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THERMAL NEUTRON ABSORPTION AND SCATTERING CROSS-SECTIONS OF ALL ELEMENTS

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THERMAL NEUTRON ABSORPTION AND SCATTERING CROSS-SECTIONS OF ALL ELEMENTS

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Abstract

This memorandum is to be published as chapter 7 of a book "Nuclear Data for Reactor Design, Vol. 1" to be published by Pergamon Press. It is a critical assessment of experimental data relating to the absorption cross-sections of the natural elements at 2200 m/sec. Average values for the slow neutron scattering cross-sections are given also.

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Tables

7.1 INTRODUCTION

In this chapter we give recommended values for the thermal neutron absorption and scattering cross-sections of all the chemical elements, which are assumed to be of natural isotopic composition. Atomic weights and densities are given also.

7.2 DESCRIPTION OF TABLE 7.1

Columns 1 and 2. These are self-explanatory.

Column 3. The atomic weights are given in the chemical scale, i.e. the atomic weight for atmospheric oxygen of natural isotopic composition is taken to be 16.0000. Avogadro's number in the same scale is

$$N_o = (6.02338 \pm 0.00016) \times 10^{23} \text{ atomic mass units/gram;}$$

see chapter 1, section 1.2.

Column 4. The densities are for materials at 20°C. The gases are assumed to be at a pressure of 760 mm. Hg. For some elements, if allotropic forms exist at room temperature, the density is given for each form. The reader should exercise due care in using these data, because there are variations of density between different samples of the same element, depending on the purity and the method of manufacture. The values given in Table 7.1 are typical of those encountered in practice. They are mostly drawn from the following works of reference: the Handbook of Chemistry and Physics (1961); the Rare Metals Handbook (2nd edition, 1961); Metal Physics and Physical Metallurgy (1958); The Rare Earths (1961).

Column 5. The absorption cross-sections given in Table 7.1 are for monokinetic neutrons of speed 2200 m/sec. If a cross-section is known to deviate significantly from the 1/v-law we give a value for g_o, by which we denote Westcott's g-factor for a Maxwellian neutron distribution at 20.44°C; WESTCOTT (1960) and PATTENDEN (1958). For most light elements σ_A obeys the 1/v-law accurately at low neutron energies, because the resonance levels are very widely spaced. For heavier elements, say $Z > 40$, the resonance spacing is much smaller so that there is a greater likelihood of finding a resonance near the thermal region, and large values of σ_A may result ($\sigma_A > 10$ barns).

We have preferred to avoid confusing the table with lists of references. For 35 elements details of the available data may be found in chapters 3, 4, 5, or 6. For the remainder, the majority of the references may be found in BNL 325 (1958, 1960); a few of these elements, which present features of special interest, are discussed more or less briefly in section 7.3 below. The absorption cross-sections have mostly been determined by comparative measurements, and it should be noted that we revised these data, using for the reference cross-sections the recommended values given in chapter 3.

The methods of measurement have been described and discussed in chapters 3 and 6. For most elements the best data on σ_A are from pile oscillator measurements. For an element with low energy resonances, or a large resonance absorption

integral, measurements in well-moderated spectra, such as those of POMERANCE (1951, 1952)*, ROSE et al. (1958), JOWITT et al. (1959), TATTERSALL et al. (1960), and CARRE et al. (1961)*, are much to be preferred. The measurement of very small absorption cross-sections ($\leq$ 20 millibarns) is not yet very satisfactory, particularly if the activation method is not applicable.

Column 6. The scattering of slow neutrons by an atom depends not only on the neutron energy but also to some extent on the chemical environment of the atom: the reader is referred to the discussion in chapter 4, section 4.3. However, slow neutron scattering is usually treated somewhat cursorily in thermal reactor calculations - apart from the effects of moderators - and for most materials the effective scattering cross-section is not needed very accurately.

Usually, unless $\sigma_A >> \sigma_S$, the most reliable values for σ_S are obtained by subtracting σ_A from $\sigma_T(E)$ in the neighbourhood of 0.025 eV. The total cross-section data are displayed graphically in BNL 325 (1958 and 1960). In polycrystalline materials the coherent scattering varies abruptly with energy in the thermal neutron region. However the values of σ_S given in Table 7.1 are intended to be average values about 0.0253 eV.

Columns 7 and 8. These two columns give the macroscopic absorption and scattering cross-sections respectively. The macroscopic cross-section is the sum of the cross-sections of all nuclei in 1 cm^3. It is obtained by multiplying the microscopic cross-section from column 5 or 6 by n, where

$$n = 0.60234\, \rho/A.$$

A is the atomic weight from column 3 and ρ is the density from column 4.

Column 9. The absorption cross-section per gram is useful for instance when activating a sample in a reactor. It is obtained by multiplying the microscopic absorption cross-section by the factor 0.60234/A.

7.3 NOTES ON THE ABSORPTION CROSS-SECTIONS OF Be, C, N, O, A, Ne, Mg, Al, Sc, Fe, Cu, Kr, AND Dy, AND THE SCATTERING BY Ge

Be. Values of about 6.2 $\pm$ 1.3 millibarns have been reported for σ_A^o in highly purified samples, but about 9 or 10 millibarns seems to be the best attainable in large scale production; GERATSEVA et al. (1956), PALEVSKY & SMITH (1952), LOCKETT & GREEN (1954), and JOWITT et al. (1958).

C. From intercomparisons made in America, England, and France, it seems that the best samples of reactor grade graphite have a capture cross-section of about 3.65 $\pm$ 0.15 millibarns at 2200 m/sec; NICHOLS (1960), SMALL & TATTERSALL (1960). Allowing for capture in interstitial air and in other impurities the cross-section of pure carbon is likely to be somewhat lower,

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*POMERANCE, and CARRÉ et al. used "local oscillators". In a local oscillator the absorbing sample is oscillated very near to the neutron counter. As we have remarked before, the efficiency of the neutron counter obeys the 1/v-law approximately. This factor much reduces the importance of any epithermal neutron absorption. Unless there is a resonance in the thermal region the instrument measures comparative values of $\sigma_A(kT)$, to a good approximation, where T is the absolute temperature of the thermal neutrons and k is Boltzmann's constant.

perhaps 3.4 ± 0.2 millibarns. These estimates are based predominantly on measurements by the reactivity method. It may be questioned whether this method is capable of such fine accuracy, in the presence of scattering effects, so in Table 7.1 we have assigned rather more uncertainty to the result. It seems that a definitive measurement of this important cross-section has yet to be made.

N. Thermal neutron absorption is predominantly due to the $N^{14}(n,p)$ reaction. The radiative capture cross-section is only about 0.10 barns.

O. Thermal neutron capture in oxygen is probably caused mainly by the $O^{17}(n,\alpha)$ reaction. The capture cross-sections of O^{16} and O^{17} have not been measured, but are apparently very small; this may be inferred from diffusion measurements with D_2O and the activation cross-section of deuterium.

Ne. The value of σ_A recommended in Table 7.1 is from recent measurements by SPRINGER & WIEDEMANN (1960) and by CARRÉ et al. (1961).

Mg. JENKINS (1962) has pointed out that thermal neutron absorption in magnesium samples may be significantly affected by the presence of impurities, such as gadolinium. The best available measurements are listed in Table 7.2; all were made by the pile oscillator method. We do not accept the high precision claimed by JOWITT et al. (1958) as they made no attempt to establish the purity of their samples: the resonance integral determined by the same experimental group - TATTERSALL et al. (1961) - appears surprisingly large. There is a need for improved measurements.

Al. The best measurements of the absorption cross-section were made by the pile oscillator method and are listed in Table 7.3. As with Mg, JOWITT et al. (1958) have claimed rather high precision, but apparently they did not have their samples analysed for impurities. The epicadmium resonance integral may be estimated as about 220 ± 90 millibarns, but direct measurements give somewhat smaller values, possibly due to deviations from the idealised Fermi spectrum in experimental environments.

A. The data on σ_A are listed in Table 7.4. Absorption is mainly due to radiative capture in A^{40}, forming A^{41} which decays by beta emission with a half-life of 110 minutes. Capture in A^{37} and A^{39} accounts for only 0,020 ± 0.004 barns of the average absorption cross-section in the natural isotopic mixture. The activation measurement by KATCOFF (1952) is a little below the more reliable absorption measurements by COLMER & LITTLER (1950) and by SPRINGER & WIEDEMANN (1960). Further activation measurements of this important parameter are desirable.

Sc. The value of σ_A recommended in Table 7.1 is from measurements by POMERANCE (1952b), LOCKETT & BOWELL (1953), and LYON (1953). These measurements were in very good agreement. A significantly higher value, $\sigma_A^0 = 28.4 \pm 1.0$ barns, has been reported recently by WOLF (1960) from activation measurements with cadmium differences. The discrepancy needs further investigation. This rather large absorption cross-section is mainly caused by a negative energy resonance at about -137 eV, according to PATTENDEN (1955).

Fe. Iron has been used as a reference standard in one or two measurements. It seems to have no special merit for this purpose, so we did not discuss it in chapter 3; however the best available data on σ_A are listed in detail in Table 7.5.

Cu. Copper has been used as a reference standard for one or two measurements. This cannot be recommended; the data on the thermal neutron absorption cross-section are detailed in Table 7.6, and it will be noticed that the consistency of recent measurements is not as good as should be expected. Further work is needed to clarify the discrepancy.

Ge. The total cross-section, $\sigma_T(E)$, was measured by WU et al. (1947) by the transmission method, using time-of-flight with a pulsed cyclotron. The cross-section has an unusual energy dependence below about 0.3 eV, which has been attributed somewhat vaguely to coherent scattering effects. It would probably be of interest to re-measure the cross-section with a variety of samples and to attempt quantitative comparisons with theory.

Kr. $\sigma_T(E)$ was measured by COCKING (1957) by the transmission method with a fast neutron chopper; the data are shown graphically in BNL 325 (1958). As krypton is a monatomic free gas the separation of scattering and absorption is fairly straightforward. COCKING (1957) reported that $\sigma_A = 30.6 \pm 1.8$ barns at 2200 m/sec, but this was a misprint for σ_T, according to COCKING (1961). A better value is $\sigma_T^{\circ} = 29.7$ barns, from a smooth curve through the data in BNL 325 (1958). The scattering cross-section at a few electron volts energy is about 8.0 ± 0.6 barns, and it is about 1.2 ± 0.8 barns larger at 2200 m/sec, because of resonance contributions and Doppler broadening. Hence $\sigma_A^{\circ} = 20 \pm 2.2$ barns. A somewhat higher but less accurate value, $\hat{\sigma}_A = 30 \pm 5$ barns, was obtained by MACNAMARA & THODE (1950) with NRX reactor neutrons. This large thermal neutron absorption cross-section is mainly caused by a negative energy resonance at about -3 to -10 eV in Kr^{83}.

Dy. MOORE (1960) has reported comparative transmission measurements of boron and dysprosium, using a slow neutron chopper. These seem to show that $\sigma_A(Dy)$ obeys the 1/v law in the range 0.001 to 0.4 eV at least. Although this disagrees markedly with the early work of STURM (1947), it is probably not seriously in conflict with the other data reproduced in BNL 325 (1958), from the measurements of BRILL & LICHTENBERGER (1947), BROCKHOUSE (1953) and SAILOR et al. (1954). However further measurements are desirable.

TABLE 7.1

Absorption and scattering cross-sections of the natural elements for neutrons of 2200 m/sec

1	2	3	4	5		6	7	8	9
Atomic No. and chem. symbol		Atomic weight (chem. scale)	Density; g/cm^3 at 20°C	Absorption cross-section at 2200 m/sec; barns		Average scattering cross-section; barns	Absorption cross-section per cm^3; cm^{-1}	Average scattering cross-section per cm^3; cm^{-1}	Absorption cross-section per gram; cm^2/g
1	H	1.0080	0.0837×10^{-3}	0.331 ± 0.003	a	38 ± 4 (gas)	0.0166×10^{-3}	1.90	0.198
2	He	4.0028	0.166×10^{-3}	0.007 ± 0.001		0.82 ± 0.08	0.175×10^{-6}	20×10^{-6}	0.00105
3	Li	6.941	0.534	71.0 ± 1.5	a	1.0 ± 0.3	3.29	0.046	6.16
4	Be	9.013	1.84	0.0062 ± 0.0013	b	7 ± 1	0.76×10^{-3}	0.86	0.41×10^{-3}
5	B	10.813	2.34 (amorphous)	758 ± 3.0 (ANL standard)	a	4 ± 1	98.8	0.52	42.2
6	C	12.012	1.6	0.0034 ± 0.0003	b	4.8 ± 0.2	0.27×10^{-3}	0.39	0.170×10^{-3}
7	N	14.008	1.17×10^{-3}	1.93 ± 0.04	b	10.5 ± 1	0.097×10^{-3}	0.53×10^{-3}	0.083
8	O	16.000	1.33×10^{-3}	~0.0001	b	4.22 ± 0.3	$\sim 5 \times 10^{-9}$	0.211×10^{-3}	$\sim 4 \times 10^{-6}$
9	F	18.999	1.58×10^{-3}	0.0094 ± 0.002		3.8 ± 0.2	0.47×10^{-6}	0.19×10^{-3}	0.30×10^{-3}
10	Ne	20.172	0.839×10^{-3}	0.036 ± 0.008	b	2.4 ± 0.1	0.90×10^{-6}	60×10^{-6}	0.0011
11	Na	22.991	0.971	0.536 ± 0.007	a	3.3 ± 0.3	0.0137	0.084	0.0141
12	Mg	24.311	1.74	0.064 ± 0.005		3.4 ± 0.4	0.00276	0.15	0.00159
13	Al	26.983	2.699	0.229 ± 0.005		1.4 ± 0.1	0.0138	0.084	0.00511
14	Si	28.08	2.42	0.16 ± 0.02		2.1 ± 0.4	0.0083	0.11	0.00343

a = Data reviewed in detail in chapter 3

b = See notes in sub-section 7.3

TABLE 7.1 continued

Absorption and scattering cross-sections of the natural elements for neutrons of 2200 m/sec

1	2	3	4	5		6	7	8	9
Atomic No. and chem. symbol		Atomic weight (chem. scale)	Density; g/cm^3 at 20°C	Absorption cross-section at 2200 m/sec; barns		Average scattering cross-section; barns	Absorption cross-section per cm^3; cm^{-1}	Average scattering cross-section per cm^3; cm^{-1}	Absorption cross-section per gram; cm^2/g
15	P	30.975	1.83 (yellow) 2.20 (red)	0.20 ± 0.02		4 ± 1	0.0071 0.0086	0.14 0.17	0.0039
16	S	32.066	2.07 (orthorhomb) 1.96 (monoclinic)	0.52 ± 0.02		1.1 ± 0.2	0.0202 0.0191	0.043 0.040	0.0098
17	Cl	35.457	2.99×10^{-3}	33.8 ± 1.1		14 ± 3	1.72×10^{-3}	0.71×10^{-3}	0.574
18	A	39.944	1.66×10^{-3}	0.62 ± 0.03	b	0.7 ± 0.2	0.0155×10^{-3}	0.018×10^{-3}	0.0093
19	K	39.100	0.87	2.07 ± 0.07		2.1 ± 0.3	0.0277	0.028	0.0319
20	Ca	40.08	1.54	0.44 ± 0.02		3.0 ± 1.5	0.0102	0.07	0.0066
21	Sc	44.96	3.02	23.4 ± 1.0	b	25 ± 2	0.95	1.0	0.313
22	Ti	47.90	4.54	5.8 ± 0.4		4.4 ± 0.6	0.33	0.25	0.073
23	V	50.95	5.96	5.00 ± 0.07	a	5.2 ± 0.5	0.352	0.37	0.0591
24	Cr	52.01	7.1	3.1 ± 0.2		4.0 ± 0.4	0.255	0.33	0.036
25	Mn	54.94	7.4	13.2 ± 0.1	a	2.4 ± 0.3	1.07	0.19	0.144

a = Data reviewed in detail in chapter 3 b = See notes in sub-section 7.3

TABLE 7.1 continued

Absorption and scattering cross-sections of the natural elements for neutrons of 2200 m/sec

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Atomic No.	and chem. symbol	Atomic weight (chem. scale)	Density; g/cm^3 at 20°C	Absorption cross-section at 2200 m/sec; barns		Average scattering cross-section; barns	Absorption cross-section per cm^3; cm^{-1}	Average scattering cross-section per cm^3; cm^{-1}	Absorption cross-section per gram; cm^2/g
26	Fe	55.85	7.87	2.56 ± 0.05	b	10.7 ± 1	0.218	0.91	0.0276
27	Co	58.94	8.9	37.8 ± 0.7	a	7 ± 1	3.44	0.64	0.386
28	Ni	58.71	8.9	4.6 ± 0.1		15.7 ± 1.3	0.42	1.43	0.047
29	Cu	63.54	8.9	3.84 ± 0.08	b	6.2 ± 0.8	0.324	0.52	0.0364
30	Zn	65.38	7.1	1.10 ± 0.02		3.0 ± 0.4	0.072	0.20	0.0101
31	Ga	69.72	5.91	2.87 ± 0.15		4.6 ± 0.5	0.147	0.23	0.0248
32	Ge	72.60	5.32	2.45 ± 0.20		3.5 ± 1 b	0.108	0.15	0.0203
33	As	74.91	3.7 (amorphous)	4.29 ± 0.22	c	6 ± 1	0.128	0.18	0.0345
34	Se	78.96	4.8 (hexagonal)	12.3 ± 0.4		9 ± 2	0.450	0.33	0.094
35	Br	79.916	3.12	6.6 ± 0.2	c	5.7 ± 0.5	0.155	0.13	0.050
36	Kr	83.8	3.45×10^{-3}	20 ± 2.2 ($g_o \approx 0.995$)	b	7.5 ± 0.7	0.57×10^{-3}	0.19×10^{-3}	0.165
37	Rb	85.48	1.53	0.73 ± 0.07		5.0 ± 0.5	0.0079	0.054	0.0051
38	Sr	87.63	2.54	1.21 ± 0.06		6 ± 2	0.0211	0.10	0.0083
39	Y	88.92	4.48	1.3 ± 0.1	c	7.4 ± 1.5	0.039	0.22	0.0088

a = Data reviewed in detail in chapter 3 b = See notes in sub-section 7.3 c = See also chapter 6

TABLE 7.1 continued

Absorption and scattering cross-sections of the natural elements for neutrons of 2200 m/sec

1	2	3	4	5		6	7	8	9
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40	Zr	91.22	6.5	0.185 ± 0.004		6.0 ± 0.5	0.0079	0.26	0.00122
41	Nb	92.91	8.5	1.17 ± 0.02	c	5.2 ± 1.0	0.064	0.29	0.0076
42	Mo	95.95	10.2	2.70 ± 0.04		4.9 ± 0.8	0.173	0.31	0.0169
43	Tc	(99)	11.5	22 ± 3	c	9 ± 3	1.54	0.63	0.134
44	Ru	101.1	12.2	2.56 ± 0.12		6.1 ± 0.7	0.186	0.44	0.0153
45	Rh	102.91	12.4	143 ± 5 ($g_o = 1.023$)	c	5 ± 1	10.4	0.36	0.84
46	Pd	106.7	11.9	8.0 ± 1.5		3.6 ± 0.6	0.54	0.24	0.045
47	Ag	107.880	10.5	62.9 ± 0.8 ($g_o = 1.004$)	a	5.2 ± 1.2	3.69	0.30	0.351
48	Cd	112.41	8.65	2430 ± 35 ($g_o = 1.32$)	c	7 ± 1	112.6	0.32	13.02
49	In	114.82	7.3	190 ± 2 ($g_o = 1.019$)	a	2.2 ± 0.5	7.28	0.084	0.997

a = Data reviewed in detail in chapter 3 c = See also chapter 6

TABLE 7.1 continued

Absorption and scattering cross-sections of the natural elements for neutrons of 2200 m/sec

1	2	3	4	5		6	7	8	9
Atomic No. and chem. symbol		Atomic weight (chem. scale)	Density; g/cm^3 at 20°C	Absorption cross-section at 2200 m/sec; barns		Average scattering cross-section; barns	Absorption cross-section per cm^3; cm^{-1}	Average scattering cross-section per cm^3; cm^{-1}	Absorption cross-section per gram; cm^2/g
50	Sn	118.70	7.29 (tetragonal) 5.77 (gray)	0.625 ± 0.015		3.7 ± 1.0	0.0231 0.0183	0.14 0.11	0.00317
51	Sb	121.76	6.69	5.5 ± 0.3		4.3 ± 0.5	0.182	0.14	0.0272
52	Te	127.61	6.24	4.7 ± 0.1 ($g_o = 1.012$)		5 ± 1	0.138	0.15	0.0222
53	I	126.91	4.93	6.45 ± 0.3	c	4.2 ± 0.7	0.151	0.098	0.0306
54	Xe	131.30	5.45×10^{-3}	39 ± 6		4.3 ± 0.4	0.00098	0.11×10^{-3}	0.18
55	Cs	132.91	1.90	29 ± 1	c	7 ± 3	0.25	0.06	0.131
56	Ba	137.36	3.5	1.2 ± 0.15		12 ± 4	0.0184	0.18	0.0053
57	La	138.92	6.17	9.0 ± 0.3	c	12 ± 4	0.241	0.32	0.0390
58	Ce	140.13	6.77	0.80 ± 0.08		4 ± 1	0.023	0.12	0.0034
59	Pr	140.92	6.78	11.6 ± 0.6	c	4 ± 1	0.336	0.12	0.0496
60	Nd	144.27	7.00	46 ± 2		20 ± 4	1.34	0.58	0.192
61	Pm	(145)	6.8						

c = See also chapter 6

TABLE 7.1 continued

Absorption and scattering cross-sections of the natural elements for neutrons of 2200 m/sec

1	2	3	4	5		6	7	8	9
Atomic No. and chem. symbol		Atomic weight (chem. scale)	Density; g/cm^3 at 20°C	Absorption cross-section at 2200 m/sec; barns		Average scattering cross-section; barns	Absorption cross-section per cm^3; cm^{-1}	Average scattering cross-section per cm^3; cm^{-1}	Absorption cross-section per gram; cm^2/g
62	Sm	150.35	7.54	5600 ± 200 ($g_o = 1.617$)	c	35 ± 5	169		22.4
63	Eu	152.0	5.26	4120 ± 230 ($g_o = 0.9924$)	c	8.3 ± 2	85.9	0.17	16.3
64	Gd	157.26	7.90	46000 ± 1000 ($g_o = 0.854$)	c	160 ± 20	139	4.8	176
65	Tb	158.93	8.27	46 ± 5	c		1.44		0.174
66	Dy	162.51	8.54	1050 ± 60	b	105 ± 20	33.2	33	3.89
67	Ho	164.94	8.80	66 ± 3		27 ± 8	2.12	0.87	0.241
68	Er	167.27	9.05	160 ± 8 ($g_o = 1.056$)		10 ± 4	5.21	0.33	0.576
69	Tm	168.94	9.33	126 ± 6		7 ± 3	4.19	0.23	0.449
70	Yb	173.04	6.98	37 ± 4 (not 1/v.?)		12 ± 5	0.90	0.29	0.129
71	Lu	174.99	9.84	≈ 110 ($g_o \approx 1.34$)			3.7		0.38

b = See notes in sub-section 7.3 c = See also chapter 6

TABLE 7.1 continued

Absorption and scattering cross-sections of the natural elements for neutrons of 2200 m/sec

1	2	3	4	5	6	7	8	9
Atomic No. and chem. symbol		Atomic weight (chem. scale)	Density; g/cm^3 at 20°C	Absorption cross-section at 2200 m/sec; barns	Average scattering cross-section; barns	Absorption cross-section per cm^3; cm^{-1}	Average scattering cross-section per cm^3; cm^{-1}	Absorption cross-section per gram; cm^2/g
72	Hf	178.58	13.3	104 ± 5 ($g_o = 1.020$)	8 ± 2	4.67	0.36	0.351
73	Ta	180.95	16.6	20.0 ± 1	5 ± 2	1.11	0.28	0.067
74	W	183.86	19.3	18.7 ± 0.8	4 ± 1.5	1.18	0.25	0.0613
75	Re	186.22	21.0	86 ± 4	14 ± 4	5.84	0.95	0.278
76	Os	190.2	22.5	15.2 ± 0.8	15 ± 4	1.08	1.07	0.0481
77	Ir	192.2	22.4	445 ± 21 ($g_o = 1.013$)		31.2		1.39
78	Pt	195.09	21.4	9.0 ± 0.6	10 ± 1	0.59	0.66	0.0278
79	Au	197.0	19.3	98.4 ± 0.5 ($g_o = 1.005$) a	9.3 ± 1.0	5.81	0.55	0.301
80	Hg	200.61	13.55	380 ± 20 ($g_o = 0.998$)	20 ± 5	15.5	0.81	1.14
81	Tl	204.39	11.85	3.4 ± 0.5	14 ± 2	0.119	0.49	0.0100
82	Pb	207.21	11.34	0.172 ± 0.003	11 ± 1	0.00567	0.36	0.000500

a = Data reviewed in detail in chapter 3

TABLE 7.1 continued

Absorption and scattering cross-sections of the natural elements for neutrons of 2200 m/sec

1	2	3	4	5		6	7	8	9
Atomic No. and chem. symbol		Atomic weight (chem. scale)	Density; g/cm^3 at 20°C	Absorption cross-section at 2200 m/sec; barns		Average scattering cross-section; barns	Absorption cross-section per cm^3; cm^{-1}	Average scattering cross-section per cm^3; cm^{-1}	Absorption cross-section per gram; cm^2/g
83	Bi	209.00	9.78	0.034 ± 0.002		9 ± 1	0.00096	0.25	0.000098
84	Po	(209)	9.4						
85	At	(210)							
86	Rn	(222)	9.07×10^{-3}	≈ 0.72			$\approx 1.77 \times 10^{-5}$		≈ 0.00195
87	Fr	(223)							
88	Ra	226.05	5	20 ± 3			0.266		0.0533
89	Ac	227	10.1	620 ± 120			16.6		1.64
90	Th	232.05	11.3	7.36 ± 0.10 ($g_o = 0.997$)	d	12.7 ± 0.2	0.216	0.37	0.0191
91	Pa	231	15.4	200 ± 20	d		8.0		0.52
92	U	238.07	18.7	7.605 ± 0.032 ($g_o = 0.9866$)	e	8.1 ± 0.7	0.360	0.38	0.0192

d = Data reviewed in detail in chapter 5

e = From data reviewed in chapters 2, 4, and 5

TABLE 7.2

MAGNESIUM; absorption cross-section for neutrons of 2200 m/sec

Reference	σ_A° millibarns	Method and remarks
COLMER & LITTLER (1950)	60 ± 7	Pile oscillator method in GLEEP. Original value revised assuming σ_A = 767 ± 7 barns at 2200 m/sec for the boron used in calibration, and 1 ± 1 millibarns subtracted to allow for resonance absorption
HARRIS et al. (1950)	63	Pile oscillator method in CP3. Original value revised assuming σ_A = 757.7 ± 3.0 barns at 2200 m/sec for ANL standard boron, and 1 ± 1 millibarns subtracted to allow for resonance absorption
POMERANCE (1951)	62 ± 6	Local oscillator at Oak Ridge. Revised using σ_A[Au] = 98.4 ± 0.5 barns for the reference standard
JOWITT et al. (1958)	73 ± 2	Measured with a pile oscillator in a thermal well. Harwell standard boron used for calibration
Mean value	64 ± 5	The data were weighted equally because of the possible effects of impurities

TABLE 7.3

ALUMINIUM; absorption cross-section for neutrons of 2200 m/sec

Reference	σ_A° millibarns	Method and remarks
COLMER & LITTLER (1950)	225 ± 8	Pile oscillator method in GLEEP. Original value revised assuming σ_A = 767 ± 7 barns at 2200 m/sec for the boron used in calibration, and 4 ± 3 millibarns subtracted to allow for resonance absorption.
HARRIS et al. (1950)	231	Pile oscillator method in CP3. Original value revised assuming σ_A = 757.7 ± 3.0 barns at 2200 m/sec for ANL standard boron, and 4 ± 3 millibarns subtracted to allow for resonance absorption
POMERANCE (1951)	228 ± 11	Local oscillator at Oak Ridge. Revised using σ_A[Au] = 98.4 ± 0.5 barns for the reference standard
BENOIST et al. (1951)	233 ± 6	Pile oscillator method in ZOE. Original value revised assuming σ_A = 759 ± 9 barns for the boron used in calibration, and 3 ± 2 millibarns subtracted to allow for resonance absorption
JOWITT et al. (1958)	246 ± 3	Pile oscillator in a thermal well. Harwell standard boron used in calibration
BROSE & BECKURTS (1960)	220 ± 13	Comparison of integrated neutron flux distributions in Al and paraffin; calibrated by pulsed neutron method. Corrected for various epithermal contributions
TATTERSALL (1962)	219 ± 4	Pile oscillator measurements in a thermal well using a Canadian sample.
Mean value	229 ± 5	The data were weighted equally because of possible effects of impurities

TABLE 7.4

ARGON; absorption cross-section for neutrons of 2200 m/sec

Reference	σ_A^o barns	Weight	Method and comments
LICHTENBERGER et al. (1943)	0.62	0	Reactivity measurement, probably based on a value of 703 barns for the boron reference cross-section
WATTENBERG & WEST (1943)	0.74	0	From activation of A^{40}. Details not available. Original value increased by 0.02 barns to allow for absorption in A^{37} and A^{39}
COLMER & LITTLER (1950)	0.67 ± 0.04	0.5	Pile oscillator measurement. Original value revised assuming σ_A^o = 767.2 ± 3.5 barns for Harwell standard boron
KATCOFF (1952)	0.574 ± 0.03	0.5	From activation measurements. Revised assuming $\hat{\sigma}_A$ = 99.1 barns for the gold neutron flux monitor in the sub-Cd spectrum used, and allowing for absorption in A^{37} and A^{39}
SPRINGER & WIEDEMANN (1960)	0.61 ± 0.03	1	From transmission measurements at long wavelengths, with samples at 77°K
Weighted mean	0.62 ± 0.03		

Note: in argon of natural isotopic composition the cross-section for activation of A^{41} of 110 min half-life is 0.020 ± 0.004 barns lower than σ_A.

TABLE 7.5

IRON; absorption cross-section for neutrons of 2200 m/sec

Reference	σ_A^o barns	Weight	Method and Remarks
HARRIS et al. (1950)	2.60	0.4	Measured with a pile oscillator. Original value revised assuming σ_A = 757.7 ± 3.0 barns at 2200 m/sec for ANL standard boron, and 0.05 ± 0.03 barns subtracted to allow for resonance absorption
GRIMELAND et al. (1951)	2.50 ± 0.08	0.9	Measured with a pile oscillator. Original value revised assuming σ_A = 759.4 ± 9 barns at 2200 m/sec for the boron used in calibration, and corrected for resonance absorption as above
POMERANCE (1951)	2.48 ± 0.13	0.7	Measured with a local oscillator. Revised assuming σ_A[Au] = 98.4 ± 0.5 barns at 2200 m/sec for the reference standard
POMERANCE (1952a)	2.61 ± 0.20	0.3	From measurements with a local oscillator using enriched samples. Revised as above
WADE (1957)	2.59 ± 0.16	0.2	From reactivity measurements with Cd differences. Revised assuming $\hat{\sigma}_A$[Au] = 99.3 ± 0.7 barns in the sub-Cd spectrum used.
TATTERSALL et al. (1960)	2.65 ± 0.10	1	Measured with a pile oscillator in a thermal well. Harwell standard boron used for calibration.
Weighted mean value	2.565 ± 0.07		

TABLE 7.6

COPPER; absorption cross-section for neutrons of 2200 m/sec velocity

Reference	σ_A^o barns	Weight	Method and comments
HARRIS et al. (1950)	3.83	0	Reactivity oscillator. Revised assuming σ_A = 757.7 ± 3.0 barns at 2200 m/sec for ANL standard boron, and corrected for resonance absorption
BENDT & RUDERMAN (1950)	3.39 ± 0.31	0	Transmission, using time-of-flight with a pulsed cyclotron. Extrapolated from lower energies assuming the scattering cross-section is constant
COLMER & LITTLER (1950)	3.76 ± 0.25	0	Reactivity oscillator. Revised assuming σ_A = 767.2 ± 3.5 barns at 2200 m/sec for Harwell standard boron, and corrected for resonance absorption
GRIMELAND et al. (1951)	3.67 ± 0.08	0	Reactivity oscillator; corrected for resonance absorption. Revised assuming σ_A = 759 ± 9 barns at 2200 m/sec for the boron used in calibration
POMERANCE (1951)	3.70 ± 0.19	0.3	Local oscillator. Revised assuming σ_A[Au] = 98.4 ± 0.5 barns at 2200 m/sec
POMERANCE (1952a)	3.74 ± 0.25	0.1	From measurements with a local oscillator using isotopically enriched samples. Revised as above
WADE (1957)	3.84 ± 0.16	0.3	From reactivity measurements with cadmium differences. Revised assuming σ_A[Fe] = 2.565 ± 0.07 barns at 2200 m/sec for the reference standard
JOWITT et al. (1958)	4.0 ± 0.1	0.7	Reactivity oscillator in a thermal well. Harwell standard boron used for calibration
SEPPI et al. (1958)	3.63 ± 0.17	0.3	Transmission measurement with a crystal spectrometer at long wavelengths, extrapolated assuming σ_A obeys the 1/v law
KEATING et al. (1958)	3.907 ± 0.033	1	Transmission measurement with a slow-neutron chopper. Extrapolated from the long wavelength region
DONAHUE et al. (1960)	3.78 ± 0.04	1	Reactivity measurement in a thermal well. Revised assuming σ_A[Au] = 98.4 ± 0.5 barns at 2200 m/sec
Weighted mean value	3.84 ± 0.08		

References

BENDT P. J. & RUDERMAN I. W. (1950) Phys. Rev. 77, 575.

BENOIST P., KOWARSKI L. & NETTER F. (1951) J. Phys. Rad. 12, 584.

BRILL T. & LICHTENBERGER H. V. (1947) Phys. Rev. 72, 585.

BROCKHOUSE B. N. (1953) Can. J. Phys. 31, 432.

BROSE M. & BECKURTS K. H. (1960) Nukleonik 2, 139.

CARRÉ J. C., ROBIN M. & VIDAL R. (1961) Comptes rendus 252, 3973.

COCKING S. (1957) J. Nucl. En. 6, 113.

COCKING S. (1961); private communication.

COLMER F. C. W. & LITTLER D. J. (1950) Proc. Phys. Soc. 63A, 1175.

DONAHUE D. J., BENNETT R. A. & LANNING D. D. (1960) Nucl. Sci. Eng. 7, 184.

GERATSEVA L. A., KAMAYEV A. V., KRASIN A. K. & MOROSOV I. G. (1956) Geneva 5, 13.

GRIMELAND B., HELLSTRAND E. & NETTER F. (1951) Comptes rendus 232, 2089.

HARRIS S. P., MUEHLHAUSE C. O., RASMUSSEN S., SCHROEDER H. P. & THOMAS G. E. (1950) Phys. Rev. 80, 832.

HUGHES D. J. (1953) "Pile Neutron Research" page 251, (Addison - Wesley).

JENKINS P. D. (1962); private communication.

JOWITT D., PATTENDEN S. K., ROSE H., SMALL V. G. & TATTERSALL R. B. (1958) AERE R/R 2516.

KATCOFF S. (1952) Phys. Rev. 87, 886

KEATING D. T., NIEDHARDT W. J., GOLAND A. N. (1958) Phys. Rev. 111, 261.

LICHTENBERGER H. V., FOWLER & WATTENBERG A. (1943) unpublished. Quoted by KATCOFF (1952)

LOCKETT E. E. & BOWELL E. (1953) Phys. Rev. 89, 657.

LOCKETT E. E. & GREEN A. (1954), unpublished.

LYON W. S. (1953) Phys. Rev. 89, 1307

MELKONIAN E., RAINWATER L. J., HAVENS W. W. & DUNNING J. R. (1948) Phys. Rev. 73, 1399

MOORE W. E. (1960) KAPL - 2000 - 12, 19

NICHOLS P. F. (1960) Nucl. Sci. Eng. 7, 395

PALEVSKY H. & SMITH R. R. (1952), cited by HUGHES (1953)

PATTENDEN N. J. (1955) Proc. Phys. Soc. 68A, 104

PATTENDEN N. J. (1958) Proc. Geneva II, 16, 44

POMERANCE H. S. (1951) Phys. Rev. 83, 641

POMERANCE H. S. (1952a) ORNL 1304

POMERANCE H. S. (1952b) ORNL 1415, 15

ROSE H., COOPER W. A. & TATTERSALL R. B. (1958) Proc. Geneva II, 16, 34

SAILOR V. L., LANDON H. H. & FOOTE H. L. (1954) Phys. Rev. 96, 1014

SEPPI E. J., LEONARD B. R. & FRIESEN W. J. (1958) HW55879, 5

SMALL V. G. & TATTERSALL R. B. (1960), unpublished

SPRINGER T. & WIEDEMANN W. (1960) Zeitschr. Naturforsch. 15a, 828

STURM W. J. (1947) Phys. Rev. 71, 757 (1947)

TATTERSALL R. B., ROSE H., PATTENDEN S. K. & JOWITT D. (1960) J. Nucl. En. (A) 12, 32

TATTERSALL R. B. (1962); private communication

WADE J. W. (1957) DP207

WATTENBERG A. & WEST J. (1943) unpublished. Quoted by KATCOFF (1952)

WESTCOTT C. H. (1960) AECL 1101

WOLF G. (1960) Nukleonik 2, 255

Bibliography

The Handbook of Chemistry and Physics, 42nd edition by C. D. Hodgman, (Chem. Rubber Publishing Co., 1960).

A Handbook of Lattice Spacings and Structures of Metals and Alloys, W. B. Pearson, (Pergamon, 1958).

The Rare Earths, edited by F. H. Spedding and A. H. Daane, (Wiley, 1961).

The Rare Metals Handbook, 2nd edition by C. A. Hampel, (Reinhold, 1961).