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**EVALUATED NEUTRON-INTERACTION AND
GAMMA-RAY-PRODUCTION CROSS SECTIONS OF
 ^{9}B FOR ENDF/B-IV**

MAT NO. 1289

R. J. Howerton

S. T. Perkins

June 18, 1974

Prepared for U.S. Atomic Energy Commission under contract No. W-7405-Eng-48

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Contents

Abstract	1
General Comments	1
Elastic Scattering	1
Cross Section	1
Angular Distributions, Normalized Probabilities	2
(n, 2n) Reaction	2
Cross Section	2
First Neutron	3
Second Neutron	3
Other Reactions	4
(n, p) Cross Section	4
(n, d) Cross Section	4
(n, t) Cross Section	4
(n, α) Cross Section	5
(n, γ) Cross Section	5
(n, X γ) Cross Section	5
Comparison with Integral Experiments	6
Fast Critical Assemblies	6
LLL Pulsed-Sphere Experiment	6
References	9
Appendix A: Estimated Uncertainties (in Percent) in the Evaluated Cross Sections	12

EVALUATED NEUTRON-INTERACTION AND GAMMA-RAY-PRODUCTION CROSS SECTIONS OF ^9Be FOR ENDF/B-IV

MAT NO. 1289

Abstract

The methods used to produce evaluated neutron-interaction and photon-production cross sections for ENDF/B-IV are discussed. This evaluation is identical with the Be evaluation in the Defense Nuclear

Agency working cross section library, MAT 4154. The evaluated neutron-interaction data have been tested by comparing calculated with experimental parameters for appropriate integral experiments.

General Comments

The neutron energy range covered extends from 0.00001 eV to 20 MeV. In addition to elastic scattering, which is everywhere energetically possible, the reactions shown in Table 1 have thresholds at energies less than 20 MeV.¹

For the (n, np), (n, nd), (n, 2t) and (n, nt) reactions, there are no measurements; since the thresholds are sufficiently high, these cross sections are considered negligible. Since ^5He is unstable, decaying to a neutron and an alpha particle with a ground-state half-

life of about 2×10^{-21} sec, the (n, n α) decay mode is a component of the (n, 2n) reaction. The inelastic scattering reaction is also a component of the (n, 2n) reaction, since the $^9\text{Be}^*$ recoil nucleus always decays to a neutron and two alpha particles. The ways in which the cross sections are selected for elastic scattering and for the (n, 2n), (n, p), (n, d), (n, t), (n, α), (n, γ), and (n, X γ) reactions are discussed below. Estimated errors for all reactions over the entire energy range are given in Appendix A.

Elastic Scattering

CROSS SECTION

The free-atom cross section is used for all energies less than the usual upper limit set by the molecular binding energy (about 10 eV). This is effectively only the nuclear part of the cross section for

a stationary target at zero degrees Kelvin. It should be strongly emphasized that these numbers are meaningless in the absence of a proper thermal treatment, either by the processing code or by the neutronics code that uses these numbers.

Table 1. Reactions with thresholds below 20 MeV.

Reaction	Threshold (MeV)
$n, 2n$	1.85
n, p	14.26
n, np	18.76
n, d	16.29
n, nd	18.55
n, t	11.60
n, nt	19.65
$n, 2t$	14.34
n, α	0.67
$n, n\alpha$	2.74
n, γ	exergic

From 0.00001 eV to 0.01 MeV, the scattering cross section was set equal to 6b. From 0.01 MeV to the (n, α) threshold of 0.67 MeV, the scattering cross section is essentially equal to the total cross section, because the (n, γ) cross section is negligible. The total cross section used here was based on the data of Refs. 2 through 6.

Above the (n, α) threshold, the scattering cross section was taken as the dif-

ference between the total and nonelastic cross sections, with the nonelastic cross section set equal to the sum of its parts. From 0.67 to 2 MeV, the evaluated total cross section was based on Refs. 2 through 9. Above 2 MeV, we relied on the results of Ref. 10 for the 2.7 MeV resonance and of Ref. 11 for the energy region up to 15 MeV. The extension to 20 MeV was based on data from Refs. 12 through 14.

ANGULAR DISTRIBUTIONS, NORMALIZED PROBABILITIES

For energies less than 7 MeV, experimental differential scattering data are given in Refs. 15 through 25. These data were used to determine the normalized probabilities. Below the $(n, 2n)$ threshold, the scattering consists only of elastic scattering, since there is no inelastic scattering. We took into account the change in shape of the angular distribution in going through the scattering resonances. At 14 MeV, the probabilities were based on the results of Refs. 26 through 28. A smooth extrapolation was made to 20 MeV. The results are consistent with Wick's limit at all incident energies.

$(n, 2n)$ Reaction

CROSS SECTION

The total $(n, 2n)$ cross section is based on the $(n, 2n)$ cross sections and nonelastic-minus-absorption cross sections listed by Perkins,²⁹ augmented by the more recent $(n, 2n)$ data of Refs. 30 and 31. The nonelastic measurements of Refs. 32 and 33 were also taken into

account. The 20 MeV point was obtained by: (a) interpolating nonelastic cross sections between the 14 MeV value and the value at 25.5 MeV quoted in Ref. 34, and (b) subtracting the other partial nonelastic reaction cross sections from the interpolated nonelastic cross section.

The total $(n, 2n)$ cross section is subdivided into four partial reactions, each

of which is described by the following time-sequential decay:

where the W_i 's are the level excitation energies. The four decay channels used are shown in Table 2.

Table 2. Decay channels for the (n,2n) reaction.

W_9 (MeV)	W_8 (MeV)
1.68	0
2.43	0 (8-1/3% BR)
	2.94 (91-2/3% BR)
6.76	0
11.28	11.4

Note that the ${}^9\text{Be}(9.1 \text{ MeV})$ transition in Ref. 29 has been replaced by ${}^9\text{Be}(11.28 \text{ MeV})$. The branching ratios employed here are essentially the same as those in Ref. 29.

FIRST NEUTRON

For each of the four partial (n, 2n) reactions, the first neutron is described as an inelastic scattering event from a narrow level. This assumption introduces some error into three out of the four reactions, since their levels are in fact wide. The experimental center-of-mass angular distribution of the (n, n') neutron from ${}^9\text{Be}(2.43 \text{ MeV})$ is described by a P_6 Legendre expansion. All other (n, n') neutrons are assumed to be isotropic in their center-of-mass systems. The energy-angle correlation for first neutrons is preserved.

SECOND NEUTRON

The description of the second neutron from each partial reaction neglects the energy-angle correlation. This is a valid approximation for this reaction, as has been discussed previously.³⁵ Most of the levels involved in the time-sequential reaction for the second neutron are wide; their center-of-mass widths are given in Table 3.^{36,37} In obtaining the energy and angular distributions for these second neutrons, the wide levels were described by single-level dispersion theory. The level distributions thus obtained for ${}^9\text{Be}$ and ${}^8\text{Be}$ were subsequently integrated, using the equations in Ref. 29. The integration scheme uses bins of equal probability in excitation energy, and calculations are performed at the average excitation energy within the bin. (This mode of integration appeared to be the most economical one to use in this case.) The effective threshold values for the 6.76 and 11.28 MeV level excitations were assumed to be at incident neutron energies of 7 and 1 MeV,

Table 3. Center-of-mass widths used for second-neutron calculation.

W_9 (MeV)	Γ_9 (MeV)
1.68	0.21
2.43	0
6.76	2
11.28	0.575
W_8 (MeV)	Γ_8 (MeV)
0	0
2.94	1.56
11.4	7

respectively. This allows a better incorporation of the wide-level effects. In these calculations, the center-of-mass angular distribution of the recoiling ^9Be nucleus was required to be consistent with the description of the first neutron mentioned above. The subsequent decay breakup into ^8Be and a neutron was assumed to be isotropic in the $(^9\text{Be}, n)$ center-of-mass system.

Table 4 shows the number of excitation-energy bins used in calculating the $\ell = 0$ Legendre moments of the transference function for second neutrons. The integration scheme with the number of bins indicated here introduces some discontinuities into the output spectra, particularly at low incident neutron energies. An increase in the number of bins, however, does not appear to be economically feasible.

The angular distributions for second neutrons in the laboratory frame-of-reference were obtained from a P_9 Legendre expansion of the transference function. The bottom half of Table 4 shows the number of excitation-energy bins used in these calculations. The Legendre moments from the P_9 Legendre

Table 4. Number of excitation-energy bins used for second-neutron calculations of:

I. $\ell = 0$ Legendre moments of the transference function.

W_9 (MeV)	No. bins	W_8 (MeV)	No. bins
1.68	30	0	N^a
2.43	N^a	2.94	50
6.76	70	11.4	10
11.28	10		

II. Angular distributions in the laboratory frame-of-reference.

W_9 (MeV)	No. bins	W_8 (MeV)	No. bins
1.68	3	0	N^a
2.43	N^a	2.94	5
6.76	7	11.4	5
11.28	5		

^aN means the level was assumed to be narrow.

expansion were integrated over the energy of the second neutron in order to obtain the Legendre coefficients of the lab-system angular distributions, which then led directly to the angular distributions themselves.

Other Reactions

(n, p) CROSS SECTION

This cross section was estimated from the known threshold value and the single measurement at 15.5 MeV given in Ref. 38.

(n, d) CROSS SECTION

This cross section is based in its entirety on the known threshold value

and the data between 16.5 and 18.8 MeV reported in Ref. 39.

(n, t) CROSS SECTION

The cross section for the (n, t) reaction is based on an (n, t_0) and an (n, t_1) component, which proceed through the ground state and 0.477 MeV levels of ^7Li ,

respectively. The total (n, t) cross section near 14 MeV was determined from Refs. 40 and 41. Except for noting the trends of the cross section with energy, the results of Ref. 42 were neglected, due to the large uncertainties in these results.

The (n, t_1) cross section from 13.6 to 14.7 MeV was based on results from Ref. 43. Both in this work and in Ref. 42, the cross section increases with increasing energy near 15 MeV. The measured total cross sections reported in Refs. 12 and 14 show a "bump" in the cross section above 15 MeV. We have assumed here that this total-cross-section bump is due to the (n, t_1) cross section (we could equally well have assumed that it is due to the $(n, 2t)$ cross section, with a threshold at 14.34 MeV, or to statistical fluctuations).

The (n, t_0) cross section was drawn smoothly from zero at threshold to a value at 14 MeV which is the difference between the total (n, t) cross section and the (n, t_1) cross section; above 14 MeV,

the (n, t_0) cross section was decreased smoothly.

(n, α) CROSS SECTION

This cross section was based on the measurements reported in Refs. 42, 44, and 45 for neutron energies less than 8.6 MeV. It was artfully interpolated into the three values given at 14 MeV by Refs. 41, 46, and 47 and then smoothly extrapolated to 20 MeV. Note that the measured cross section is to ${}^6\text{He}(0 \text{ MeV})$, which beta-decays to ${}^6\text{Li}$; for higher states, ${}^6\text{He} \rightarrow \alpha + 2n$.

(n, γ) CROSS SECTION

This cross section was assumed to be inversely proportional to incident neutron speed below 100 eV, with a 2200-m/s cross section of 9.5 mb. It was then extrapolated linearly on a log-log basis to 0.1 mb at 1 keV, and then held constant at this value up to 20 MeV.

$(n, X\gamma)$ Cross Section

Gamma rays in ${}^9\text{Be}$ are produced by the (n, γ) and (n, t) reactions. At thermal energies, Ref. 48 lists the gamma-ray energies as 0.8535, 2.59, 3.368, 3.444, 5.958, and 6.81 MeV, and it gives the corresponding $(n, X\gamma)$ cross sections. The multiplicities and photon spectrum obtained from these data were utilized at an assigned energy of 0.00001 eV. The photon spectrum was assumed to be independent of incident neutron energy. The multiplicity $M(E_0)$, however, varies

with the incident neutron energy E_0 as

$$M(E_0) = M(0)(E_{c-m} + Q_{n, \gamma})/Q_{n, \gamma}$$

where $M(0)$ is the multiplicity at thermal energies, $Q_{n, \gamma}$ is the Q-value for the (n, γ) reaction, and E_{c-m} is the center-of-mass energy

$$E_{c-m} = \left(\frac{A}{A+1} \right) E_0$$

Using this equation, energy is conserved. As the incident neutron energy is increased, there are undoubtedly higher levels of ^{10}Be that are also excited. However, these higher levels and their transitions have been only partially identified. The component relevant to the (n, t_1) cross section is

in fact equal to this cross section (since its multiplicity is unity)

The angular distribution of the gamma rays from the (n, t_1) reaction is isotropic, as reported in Ref. 43. The angular distribution of the capture gamma rays is assumed to be isotropic.

Comparison with Integral Experiments

FAST CRITICAL ASSEMBLIES

The evaluated beryllium cross sections were used in conjunction with the ENDF/B-IV uranium cross sections (^{235}U and ^{238}U) to calculate a series of fast critical assemblies.* The results of the calculations are shown in Table 5. All assemblies were calculated with the 175-group TART Monte Carlo code,⁵³ so that approximations made in using the evaluated data are negligible. The agree-

* ^{238}U was used for the other trace uranium isotopes.

ment between calculated values and the experimental value of unity is good.

LLL PULSED-SPHERE EXPERIMENT

The evaluated beryllium cross sections were also used to calculate the 14-MeV beryllium pulsed-sphere experiment,⁵⁴ the calculation again being performed by the TART code.⁵³ The results are shown in Fig. 1. The conversion from neutron time-of-flight to energy is given in Table 6. The results are in relatively good agreement, except at low energies.

Table 5. Beryllium-reflected critical assemblies of ^{235}U .

Reference	Beryllium thickness (cm)	k	Δk	Median fission energy (MeV)
49	0	1.005	0.003	0.90
50	2.22	0.995	0.003	0.79
50	3.26	0.996	0.003	0.74
50	5.44	0.997	0.003	0.64
50	9.27	0.996	0.003	0.50
51, 52	11.79	0.985	0.004	0.46

Fig. 1. Beryllium 9 - 0.8 M. F. P. - 30 Deg.

Table 6. Relationship between neutron time-of-flight and nominal energy for the ^9Be pulsed sphere.

Time-of-flight (ns)	Energy (MeV)	Time-of-flight (ns)	Energy (MeV)
150	13.7	280	3.9
160	12.0	290	3.6
170	10.6	300	3.4
180	9.5	310	3.2
190	8.5	320	3.0
200	7.7	330	2.8
210	7.0	340	2.6
220	6.3	350	2.5
230	5.8	360	2.35
240	5.3	370	2.25
250	4.9	380	2.1
260	4.5	390	2.0
270	4.2	400	1.9

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Appendix A: Estimated Uncertainties (in Percent) in the Evaluated Cross Sections

	ENDF/B designation			Neutron energy (MeV)										
	MF	MT	Thermal	0.001	0.03	0.1	0.5	1	3	5	10	15	20	
Neutron Cross Sections														
Total	3	1	5	5	5	5	5	5	5	5	5	5	5	5
Elastic	3	2	3	3	3	3	3	10	10	10	10	10	10	20
n, 2n														
Total	-	-	-	-	-	-	-	-	10	10	15	20	40	
First neutron	3	6	-	-	-	-	-	-	20	20	25	30	50	
	3	7	-	-	-	-	-	-	20	20	20	20	50	
	3	8	-	-	-	-	-	-	-	-	30	30	50	
	3	9	-	-	-	-	-	-	-	-	-	36	50	
Second neutron	3	46	-	-	-	-	-	-	20	20	25	30	50	
	3	47	-	-	-	-	-	-	20	20	20	20	50	
	3	48	-	-	-	-	-	-	-	-	30	30	50	
	3	49	-	-	-	-	-	-	-	-	-	30	50	
n, γ	3	102	10	100	100	100	100	100	100	100	100	100	100	
n, p	3	103	-	-	-	-	-	-	-	-	-	-	100	100
n, d	3	104	-	-	-	-	-	-	-	-	-	-	-	25
n, α	3	107	-	-	-	-	-	25	25	25	50	30	100	
n, t ₀	3	740	-	-	-	-	-	-	-	-	-	50	100	
n, t ₁	3	741	-	-	-	-	-	-	-	-	-	25	100	
Neutron energy distribution														
n, 2n														
First neutron	(a)	(a)							(a)	(a)	(a)	(a)	(a)	
Second neutron	5	46	-	-	-	-	-	-	20	20	20	20	20	
	5	47	-	-	-	-	-	-	20	20	20	20	20	
	5	48	-	-	-	-	-	-	-	-	20	20	20	
	5	49	-	-	-	-	-	-	-	-	-	20	20	
Neutron angular distribution														
n, 2n														
First neutron	4	6	-	-	-	-	-	-	20	20	20	30	50	
	4	7	-	-	-	-	-	-	20	20	20	20	50	
	4	8	-	-	-	-	-	-	-	-	30	30	50	
	4	9	-	-	-	-	-	-	-	-	-	30	50	
n, 2n														
Second neutron	4	46	-	-	-	-	-	-	20	20	20	20	50	
	4	47	-	-	-	-	-	-	20	20	20	20	50	
	4	48	-	-	-	-	-	-	-	-	20	20	50	
	4	49	-	-	-	-	-	-	-	-	-	20	50	
Photon production														
Cross section														
n, X γ	12	102 741	10	100	100	100	100	100	100	100	100	25	100	
Energy distribution														
n, X γ	15	102	20	50	50	50	50	50	50	50	50	20	50	
	15	741	-	-	-	-	-	-	-	-	-	3	3	
Angular distribution														
n, X γ	14	102	0	10	10	20	20	20	20	20	20	20	20	
	14	741	-	-	-	-	-	-	-	-	-	20	20	

(a) States are required to be sharp by the current ENDF/B format.
In fact, these discrete states have widths of MeV's.