions, normalized Legendre coefficients. Note that $\pi^0(E \rightarrow E') = p(E \rightarrow E')$, the usual normalized energy probability (per MeV).	$\pi^l(E \rightarrow E')$
5	Nuclear temperature tables	$T(E)$
6 ^b	Cumulative probability distribution	$I(E')$
7	Average neutrons per fission (prompt or delayed)	$\bar{\nu}(E)$
8	Histogram form of energy distribution	$P(E, E'_1) = P(E, E'_2)$
10	Total average energy deposit (MeV)	$\bar{E}(E)$
11	Local average energy deposit (MeV)	$E_{loc}(E)$
80	Maxwellian average reaction rates (barn-cm/sh) ^c	$\overline{\sigma v} \text{ (kT)}$
99	Supplemental parameters	See Table A4.

^aAngular data are expressed in the center of mass (CM) system for all two-body breakups. Multibody breakups are, of course, in the lab (L) system.

^bIf I = 6 data is accompanied by temperature tables (I = 5), the I = 6 distribution pertains to the first energy entry in the I = 5 tables.

^csh = 1 shake = 10^{-8} sec.

Table A3. Reaction descriptors (C numbers).

C-reaction type		C-reaction type		C-reaction type		C-reaction type	
Miscellaneous data	1 ^a Total	20 (y,n'pγ)	Charged particle and/or γ formation	40 (y,pγ)	60	Auxiliary data	
	2 ^a Absorption	1 (y,pn'γ)		1 (y,dγ)	1		
	3 ^a Nonelastic	2 (y,n'dγ)		2 (y,tγ)	2		
	4 ^a Nonelastic neutron emission	3 (y,n'2α-γ)		3 (y,t2αγ)	3		
		4 (y,n'tγ)		4 (y, ³ Heγ)	4		
	5	5 (y,n' ³ Heγ)		5 (y,αγ)	5		5 Activation
	6	6 (y,n'αγ)		6 (y,γ)	6		6 Fractional yield to (Z2, A2) by any fission process
	7	7 (y,n'3αγ)		7	7		
	8	8 (y,n't2αγ)		8	8		
	9	9		9	9		
Neutrons + γ only	10 Elastic	30	Particle or γ production			Atomic	
	1 (y,n'γ)	1		50 (y,Xp)	9		
	2 (y,2nγ)	2		1 (y,Xd)	70 Total		
	3 (y,3nγ)	3		2 (y,Xt)	1 Coherent scattering		
				3 (y,x ³ He)	2 Incoherent scattering		
	4 (y,4nγ)	4		4 (y,Xα)	3 Photoelectric		
	5 (y,Xf)(total fission,	5		5 5(y,Xγ)	4 Pair production		
	6 (y,n'f)	7		6 (y,Xn)	5		
	7 (y,2nf)	8		7	6		
	8 (y,3nf)	9		8	7		
	9			9	8		
					9		
					80 Open		
					↓		
					99		

^aNot usually stored in the system, but obtained for output display by combining other data.

Table A4. Specification of the C number for supplemental parameters (I = 99).

C interval	Incident particle
1 - 49	Neutrons
50 - 74	Photons
75 - 99	Charged particle
C number	Parameters
1	Thermal scattering law, $S(\alpha, \beta)$
10 n, el	Resonance data (background cross section)
11 n, γ	
12 n, f	
13 n, p	
14 n, d	
15 n, t	
16 n, ^3He	
17 n, α	
18 n, x	
20	Resolved resonance parameters
21	Unresolved resonance parameters
51	Form factors (coherent scattering), $G(q)$
52	Form factors (incoherent scattering), $K(q)$

Table A5. Reaction modifier, S.

S	Reaction parameter	X-field definition
00 or blank	No X-field data	—
01	Level excitation ^a	W_1 (MeV)
03	γ -ray production	E_γ (MeV)
04	Material temperature	kT (MeV) (for thermal-scattering models)
05	Activation ^b	$(ZA)_2$ W_2 (MeV) τ_2 (s)
06	Bulk information for Doppler broadening or self-shielding	kT (MeV) ND ($\times 10^{-24}$) Th (cm) $\bar{v}$ (cm/shake) ^c
07	Delayed group half-lives	$\tau_{1/2}$ (s)
08	Completely correlated second neutron	W_1 (MeV) level in cluster model

^a X_1 corresponds to the initial nucleus in a sequence of de-excitations, X_2 to the second nucleus, etc.

^b $(ZA)_2 = 1000Z_2 + A_2$ of product nucleus.

^cThese are self-shielding and boundary-motion parameters (material temperature, atom density, region thickness, and boundary speed, respectively) from a preprocessor code.