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LAWRENCE LIVERMORE LABORATORY

University of California/Livermore, California

EVALUATED NEUTRON INTERACTION AND GAMMA-RAY PRODUCTION

CROSS SECTIONS OF BE⁹ FOR ENDF/B-III

MAT NO. 1154

R. J. Howerton

S. T. Perkins

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Abstract

The methods used to produce evaluated neutron interaction and photon production cross sections for Version III of ENDF/B are discussed.

I. GENERAL COMMENTS

The neutron energy range covered extends from 0.0001 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 α	2.74
n, γ	exoergic

^{*} This work was performed under the auspices of the U. S. Atomic Energy Commission.

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 α) reaction is a decay mode for the (n,2n) reaction since He⁵ is unstable, decaying to a neutron and an alpha particle with a half-life of about 2×10^{-21} seconds. The inelastic scattering reaction is also a decay mode for the (n,2n) reaction since the Be^{9*} recoil nucleus always decays to a neutron and two alpha particles. The way in which the cross sections are selected for elastic scattering, (n,2n), (n,p), (n,d), (n,t), (n, α), (n, γ), and (n,X γ) reactions is discussed below.

II. ELASTIC SCATTERING

A. 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 equal to 6 barns from 0.0001 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 .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 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.

B. 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 30% at 20 MeV.

III. (n,2n) REACTION

A. 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 +10%. At 14 MeV, however, it is much worse, the uncertainty being in the range of +20%, and at 20 MeV about 40%.

B. 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, $\text{Be}^9(n, n_1)\text{Be}^{9*}(n_2)\text{Be}^{8*}$. Levels excited were at 2.43, 6.76 and 9.1 MeV in Be^{9*} , and 0., 2.90 and 11.4 MeV in Be^{8*} . The experimental center of mass angular distribution of the inelastically scattered neutron from Be^{9*} (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 spectrum was taken equal to that at 2 MeV, although modified so as not to violate energy conservation. Similarly, the 20 MeV spectrum

was taken equal to that at 14.6 MeV. The energy distributions are probably accurate to +25%.

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

IV. OTHER REACTIONS

A. (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.

B. (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 +25% for this cross section.

C. (n,t) Cross Section

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

The cross section was based on the work in Ref. 41, from 13.6 - 14.7 MeV. Above this energy, there is a resonance structure seen in the total cross section reported in Ref. 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 by Ref. 41. The uncertainty in the cross section is about +50% at 14 MeV, increasing several times at higher energies.

D. (n, α) Cross Section

The cross section was based on the measurements reported in Ref. 42, 40 and 43 for neutron energies less than 8.6 MeV. It was then artfully interpolated into the three values given at 14 MeV, Refs. 44, 39 and 45, and then smoothly extrapolated to 20. MeV. Note that the measured cross section is to He^6 (0. MeV) which beta decays to Li^6 ; higher states in $\text{He}^6 \rightarrow \alpha + 2n$. Below 8.6 MeV, the uncertainty is about +25%, from 8.6 to 14 MeV being at least +50%, and being about +30% at 14 MeV. For higher energies the uncertainty probably reaches a factor of two at 20 MeV.

E. (n, γ) Cross Section

The 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 where the cross section is known to $\pm 10\%$, the uncertainty is at least $\pm 100\%$. Fortunately, the cross section is small.

V. (n, γ) CROSS SECTION

Gamma rays in Be^9 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, γ) cross sections. We have assumed that these energies and their multiplicities are independent of energy, and have used them in conjunction with our (n, γ) cross section to develop this component of the (n, γ) cross section. This violates energy conservation as the incident neutron energy is increased. We intentionally used this approach to call attention to the paucity of information. As the incident energy is increased, there are, no doubt, higher levels of ^{10}Be which are excited. Higher levels have not been identified. We could have conserved energy by using energy dependent multiplicities. We chose to emphasize the problem by the presentation used. 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 sections is however small.

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