Total Cross Sections Measured with Photo-Neutrons*

R. FIELDS, B. RUSSELL, D. SACHS, AND A. WATTENBERG**
Argonne Laboratory, University of Chicago, Chicago, Illinois
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The total neutron cross sections of twenty-three elements have been measured by use of six photo-neutron sources ranging from 0.024 Mev to 0.83 Mev. The cross sections of the lighter elements behave very anomalously; broad resonances in the scattering are observed in F, Na, Mg, Al, and S. Nickel has the exceptionally high cross section of 23×10^{-24} cm² at 0.024 Mev. The cross sections of elements of atomic weight about 110 show very little variation with energy and are about 7×10^{-24} cm². Three heavy elements have cross sections of about 13×10^{-24} cm² at 0.024 Mev and decrease monotonically to about half that value at 0.83 Mev.

INTRODUCTION

THE determination of the homogeneous nature and the energy of the neutrons emitted by some of the photo-neutron sources made feasible studies of neutron cross sections at known energies. The first study undertaken was the determination of the total cross sections of twenty-four elements by means of simple transmission measurements.

The photo-neutron sources used emit neutrons in the energy range from 0.02 to 0.83 Mev. From other work in this energy region, capture cross sections are thought to be less than 10 percent of the total cross sections except for the case of boron. Therefore, in the experiment reported here, the transmission measurements are really a determination of scattering cross sections.

EXPERIMENTAL

The original experimental data for all the sources are rather lengthy; therefore the data for only one of the sources (Table I) are presented here as a sample.

The source and the detector used in these measurements are the same as those previously described. The energies of the neutrons emitted by these sources are those listed in Table V of the preceding article. The apparatus was mounted six feet above the floor in a large room in the manner shown in Fig. 5 of the preceding article.

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** Now a Fellow of the Institute for Nuclear Studies of the University of Chicago.

The scatterers were machined from pure metal for the elements: Al, Fe, Ni, Cu, Zn, Ag, Cd, Sn, Sb, Pb, and Bi. Magnesium was used in the form of an alloy containing 3 percent aluminum. In the cases of P, I, and W, the pure element as a powder was tightly packed into a cell made of sheet iron with front and back faces 0.065 cm thick. Powdered sulfur was pressed into a briquette of the desired size. The remaining elements were measured as compounds

TABLE I. Data for Sb+Be source (0.024 Mev).

Element	Compound	gms/cm²	Total counts	Corrected average transmission	Std error	Cross section (in 10^{-24} cm²)
Be		1.306	40,000	0.642	0.001	5.1
Be		1.725	20,000	.566	.006	4.9
B	B_4C	2.432	42,000	.490	.003	5.6
B	B_4C	2.574	42,000	.481	.002	5.4
O	BeO	3.081	36,000	.525	.003	3.6
F	BeF_2	3.037	22,000	.625	.005	3.5
Na	NaI	7.35	80,000	.698	.003	5.1
Mg	3% Al Alloy	3.45	75,000	.690	.001	4.4
Al		13.73	94,000	.781	.004	0.80
Al		20.61	45,000	.694	.003	0.79
P		4.85	19,000	.700	.007	3.8
S		9.02	20,000	.843	.008	1.0
K	KI	9.85	69,000	.745	.002	1.2
Fe		9.68	58,000	.798	.004	2.2
Ni		1.326	30,000	.723	.007	24.
Ni		2.710	30,000	.544	.004	22.
Cu		5.60	26,000	.652	.006	8.0
Zn		7.86	60,000	.489	.002	9.9
Ag		13.59	132,000	.545	.002	8.0
Cd		16.64	40,000	.540	.002	6.9
Sn		18.33	65,000	.576	.004	5.9
Sb		10.57	25,000	.718	.004	6.3
I		15.64	36,000	.592	.007	7.0
W		9.33	40,000	.651	.005	13.9
W		17.00	17,000	.475	.005	13.4
Pb		10.81	150,000	.698	.003	11.4
Pb		23.39	40,000	.467	.002	11.3
Bi		12.51	67,000	.645	.004	12.1

(column 2 of Table I). Dehydrated powders were put into cells similar to those used with P, I, and W, and the cells were soldered shut. These cans were 8.2×6.6 cm^2 inside; the dimensions of the other scatterers were 7.6×5.7 cm^2. The thicknesses used are given in the third column of Table I.

In measuring transmissions of those substances contained in cells, an identical empty cell was used for comparison. Transmission measurements were repeated from four to fifteen times; the total number of counts observed with each scatterer is given in the fourth column (Table I). The average and the standard error of the independent transmission measurement were calculated; the standard errors (column 6) are listed in order to give an idea of the spread in the observed values of the transmissions. The average transmissions listed in column 6 have been corrected for the (small angle) scattering-in-effect by use of the relationship

$$T_{\text{corrected}}=\frac{T_{\text{observed}}-\epsilon}{1-\epsilon}, \qquad (1)$$

where $\epsilon=0.032$ for the scatterers in cells and $\epsilon=0.026$ for the other scatterers. The number of neutrons scattered into the detector from the floor and walls of the room was found to be about 10 percent of the number coming directly from the source. This was determined by interposing a tapered lead plug, 30 cm long, between the source and the detector.

RESULTS

The cross sections (column 8 of Table I) were calculated directly from the transmissions listed. Where a compound was used the cross section of the element of interest was calculated with the aid of the values of the cross section of the other element listed in Table II. The values for carbon included in Table II are from the previous work reported in Table V of the preceding article.

At first both the $La-D_2O$ and $Ga-D_2O$ sources were being used; however, it was found that the first five values obtained with both sources were the same—confirming the previous determination of the energies of these sources as being the same.* When this was observed no further measurements with the $La-D_2O$ source were made because it is a relatively inefficient source of neutrons.

It will be noted in Table I that where several different thicknesses of an element were measured, the cross sections found generally decrease in value for the thicker scatterer (lower transmission). These variations were partly experimental and partly due to two effects which have not been corrected for, namely multiple scattering and hardening of the neutrons. Because of these two effects, the values of the cross sections measured at transmissions less than 0.60 are not considered as reliable as those measured at transmissions between 0.60 and 0.75. This has been taken into consideration in drawing up Table II which is a summary of the cross sections found. The values at 0.83 Mev for Be, C, Al, Pb,

TABLE II. Total cross sections. (All values in units of 10^{-24} cm^2.)

Element	Atomic weight	0.024 Mev Sb +Be	0.13 Mev Ga $+D_2O$	0.14 Mev* Mn +Be	0.22 Mev Na $+D_2O$	0.62 Mev La +Be	0.83 Mev Na +Be
Be	9.0	5.0	4.3	4.3	4.2	3.3	3.1
B	10.8	5.5	4.9	4.7	4.3	—	2.3
C	12.0	4.6	4.3	4.3	4.1	3.3	2.9
O	16.0	3.6	3.5	4.1	3.0	3.5	4.9
F	19.0	3.5	5.7	—	6.9	4.6	4.1
Na	23.0	5.1	3.9	4.2	3.8	5.9	4.6
Mg	24.3	4.4	4.9	5.7	8.7	4.2	3.4
Al	27.0	0.80	5.3	3.2	3.2	4.1	3.5
P	31.0	3.8	3.1	3.1	3.2	3.1	3.5
S	32.1	1.0	4.2	4.5	2.9	—	2.2
K	39.1	1.2	1.6	1.9	1.7	2.3	2.7
Fe	55.9	2.2	4.1	3.9	3.3	—	2.7
Ni	58.7	23.	6.4	4.2	5.8	3.7	3.5
Cu	63.6	8.0	6.2	5.9	5.3	—	3.8
Zn	65.4	9.9	6.6	5.4	5.1	4.7	4.3
Ag	107.9	8.0	8.1	8.1	7.8	7.3	7.2
Cd	112.4	6.9	7.6	7.3	7.3	—	7.1
Sn	118.7	5.9	6.4	6.4	6.3	6.8	6.7
Sb	121.8	6.3	6.9	6.4	6.1	5.7	6.4
I	126.9	7.0	6.6	6.5	6.1	6.8	6.7
W	183.9	13.8	10.0	9.4	8.0	7.8	7.7
Pb	207.2	11.4	10.6	10.6	8.6	6.1	5.8
Bi	209.0	12.1	10.2	9.7	8.0	—	5.9

* The Mn+Be source emits two other groups of neutrons of higher energy that constitute less than 20 percent of the total number emitted.

* In the determination of the energy of the photoneutrons it was not certain that the $Ga+D_2O$ neutrons were homogeneous. The $La+D_2O$ was known to be homogeneous, so the agreement of these cross sections tends to establish the homogeneity of the $Ga+D_2O$ neutrons.

are in agreement with those found by Good and Scharff-Goldhaber[1] for 0.90 Mev neutrons; for Cu there is a disagreement.

CONCLUSIONS

The values of the scattering cross sections for the three heavy elements (atomic weights 183 to 209) seem to vary with energy in a very similar fashion; their cross sections are all about 13×10^{-24} cm^2 at 0.024 Mev and seem to monotonically decrease to about half that value at 0.83 Mev. The five intermediate weight elements (atomic weights 107 to 127) seem to have cross sections that vary very slightly with the neutron energy between 0.024 and 0.83 Mev. We wish to point out that neutrons emitted by the sources used in this work have an appreciable spread in energy, probably at least 25 percent; therefore, one would not observe narrow resonances by the technique employed here. There are also large energy gaps in which we have no neutron sources, and it is possible that broad anomalies might have been missed in the cross section of the heavy and intermediate weight elements. However, from the similar behavior of the elements within each group, it seems more reasonable to believe that there are no broad anomalies in the scattering cross sections of the heavier elements between 0.024 and 0.83 Mev.

The de Broglie wave-length of the neutrons from the higher energy sources is of the same order of magnitude as the nuclear radius of the heavy and intermediate weight elements. Therefore one would expect an appreciable amount of P wave scattering, and it would be of value to study the angular distribution of the scattered neutrons to determine the relative contributions of the P and S wave scattering.

Nickel is exceptional in having a cross section of 23×10^{-24} cm^2 at 0.024 Mev; its scattering cross section at thermal energies is also high, 16×10^{-24} cm^2.

The light elements O, F, Na, Mg, Al, and S all have cross sections that behave very anomalously between 0.024 and 0.83 Mev. These anomalies must extend for at least several hundred electron volts because the sources employed in these experiments have spreads in energy that would not permit observation of the narrow type resonances observed in neutron capture by In and Rh at 1.4 ev. Work of others[2] has shown the existence of broad scattering resonances in He at about 1 Mev in Mg and Al at about 2.5 Mev[3]

Attempts made to measure the capture cross sections by means of activating foils showed that the capture cross sections of the light elements (with the exception of boron) are a negligible fraction of the total cross sections. This indicates that the observed anomalies are probably "broad resonances" in the scattering of neutrons.

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[1] Good and Scharff-Goldhaber, Phys. Rev. **59**, 917 (1941).

[2] H. Staub and H. Tatel, Phys. Rev. **58**, 820 (1940).

[3] MacPhail, Phys. Rev. **57**, 669 (1940).