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Neutron-Photon Multigroup Cross Sections for Neutron Energies ≤400 MEV

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NEUTRON-PHOTON MULTIGROUP CROSS SECTIONS FOR NEUTRON ENERGIES ≤400 MEV*

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ABSTRACT

Multigroup cross sections (66 neutron groups and 21 gamma ray groups) are described for neutron energies from thermal to 400 MeV. The elements considered are hydrogen, ^{10}B, ^{11}B, carbon, nitrogen, oxygen, sodium, magnesium, aluminum, silicon, sulfur, potassium, calcium, chromium, iron, nickel, tungsten and lead. These cross sections are available from the Radiation Shielding Information Center of the Oak Ridge National Laboratory.

I. INTRODUCTION

For a variety of applications, e.g., accelerator shielding,[1] the use of neutrons in radiotherapy,[2] radiation damage studies,[3] etc., it is necessary to carry out transport calculations involving medium-energy ($\gtrsim$20 MeV) neutrons. In a previous paper[4] neutron-photon multigroup cross sections in ANISN[5] format for neutron energies from thermal to 60 MeV were presented. In the present paper similar multigroup cross sections are presented for several additional elements and the energy range of the cross section for all elements considered (hydrogen, ^{10}B, ^{11}B, carbon, nitrogen, oxygen, sodium, magnesium, aluminum, silicon, sulfur, potassium, chromium, iron, nickel, tungsten and lead) is extended to 400 MeV.

At the higher energies considered here, medium-energy protons are produced. When the cross section data described here are used in transport calculations the neutron that will be produced by these medium-energy protons is not included and thus an approximation is being made. The validity of this approximation is considered in Ref. 6.

Below 14.9 MeV the cross sections are from the Radiation Shielding Information Center's fusion energy cross section library.[7] Above this energy differential elastic cross section data from optical model calculations are used and differential nonelastic cross section data from the intranuclear-cascade-evaporation model are used. A P_5 Legendre expansion is used at energies >14.9 MeV and a P_3 Legendre expansion is used at energies $\leq$14.9 MeV. Here, as in Ref. 4, it is assumed that photon production may be neglected from neutron-nucleus collisions at energies $\geq$14.9 MeV. The validity of this approximation is discussed in

Ref. 8. In the case of tungsten and lead, elastic scattering is neglected at energies ⩾14.9 MeV.

The cross section data described here are available from the Radiation Shielding Information Center of the Oak Ridge National Laboratory.

II. CROSS SECTION CALCULATIONS

For neutron energies ⩽60 MeV and those elements considered in Ref. 4, the cross sections described here are the same as those presented in Ref. 4. For neutron energies ⩽60 MeV and those elements considered here, but not included in Ref. 4 the procedures used to obtain the cross section data are described in Section II.A. Finally, after the data for all elements considered has been determined for neutron energies ⩽60 MeV the extension of these data to 400 MeV is described in Section II.B.

II.A Neutron Energies ⩽60 MeV and Elements Nitrogen, Sodium, Magnesium, Aluminum, Sulfur, Tungsten and Lead

The neutron multigroup cross sections for neutron energies ⩽14.9 MeV are taken from the fusion energy library of the Radiation Shielding Information Center (RSIC) and is based on ENDF/B-IV data.[7] For use here 35 neutron group, 21 gamma ray group cross sections were obtained by collapsing the 171 neutron group, 36 gamma ray group cross sections in the RSIC fusion energy library were used.* The cross sections used

*Private communication, R. T. Santoro, Oak Ridge National Laboratory (1978).

here correspond to 300K and infinite dilution. The fusion energy library uses a P_3 Legendre expansion at energies ≤14.9 MeV so that is what is used here.

The differential elastic scattering cross section for neutron-nucleus collisions were obtained from the optical model code, GENOA.* Two different sets of optical model parameters, due to Bercchetti and Greenless[9] (BG) and to Wilmore and Hodgson[10] (WH) are available. The BG parameters are intended for use with A>40 and the WH parameters are primarily intended for energies ≤15 MeV, so neither set of parameters is appropriate for all of the elements and energies of interest here. The actual choice of parameters used is specified below. The optical model provides not only the differential elastic scattering cross section, but also gives the total nonelastic cross section as a function of energy. These nonelastic cross sections have been used as described below.

The differential neutron production cross section from neutron-nucleus nonelastic collisions at energies ≥14.9 MeV were obtained from the intranuclear-cascade-evaporation model of nuclear reactions as implemented by Bertini.[11,12,13] Differential neutron production data from the intranuclear-cascade-evaporation model have been fitted and it is these analytic fits that are used here.[14] The intranuclear-cascade-evaporation model provides an estimate of the total energy of the photons produced by nuclear reactions, but not the photon spectrum. Here, the assumption is made, as in Ref. 4, that photons produced by neutron-

*F. G. Perey, private communication, Oak Ridge National Laboratory (1977).

nucleus nonelastic collisions at energies $\geqslant$14.9 MeV may be neglected. The validity of this approximation is discussed in Ref. 8.

The total, elastic, and nonelastic cross sections for neutrons incident on nitrogen, sodium, aluminum, magnesium, sulfur and potassium are shown as a function of energy (<100 MeV) in Figs. 1, 2 and 3, respectively. The results in the figures below 60 MeV are discussed in this section; the higher energy results will be discussed in Section II.B. In the figures, results obtained with both the BG and WH optical model parameters are given. In Fig. 3 the nonelastic cross section given by the intranuclear-cascade-evaporation model as well as by optical model are shown. In Figs. 1 to 3 the histogram values between 13.5 and 14.9 MeV are the data from the fusion energy library of the Radiation Shielding Information Center.[7] In Fig. 1 the experimental data for the total cross section in nitrogen and magnesium are from Ref. 15, and in aluminum are from the work of D. C. Larson et al.* The dashed lines in the figures indicate the cross section values that were used in the cross section compilation discussed here.

For the elements shown in Fig. 2 the angular distribution of elastically scattered neutrons (normalized in unity) were, as in Ref. 4, taken from the optical model using WH parameters for E$\leqslant$25 MeV and BG parameters for E$>$25 MeV. The optical model gives the angular distributions of scattered neutrons in the center-of-mass system. These angular

*D. C.Larson, private communication, Oak Ridge National Laboratory (1980). See also Ref. 16.

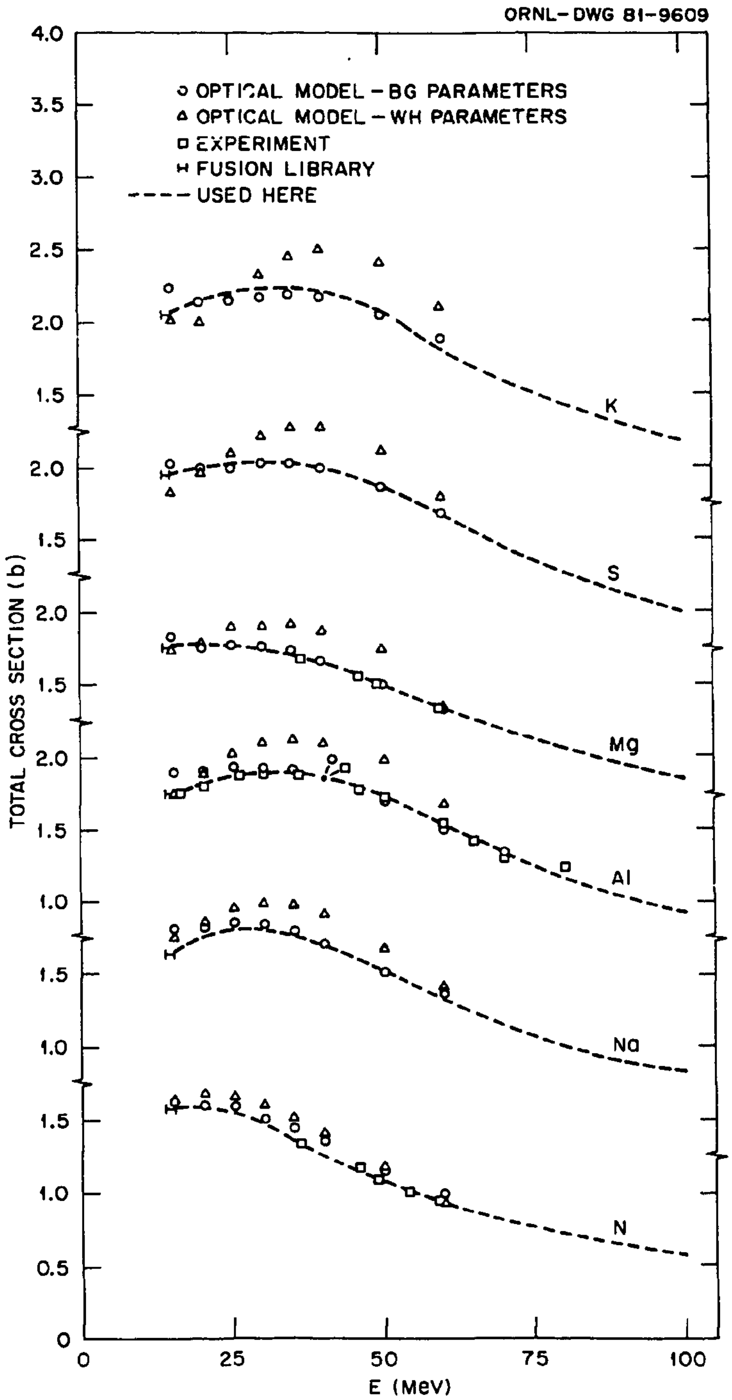

Fig. 1. Total cross section vs incident neutron energy for several elements.

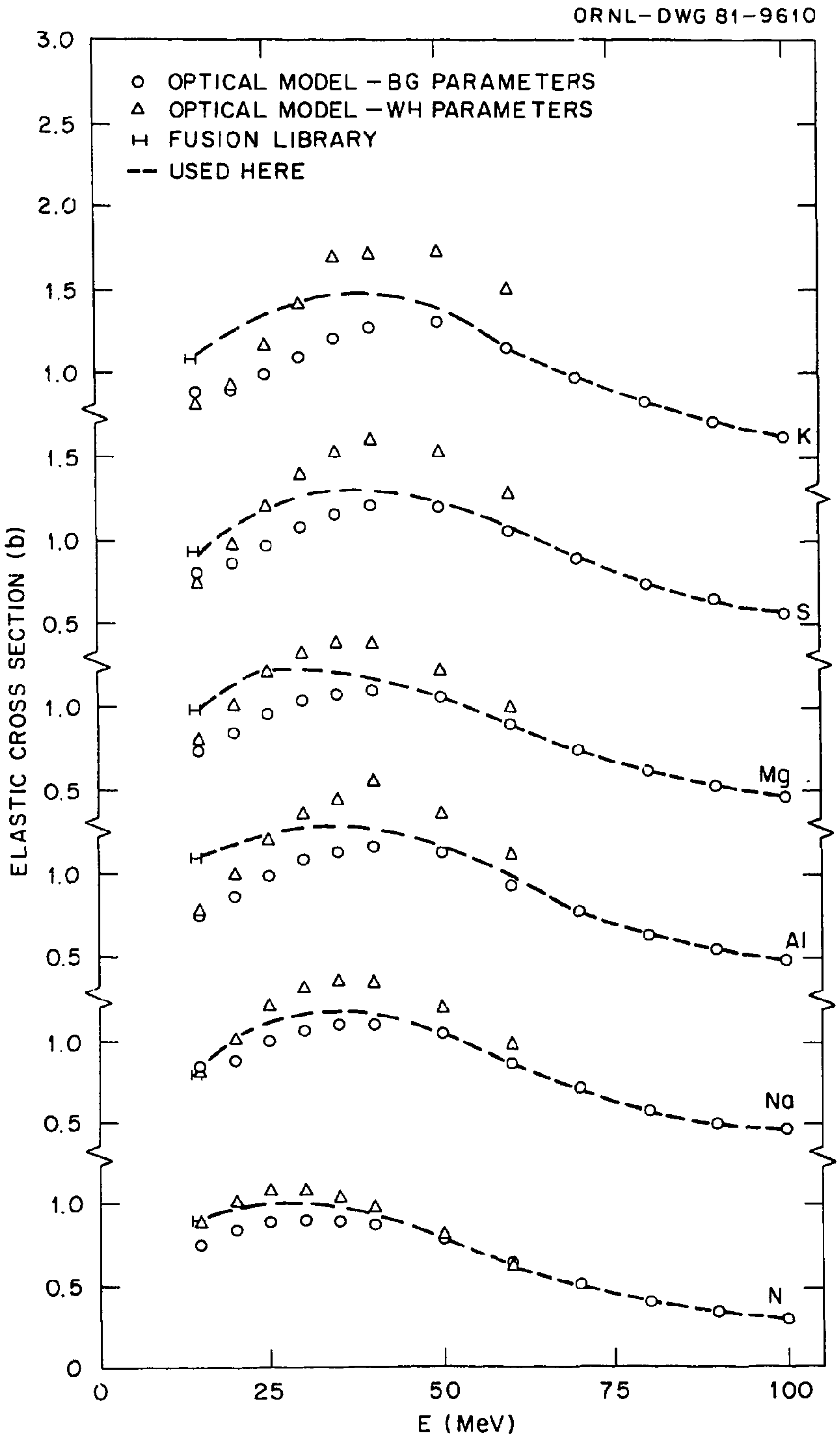

Fig. 2. Elastic cross section vs incident neutron energy for several elements.

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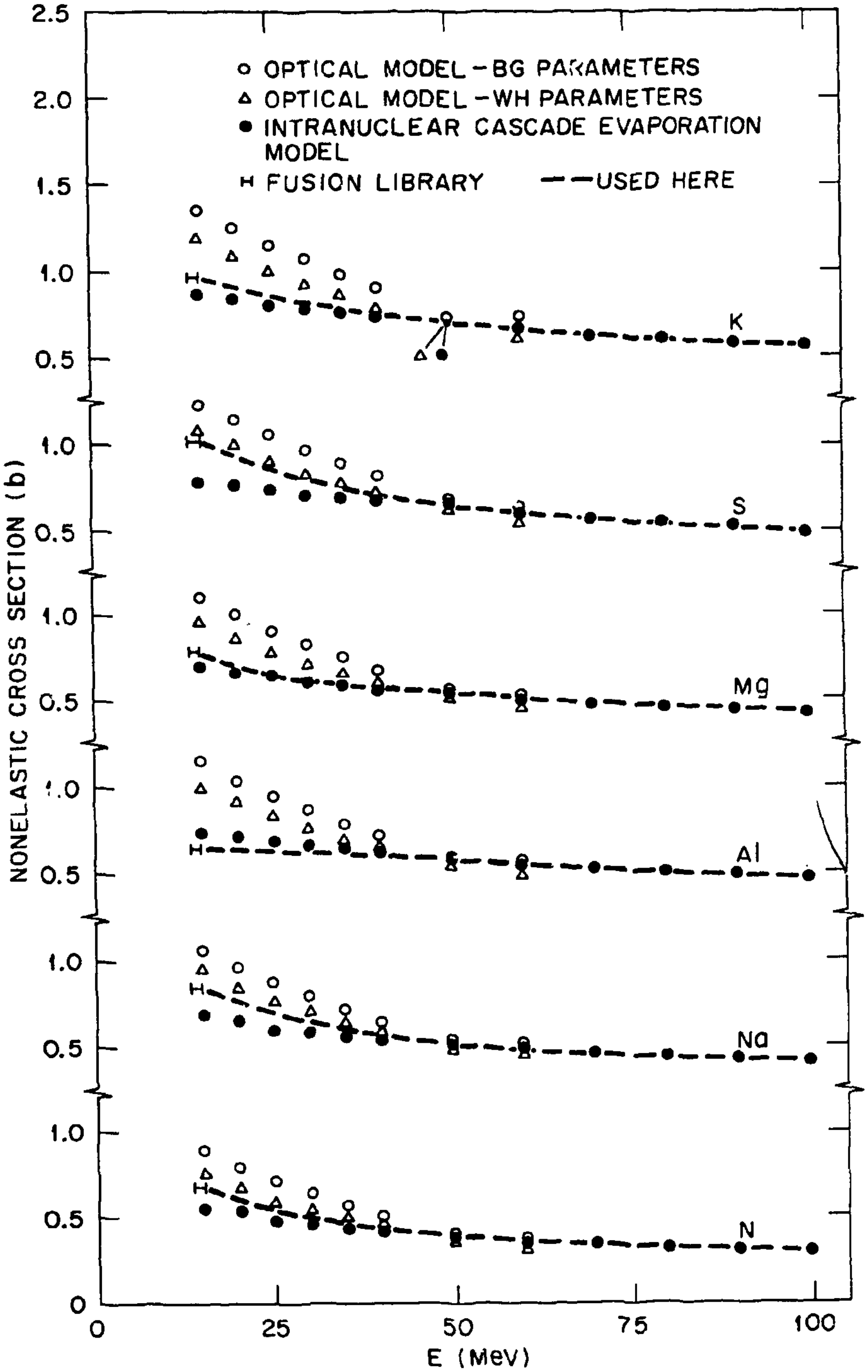

Fig. 3. Nonelastic cross section vs incident neutron energy for several elements.

distributions (not their Legendre expansion) are used here and are transformed to the laboratory system in the standard (relativistic) manner. The energy-angle distributions of neutrons from neutron-nucleus nonelastic collisions were obtained from Ref. 14. In Ref. 14 the analytic fits are averaged over the angular intervals 0 to 30°, 30° to 60°, 60° to 90°, and 90° to 180°. To obtain the Legendre expansions of these angular distributions they were assumed to be constant in the above intervals.*

In Fig. 4 the nonelastic cross section for tungsten and lead is shown as a function of energy. Results from the optical model with both WH and BG parameters and from the intranuclear-cascade-evaporation model are shown. Also shown are the histogram values (13.5 to 14.9 MeV) from the fusion energy library. Tungsten and lead are treated differently here than the other elements because of their large A. For these elements the angular distribution of elastic scattering is very forward and can not be approximated at all well by a P_5 Legendre expansion in the laboratory system. Thus, for these elements elastic scattering at energies ⩾14.9 MeV has been neglected. For some purposes this may not be a valid approximation and thus the cross sections for tungsten and lead are given with the understanding that they may not always be applicable.

The dashed line in Fig. 4 indicates the nonelastic cross section used in the compilation. The energy-angle distributions of neutrons from neutron-nucleus nonelastic collisions were taken from Ref. 14.

*Some estimates of the validity of this approximation are given in Ref. 6.

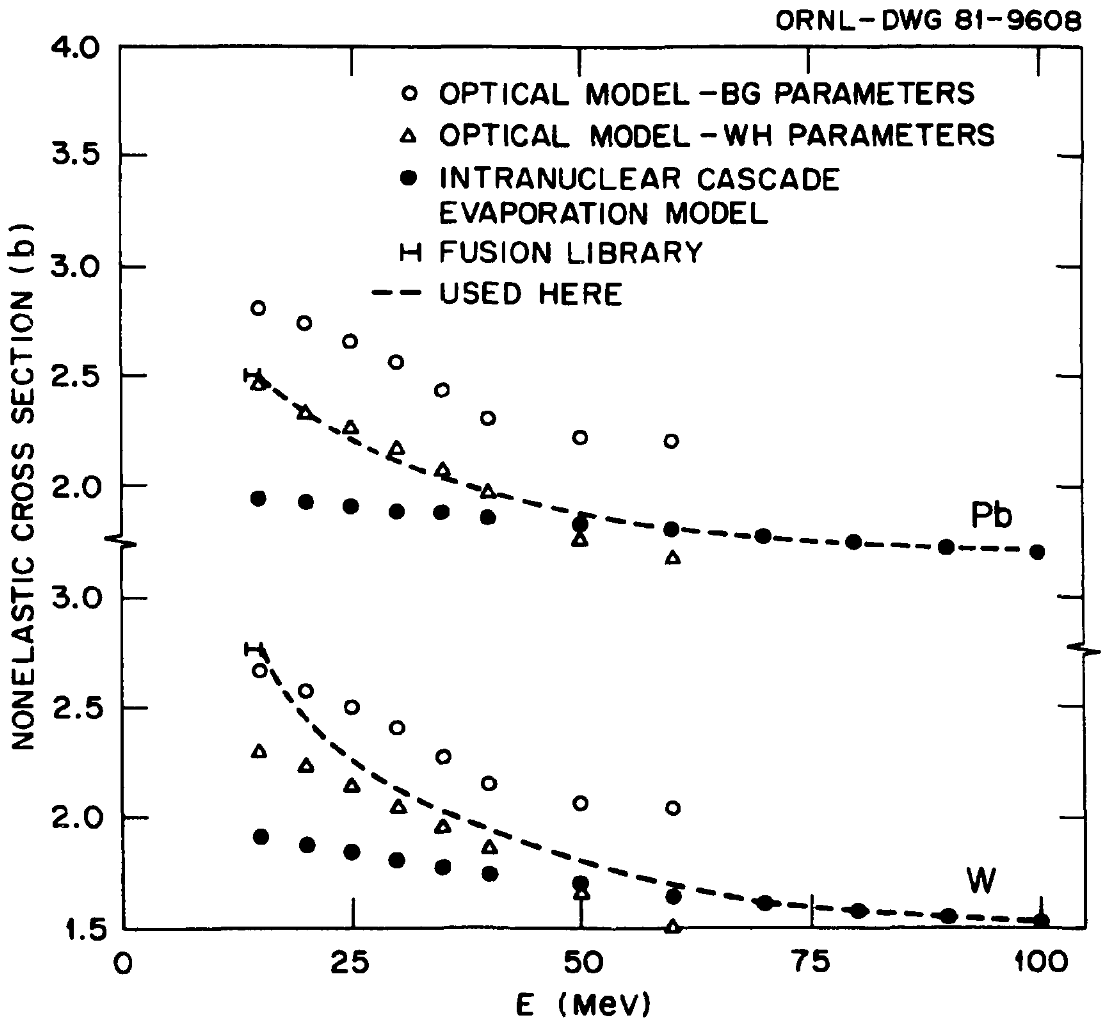

Fig. 4. Nonelastic cross section vs incident neutron energy for tungsten and lead.

II.B Neutron Energies >60 MeV and ≤400 MeV

For neutron energies >60 MeV the cross sections are obtained by a straightforward extension oт the methods used at the lower enegies.

The differential cross section for neutron-hydrogen collisions is well established experimentally and the analytic fits to the experimental differential cross section data given by Bertini[11] has been used.

For all elements considered other than hydrogen, ^{10}B, ^{11}B, tungsten and lead, the differential elastic cross section has been obtained from the optical model using BG parameters and the nonelastic cross section as well as the energy-angle distributions of produced neutrons has been obtained from Ref. 14. Nonelastic cross section information for ^{10}B and ^{11}B is not available from the intranuclear-cascade-evaporation model so the optical model nonelastic cross section obtained with BG parameter has been used. The energy-angle distribution of neutrons from nonelastic neutron-nucleus collisions for ^{10}B and ^{11}B was taken to be that for carbon, but mutiplied by $\left(\frac{10}{12}\right)^{2/3}$ and $\left(\frac{11}{12}\right)^{2/3}$, respectively. Elastic scattering from tungsten and lead was neglected as before.

In Figs. 1 to 3 the total elastic and nonelastic cross sections used in the compilations is shown for a few elements at energies between 60 and 100 MeV. In Table 1 the elastic and nonelastic cross sections used in the compilation for all elements, other than hydrogen, are shown for energies between 60 and 400 MeV.

III. MULTIGROUP CROSS SECTIONS

With the cross section data specified in Sections II.A and II.B, multigroup cross sections in the form needed for use in the discrete

Table 1

Elastic and Nonelastic Neutron-Nucleus Cross Sections (b) at Neutron Energies >60 MeV

Element	60	80	100	150	200	300	400
	Energy (MeV)						
^{10}B	0.50*	0.31	0.22	0.14	0.16	0.23	0.30
	0.30	0.32	0.33	0.36	0.38	0.41	0.43
^{11}B	0.49	0.31	0.22	0.15	0.18	0.18	0.26
	0.31	0.33	0.35	0.38	0.40	0.40	0.43
Carbon	0.50	0.37	0.25	0.17	0.19	0.27	0.34
	0.33	0.29	0.26	0.23	0.22	0.22	0.22
Nitrogen	0.63	0.40	0.28	0.19	0.21	0.30	0.38
	0.36	0.32	0.29	0.26	0.25	0.24	0.25
Oxygen	0.68	0.44	0.31	0.22	0.24	0.33	0.41
	0.40	0.35	0.33	0.29	0.28	0.27	0.28
Sodium	0.84	0.56	0.40	0.29	0.32	0.43	0.52
	0.49	0.44	0.41	0.36	0.35	0.35	0.35
Magnesium	0.88	0.60	0.43	0.30	0.33	0.44	0.53
	0.50	0.46	0.42	0.38	0.36	0.36	0.36
Aluminum	0.93	0.63	0.46	0.33	0.36	0.48	0.57
	0.55	0.50	0.47	0.41	0.40	0.41	0.40
Silicon	1.01	0.67	0.48	0.34	0.37	0.49	0.58
	0.56	0.51	0.47	0.42	0.40	0.41	0.41
Sulfur	1.04	0.73	0.54	0.38	0.41	0.54	0.64
	0.60	0.54	0.51	0.45	0.45	0.45	0.44
Potassium	1.15	0.82	0.61	0.44	0.48	0.62	0.72
	0.66	0.61	0.57	0.51	0.50	0.50	0.50
Calcium	1.17	0.85	0.63	0.46	0.49	0.63	0.73
	0.67	0.62	0.58	0.52	0.51	0.51	0.51
Chromium	1.30	0.96	0.73	0.56	0.61	0.76	0.87
	0.80	0.74	0.70	0.65	0.64	0.64	0.63

Table 1 (Cont'd)

	Energy (MeV)						
Element	60	80	100	150	200	300	400
Iron	1.34 0.83	1.01 0.77	0.78 0.73	0.59 0.68	0.64 0.66	0.80 0.66	0.91 0.66
Nickel	1.38 0.84	1.05 0.78	0.81 0.74	0.61 0.69	0.66 0.68	0.82 0.68	0.92 0.68
Tungsten+	1.66	1.58	1.53	1.46	1.45	1.50	1.48
Lead+	1.80	1.75	1.70	1.61	1.56	1.53	1.61

*For each element the elastic cross section is given on the first line and the nonelastic cross section is given on the second line.

+Elastic scattering is neglected.

ordinates codes ANISN[5] AND DOT[18] and in the Monte Carlo code MORSE[19] may be calculated in a straightforward manner. A weighting function of "$\frac{1}{E}$" has, somewhat arbitrarily, been used for neutron energies ≥14.9 MeV. The neutron and photon energy group structure at energies ≤60 MeV is that used in Ref. 4. The neutron group structure at all energies is shown in Table 2.

Transport calculations using the cross sections described here will not be presented, but the interested reader will find an example of transport results obtained using these cross sections in Ref. 1.

Table 2

Energy Group Structure

Neutron Groups			
Upper Group Energy (MeV)	Lower Group Energy (MeV)	Upper Group Energy (MeV)	Lower Group Energy (MeV)
400	375	22.5	20.0
375	350	20.0	17.5
350	325	17.5	14.9
325	300	14.9	13.5
300	275	13.5	12.2
275	250	12.2	10.0
250	225	10.0	8.19
225	200	8.19	6.70
200	180	6.70	5.49
180	160	5.49	4.49
160	140	4.49	3.68
140	120	3.68	3.01
120	110	3.01	2.46
110	100	2.46	2.02
100	90	2.02	1.65
90	80	1.65	1.35
80	70	1.35	1.11
70	65	1.11	$9.07 \cdot 10^{-1}$
65	60	$9.07 \cdot 10^{-1}$	$7.43 \cdot 10^{-1}$
60	55	$7.43 \cdot 10^{-1}$	$4.98 \cdot 10^{-1}$
55	50	$4.98 \cdot 10^{-1}$	$3.34 \cdot 10^{-1}$
50	45	$3.34 \cdot 10^{-1}$	$2.24 \cdot 10^{-1}$
45	40	$2.24 \cdot 10^{-1}$	$1.50 \cdot 10^{-1}$
40	35	$1.50 \cdot 10^{-1}$	$8.65 \cdot 10^{-2}$
35	30	$8.65 \cdot 10^{-2}$	$3.18 \cdot 10^{-2}$
30	27.5	$3.18 \cdot 10^{-2}$	$1.50 \cdot 10^{-2}$
27.5	25.0	$1.50 \cdot 10^{-2}$	$7.10 \cdot 10^{-3}$
25.0	22.5	$7.10 \cdot 10^{-3}$	$3.35 \cdot 10^{-3}$

Table 2 (Cont'd)

Neutron Groups		Photon Groups	
Upper Group Energy (MeV)	Lower Group Energy (MeV)	Upper Group Energy (MeV)	Lower Group Energy (MeV)
$3.35\cdot10^{-3}$	$1.58\cdot10^{-3}$	14.0	12.0
$1.58\cdot10^{-3}$	$4.54\cdot10^{-4}$	12.0	10.0
$4.54\cdot10^{-4}$	$1.01\cdot10^{-4}$	10.0	8.00
$1.01\cdot10^{-4}$	$2.26\cdot10^{-5}$	8.00	7.50
$2.26\cdot10^{-5}$	$1.07\cdot10^{-5}$	7.50	7.00
$1.07\cdot10^{-5}$	$5.04\cdot10^{-6}$	7.00	6.50
$5.04\cdot10^{-6}$	$2.38\cdot10^{-6}$	6.50	6.00
$2.38\cdot10^{-6}$	$1.12\cdot10^{-6}$	6.00	5.50
$1.12\cdot10^{-6}$	$4.14\cdot10^{-7}$	5.50	5.00
$4.14\cdot10^{-7}$	$1.00\cdot10^{-10}$	5.00	4.50
		4.50	4.00
		4.00	3.50
		3.50	3.00
		3.00	2.50
		2.50	2.00
		2.00	1.50
		1.50	1.00
		1.00	$4.00\cdot10^{-1}$
		$4.00\cdot10^{-1}$	$2.00\cdot10^{-1}$
		$2.00\cdot10^{-1}$	$1.00\cdot10^{-1}$
		$1.00\cdot10^{-1}$	$1.00\cdot10^{-2}$

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