

Capture Cross Sections for Thermal Energy Neutrons

CHRISTIAN LAPOINTE AND FRANCO RASETTI

Laval University, Quebec, Canada

(Received June 10, 1940)

Cross sections for capture of thermal energy neutrons were measured for several elements. The method consisted in comparing, by a BF_3 ionization chamber, the density of thermal neutrons in water and in a solution of the element investigated. In order to avoid corrections for geometry, the effect of the substance was compared with that of boron solutions of different concentrations, and consequently the measurements directly give the ratio of the cross sections of the elements investigated to the cross section of boron. Data are given for N, F, Na, P, Cl, K, V, Mn, Co, As, Se, Br, Cd, I, Ba.

MOST of the experiments on scattering and absorption of slow neutrons give values of the total (scattering+capture) cross section. When the cross section is of the order of 10^{-22} cm^2 or more, it is well known to be almost wholly due to capture. Our present knowledge about the character of the cross sections lying between 10^{-24} and 10^{-23} cm^2 is much less definite. Measurements of the scattering cross section have been performed,¹ but in most cases they are not accurate enough to give a significant value of the capture cross section by subtraction from the total cross section measured by neutron beam experiments.

EXPERIMENTAL PROCEDURE

To perform a direct measurement of the capture cross section, the simplest method which suggests itself is the one already employed by Frisch, von Halban and Koch.² It consists in measuring, by a BF_3 ionization chamber, the decrease in density of the thermal neutrons inside a certain volume of water when a given percentage of an absorbing element is added. Since Frisch, von Halban and Koch intended to compare the cross sections of boron and hydrogen, the volume of the solution had to be taken large enough so that practically all neutrons emitted by the source were slowed down to thermal velocities, and eventually

captured, either by hydrogen or by boron nuclei. The same method would be unpractical, when applied to most other substances, since it would require exceedingly large volumes of concentrated solutions. This can, however, be avoided if the cross section of the element to be investigated is measured in terms of the capture cross section of boron. An amount of solution of any volume and shape may be taken, provided one measures the concentration c_B of boron which produces the same density decrease of the thermal neutrons as the element investigated under the concentration c . Then the relation holds:

$$\sigma_B c_B = \sigma c,$$

where σ and σ_B , respectively, represent the capture cross sections of the element in question and of boron.

The neutron source consisted of 250 mg Ra and Be powder. The BF_3 ionization chamber had a diameter of 2.5 cm and a length of 8 cm. The boron disintegrations were recorded by means of a linear amplifier and a thyratron scale of four. The solution was contained in a cylindrical glass beaker, 14 cm in diameter and filled to a height of about 20 cm, the ionization chamber being immersed in the center of the solution. The neutron source, shielded by 2 cm of lead, was placed outside of the solution, on the axis of the cylinder. The number of counts, under such conditions, was already over one thousand per minute. The effect of neutrons of energies higher than thermal in the present experiment is negligible and was not corrected for. The ionization chamber and the glass cylinder were rigidly

¹M. Goldhaber and G. H. Briggs, Proc. Roy. Soc. A162, 127 (1937); A. C. G. Mitchell and E. J. Murphy, Phys. Rev. 48, 653 (1935); A. C. G. Mitchell, E. J. Murphy and M. D. Whitaker, Phys. Rev. 49, 870 (1936); 50, 133 (1936).

²O. R. Frisch, H. v. Halban and J. Koch, Proc. Danske Vidensk. Selskab 15, 10 (1938).

connected together, and the investigated solutions could be quickly drained through a stopcock at the bottom of the container and replaced with water. Many alternate measurements with water and with the solution were taken for each element. Each reading comprised about 20,000 counts and the discrepancies observed were no larger than the statistical fluctuations.

RESULTS AND DISCUSSION

Since large cross sections have already been determined by beam absorption measurements, and cross sections smaller than 10^{-24} cm² are unpractical to measure by the present method, we confined our attention to elements which, either from the values of the total and the scattering cross sections given in the literature,¹ or from the intensity of activation under slow neutron bombardment, were expected to possess capture cross sections lying between 10^{-24} and 10^{-22} cm².

The compounds employed had to answer the conditions of being sufficiently soluble in water and of not containing other strongly absorbing elements besides the one to be investigated. The concentration was chosen such as to reduce the density of the neutrons by at least ten percent, when allowed by the solubility of the compound.

Most of the elements investigated (probably all except Cd) do not possess neutron resonance levels for thermal energies, and therefore the cross section in this region will follow the $1/v$ law. The ratio of the cross sections to the cross section of boron therefore possesses a definite meaning, being independent of the velocity of the neutrons.

No corrections were required for geometrical factors, since the effect of the solution was compared with the effect of a boron solution of known concentration under the same conditions. It was first determined how the neutron density depended on the concentration of boric acid solutions. Within the limits of experimental error (about one percent) it was found that the ratio of the intensity I_0 with water to the intensity I with a boron solution of concentration c_B was a linear function of c_B , the empirical relation being

$$I_0/I = 1 + kc_B/c_H = 1 + 1.02 \times 10^3 c_B/c_H,$$

where with c_H we have indicated the hydrogen concentration. In a solution of infinite volume, the coefficient k should be equal to the ratio of the capture cross sections of boron and hydrogen. The smaller measured value evidently depends on the fact that about half of the thermal neutrons diffuse out of the solution before being captured, either by hydrogen or by boron nuclei.

In most cases, the amount of substance which had to be dissolved in water in order to absorb a measurable fraction of the neutrons was large enough to alter to an appreciable extent the hydrogen concentration. Since a change in hydrogen concentration will, in general, affect the density of the thermal neutrons, measurements were undertaken to determine the magnitude of the effect. It would not be correct to compare water with hydrocarbons or other hydrogenous substances, since a difference in the chemical bond of hydrogen might produce effects of the same order of magnitude. The procedure employed was to dissolve in water a substance which would decrease the hydrogen concentration without appreciably absorbing the neutrons. The experiment was performed by using either a 30 percent solution of H₂O₂ (hydrogen density, 5.5 percent lower than in water) or a saturated solution of oxalic acid (hydrogen concentration, 3.7 percent lower than in water). The density of neutrons was found to be lower than in water by 4.3 percent in the first case and by 3.1 percent in the second case. As an average, we assumed that a decrease of one percent in hydrogen concentration produced a decrease of 0.8 percent in neutron density. The correction has been applied to the values reported in Table I.

Part of the decrease in the number of thermal neutrons when an absorbing substance is dissolved in water will be due to capture of the neutrons through resonance levels before they have been slowed down to thermal energies, and a correction may be required therefor. In order to estimate the importance of the effect, the following experiment was performed. A rhodium plate 5 by 5 cm, shielded by Cd, was substituted for the BF₃ chamber, and irradiated. Under such conditions, it is well known that rhodium is practically activated only by neutrons of about one volt energy. The activity of rhodium was

measured (by means of a pressure ionization chamber connected to an Edelmann electrometer) when the container was filled either with water or with the solutions that had been investigated. For most elements, the characteristic resonance energies lie higher than the resonance energy of rhodium, this applying in particular to As, Br, and I. Then, the observed decrease in the number of characteristic rhodium neutrons will determine the effect of resonance absorption by the dissolved element in decreasing the number of neutrons which are slowed down to thermal velocities. Measurements performed with Cl, Co, As, Br, I, indicated that the decrease in activity of the rhodium was certainly smaller than 2 percent, and probably within one percent. Some of the above-mentioned elements (As, Br, and I) would be likely to produce a more considerable effect than others, since it is known³ that their activation is due, for an unusually high percentage, to resonance neutrons. The effect being hardly measurable, even in these cases, we decided not to correct our results for resonance capture.

A certain disagreement exists in the literature²⁻⁴ about the cross section of boron for thermal neutrons, the values given lying between 500×10^{-24} and 700×10^{-24} . The value will also, of course, depend on the average effective energy assumed for the thermal neutrons. We assumed $\sigma_B = 600 \times 10^{-24}$. Any change in the cross section of boron would evidently affect all our data by the same factor. A measurement of the cross section of Cd performed as a check on the method gave the correct value.

Table I includes all of our results. Column 3 indicates the number of hydrogen atoms per atom of the element in the solution. Column 4 gives the ratio I_0/I of the number of neutrons with water and with the solution, and the statistical error. Column 5 gives the same ratio,

³ H. H. Goldsmith and F. Rasetti, *Phys. Rev.* **50**, 328 (1936).

⁴ J. R. Dunning, G. B. Pegram, G. A. Fink and D. P. Mitchell, *Phys. Rev.* **48**, 265 (1935); E. Amaldi and E. Fermi, *Phys. Rev.* **50**, 899 (1936); G. A. Fink, *Phys. Rev.* **50**, 738 (1936); J. G. Hoffman and M. S. Livingston, *Phys. Rev.* **52**, 1228 (1937).

TABLE I. Capture cross sections for thermal neutrons.

ELE- MENT	COMPOUND USED	c_H/c	I_0/I UNCORR.	I_0/I CORR.	$\sigma \times 10^{24}$ CM ²
5 B	H ₃ BO ₃	1,000	2.02 ± 0.02	2.02	600
7 N	NH ₄ NO ₃	24.3	1.124 ± 0.006	1.086	1.2
9 F	NaF	105	0.998 ± 0.006	0.990	< 0.5
11 Na	NaF	105	0.998 ± 0.006	0.990	< 0.5
15 P	H ₃ PO ₄	43.5	1.088 ± 0.007	1.040	1.0
17 Cl	HCl	145	1.32 ± 0.01	1.32	27
19 K	KF	82	1.067 ± 0.005	1.067	3.2
23 V	VOSO ₄	190	1.094 ± 0.006	1.061	6.8
25 Mn	MnSO ₄	161	1.117 ± 0.005	1.099	9.4
27 Co	CoSO ₄	470	1.12 ± 0.01	1.12	33
33 As	As ₂ O ₃	75	1.187 ± 0.006	1.147	6.5
34 Se	H ₂ SeO ₃	75	1.283 ± 0.007	1.261	11.5
35 Br	NaBr	104	1.14 ± 0.01	1.116	7
48 Cd	Cd(NO ₃) ₂	10,000	1.49 ± 0.01	1.49	2900
53 I	NaI	115	1.133 ± 0.006	1.101	6.8
56 Ba	Ba(C ₂ H ₃ O ₂) ₂	200	1.001 ± 0.007	0.985	< 1

corrected for the change in hydrogen density as above explained. The last column gives the capture cross sections in 10^{-24} cm². The value of σ was calculated by means of the formula

$$\sigma = \sigma_B \frac{c_H}{c} \cdot 0.98 \times 10^{-3} \left(\frac{I_0}{I} - 1 \right).$$

When the element investigated possesses only one isotope, no doubt exists about the process responsible for the absorption. Some other cases may warrant a few remarks.

Cl—The weakness of the 37-minute activity of Cl³⁷ indicates that the high absorption is mainly due to capture by Cl³⁵, with formation of long-lived Cl³⁶.

K—By a similar argument, most of the absorption appears to be due to capture by K³⁹ with formation of K⁴⁰.

Se—No strong activation corresponds to the large capture cross section, which must therefore correspond to formation of stable isotopes.

Br—Both capture by Br⁷⁹ and Br⁸¹ will be important, since all activities are strong.

As it can be seen from the statistical errors reported in column 4 of the Table I, the values of the cross sections may be considered as accurate within 10 percent or better for the higher values, and within about 25 percent for the smallest.