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**EVALUATED NEUTRON-INTERACTION AND GAMMA-RAY
PRODUCTION CROSS SECTIONS OF ^9Be FOR THE DEFENSE
NUCLEAR AGENCY WORKING CROSS-SECTION LIBRARY
MAT NO. 4154**

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Abstract

The methods used to produce evaluated neutron-interaction and photon-production cross sections for the DNA library are discussed. This evaluation is identical with ENDF/B-III MAT 1154 except for the $(n, X\gamma)$ cross sections associated with the

(n, γ) reaction and the energy range which starts at 0.00001 eV. The evaluated neutron-interaction data have been tested by comparison of calculated with experimental parameters of 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 following reactions have thresholds¹ at energies less than 20 MeV:

<u>Reaction</u>	<u>Threshold (MeV)</u>
$n, 2n$	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, α	0.67
$n, n\alpha$	2.74
n, γ	exoergic

For the (n, np) , (n, nd) , and (n, nt) reactions, there are no measurements, and, since the thresholds are sufficiently high, these cross sections are considered negligible. The $(n, n\alpha)$ reaction is a decay mode for the $(n, 2n)$ reaction, 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 inelastic scattering reaction is also a decay mode for the $(n, 2n)$ reaction, since the $^9\text{Be}^*$ recoil nucleus always decays to a neutron and two alpha particles. The way in which the cross sections are selected for elastic scattering and the $(n, 2n)$, (n, p) , (n, d) , (n, t) , (n, α) , (n, γ) , and $(n, X\gamma)$ reactions is discussed below.

*DNA Subtask Code W99QAXPC102.

Elastic Scattering

CROSS SECTION

The free-atom cross section is used for all energies below the usual upper limit of the molecular binding energy (about 10 eV). This is effectively only the nuclear part of the cross section of a stationary target at zero degrees Kelvin. It is strongly emphasized that the numbers are meaningless in the absence of a proper thermal treatment by either the processing code or the neutronics code which uses these numbers.

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

Above the (n,α) threshold, the scattering cross section was taken as the difference between the total and the nonelastic, with the nonelastic being 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 this energy, we relied on the results of Ref. 10 over the 2.7 MeV resonance and of Ref. 11 up

to 15 MeV. The extension to 20 MeV was based on data from Refs. 12 through 14. The uncertainty in the cross section is about $\pm 3\%$ below the (n,α) threshold, varying up to $\pm 10\%$ at 14 MeV and $\pm 20\%$ at 20 MeV.

ANGULAR DISTRIBUTIONS, NORMALIZED PROBABILITIES

For energies less than 7 MeV, experimental differential scattering data are presented in Refs. 15 through 25. These data were used to determine the normalized probabilities. Below the $(n,2n)$ threshold, total scattering data are made up of only elastic scattering, since there is no inelastic scattering. The change in shape of the angular distribution going through the scattering resonances was taken into account. 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. The angular distributions are probably accurate to $\pm 10\%$ for energies less than or equal to 14 MeV. For energies from about 15 to 20 MeV the uncertainty increases with increasing energy and is estimated to be about $\pm 30\%$ at 20 MeV.

$(n,2n)$ Reaction

CROSS SECTION

The $(n,2n)$ cross section is based on the $(n,2n)$ cross sections and nonelastic minus absorption cross sections referenced in Perkins' work,²⁹ as well as the

new $(n,2n)$ data up to 6.4 MeV given in Ref. 30. The nonelastic results of Ref. 31 appear too large and were not used. The 20-MeV point was based on interpolating nonelastic cross sections between the 14 MeV value and the value

at 25.5 MeV quoted in Ref. 32. Below 6.4 MeV, the cross section is probably accurate to $\pm 10\%$. At 14 MeV, however, it is much worse, the uncertainty being in the range of $\pm 20\%$, and at 20 MeV about $\pm 40\%$.

ENERGY DISTRIBUTIONS, NORMALIZED PROBABILITIES

The $l = 0$ Legendre moment of the transference function has been taken from the work of Perkins.^{29,33} Briefly, this treated the $(n,2n)$ reaction as a series of time-sequential decays, ${}^9\text{Be}(n,n_1){}^9\text{Be}^*(n_2){}^8\text{Be}^*$. Levels excited were at 1.7, 2.43, 6.76, and 9.1 MeV in ${}^9\text{Be}^*$, and 0, 2.90, and 11.4 MeV in ${}^8\text{Be}^*$. The experimental center-of-mass angular distribution of the inelastically scattered neutron from ${}^9\text{Be}^*$ (2.43 MeV) was described by a P_6 Legendre expansion. All other reactions were considered to be isotropic in their respective center-of-mass systems.

The calculation was performed with the AGN-SIGMA³⁴ multigroup code with 66 groups. Lethargy widths were 0.2 for energies above 10 MeV and 0.25 for energies below 10 MeV. This introduces a spread in the emergent spectra due to the finite group widths. The threshold spec-

trum was taken to equal that at 2 MeV, although modified so as not to violate energy conservation. Similarly, the 20-MeV spectrum was taken to equal that at 14.6 MeV. The energy distributions are probably accurate to $\pm 25\%$.

ANGULAR DISTRIBUTIONS, NORMALIZED PROBABILITIES

The lab-system angular distributions were obtained by appropriately summing the partial distributions of Perkins.³³ The threshold distribution is essentially in the forward direction.

The distributions at 2 and 2.5 MeV were taken to equal that at 3 MeV; those at 5.5 and 7 MeV were taken to equal that at 4 MeV; those at 9 and 11 MeV were taken to equal that at 12 MeV; and that at 20 MeV was taken to equal that at 14.6 MeV. The accuracy of the angular distributions is probably no better than $\pm 20\%$.

The angular distributions, used in conjunction with the $(n,2n)$ energy distributions, neglect the energy-angle correlation. This is a valid approximation for this reaction for reactor calculations, as has been discussed previously.³⁵

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. 36. The accuracy of this small cross section is probably within a factor of 2.

(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. 37. The accuracy is about $\pm 25\%$ for this cross section.

(n,t) CROSS SECTION

The cross section for the (n,t) reaction is based on the assumption that all transitions proceed through ${}^7\text{Li}^*$ (0.477 MeV). This is in agreement with the results of Refs. 38 and 39 but in total disagreement with the data from Ref. 40. The uncertainties in this latter reference, however, are large enough so that the work may be neglected.

The cross section was based on the work in Ref. 41 from 13.6 to 14.7 MeV. Above this energy, there is a resonance structure seen in the total cross section reported in Refs. 12 and 14. This was assumed to be due to the (n,t) reaction and is not in conflict with the rapid increase in the cross section above 14.5 MeV seen in Ref. 41. The uncertainty in the cross section is about $\pm 50\%$ at 14 MeV, increasing several times at higher energies.

(n, α) CROSS SECTION

This cross section was based on the measurements reported in Refs. 40, 42,

and 43 for neutron energies less than 8.6 MeV. It was artfully interpolated into the three values given at 14 MeV by Refs. 39, 44, and 45 and then smoothly extrapolated to 20 MeV. Note that the measured cross section is to ${}^6\text{He}$ (0 MeV), which beta decays to ${}^6\text{Li}$; for higher states, ${}^6\text{He} \rightarrow \alpha + 2n$. Below 8.6 MeV the uncertainty is about $\pm 25\%$, from 8.6 to 14 MeV it is at least $\pm 50\%$, and at 14 MeV it is about $\pm 30\%$. For higher energies the uncertainty probably reaches a factor of two at 20 MeV.

(n, γ) CROSS SECTION

This cross section was assumed to be $1/v$ below 100 eV with a 2200-m/sec 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. Except at thermal energies, where the cross section is known to $\pm 10\%$, the uncertainty is at least $\pm 100\%$. Fortunately, the cross section is small.

(n, $X\gamma$) Cross Section

Gamma rays in ${}^9\text{Be}$ are produced by the (n, γ) and the (n,t) reactions. At thermal energies, Ref. 46 quotes gamma-ray energies of 0.8535, 2.59, 3.368, 3.444, 5.958, and 6.81 MeV and the corresponding (n, $X\gamma$) cross sections. The multiplicities and photon spectrum obtained from these data were utilized at 0.00001 eV. The photon spectrum was taken as independent of incident neutron energy. The multiplicity, however, varied with incident neutron

energy as $M(E_0) = M(0)(E_{cm} + Q_{n,\gamma})/Q_{n,\gamma}$, where $M(0)$ is the multiplicity at thermal energies, $Q_{n,\gamma}$ is the Q-value for the (n, γ) reaction, and E_{cm} is the center-of-mass energy, i.e.,

$$\left(\frac{A}{A+1}\right)E_0.$$

Thus, energy was preserved. As the incident neutron energy is increased, there are, no doubt, higher levels of ${}^{10}\text{Be}$ that

are excited. Higher levels and their transitions, however, have been only partially identified. The component relevant to the (n, t) cross section is in fact equal to the (n, t) cross section, since its multiplicity is unity. At

thermal energy, the cross section is accurate to about $\pm 10\%$. At higher energies, the photon energies are not known and the cross section could be off by orders of magnitude. The cross section is small, however.

Comparison with Integral Experiments

FAST CRITICAL ASSEMBLIES

The evaluated beryllium cross sections have been used in conjunction with the DNA uranium cross sections (^{235}U , MAT 4188; ^{238}U , MAT 4187) to calculate a series of fast critical assemblies.* The results of the calculations are shown in Table 1. All assemblies were calculated with the 175-group TART Monte Carlo code⁵¹ so that approximations made to the evaluated data were negligible. The agreement between the calculation and the experimental value of unity is good.

* Cross sections for the other trace isotopes came from the LLL Evaluated Library.

Fig. 1. Comparison of calculation (continuous line) with experiment (denoted by E's) for the 0.8-m.f.p. ^9Be pulsed sphere.

Table 1. ^{235}U beryllium-reflected critical assemblies.

Reference	Beryllium thickness (cm)	k	Δk	Median fission energy (MeV)
47	0	1.000	0.003	0.78
48	2.22	0.998	0.003	0.67
48	3.26	0.996	0.003	0.63
49,50	4.70	0.997	0.003	0.58
48	5.44	0.997	0.003	0.55
48	9.27	0.998	0.003	0.44
49,50	11.79	0.990	0.004	0.41
48	20.27	0.990	0.005	0.33

LLL PULSED-SPHERE EXPERIMENT

The evaluated beryllium cross sections were also used to calculate the 14-MeV beryllium pulsed-sphere experiment,⁵²

the calculation again being performed by the TART code.⁵¹ The results are shown in Fig. 1. The conversion of neutron time of flight to energy is given in Table 2. The results are in relatively good agreement, except at low energies.

Table 2. Relationship between neutron time of flight and nominal energy for the ⁹Be pulsed sphere.

Time of flight (nsec)	Energy (MeV)	Time of flight (nsec)	Energy (MeV)
50	13.7	180	3.9
60	12.0	190	3.6
70	10.6	200	3.4
80	9.5	210	3.2
90	8.5	220	3.0
100	7.7	230	2.8
110	7.0	240	2.6
120	6.3	250	2.5
130	5.8	260	2.35
140	5.3	270	2.25
150	4.9	280	2.1
160	4.5	290	2.0
170	4.2	300	1.9

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