The Absorption of Neutrons Detected by Boron and Lithium

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The neutron-nucleus collision cross sections of various elements have been investigated for neutrons that are detectable by means of (1) the boron and (2) lithium neutron capture reaction and that are strongly absorbed by cadmium. The collision cross section for such slow neutrons detected by boron is for hydrogen about 75 percent of that for neutrons detected by lithium, for HgO about 72 percent, for Sm about 180 percent, and for Al, B, C, Fe, and Li is the same within 10 percent for either boron or lithium detection. With either detector the absorption of cadmium and boron each approximates a single exponential, the absorption coefficient in each case not decreasing more than 25 percent for intensity reduction of 90 percent. The absorption coefficient of lithium for neutrons detected by boron decreases 40 percent, and for neutrons detected by lithium decreases about 30 percent at thicknesses that reduce the intensity 85 percent. Measurements were made with slow neutrons passed through an 8-mm paraffin layer. With lithium detection less than 10 percent increase in the absorption of Ag, HgO, boron glass (Pyrex), and Rh was observed when the temperature of the paraffin layer was changed from 293 to 90°K. The velocity distribution of the neutrons strongly absorbed by cadmium was approximately the Maxwellian for thermal equilibrium at room temperature; but when the paraffin was at the temperature of liquid air the neutron velocity distribution was too broad and flat to be described as Maxwellian for any particular temperature, although the distribution was shifted toward that for the lower temperature. The lithium reaction was found to be a sensitive detector of neutrons whose velocity is much higher than the mean thermal velocity at room temperature and well above the strong absorption range of cadmium. The collision cross section for neutrons, from paraffin at room temperature, that were filtered through 1 gram per cm² of cadmium was found to be larger in Rh, HgO, Au, and B than in cadmium. After filtering through 11.5 g per cm² of cadmium, the cadmium absorption was reduced to about a normal value for very high speed neutrons, collision cross section about 5×10^{-24} cm².

INTRODUCTION

THAT the probability of capture of neutrons is a function of the neutron velocity was shown by the well-known experiment of Fermi and his associates,[1] wherein they discovered that induced radioactivity can be greatly enhanced by surrounding the ordinary Rn–Be neutron source with paraffin or water. It was pointed out by Fermi that the increase in cross sections thus indicated was attributable to the reduction of the velocity of the neutrons by collision with hydrogen nuclei as they passed through the paraffin.

With the exception of the work in this laboratory, most of the investigation of these slow neutrons has been made with radioactive detectors. The purpose of the investigation here reported was twofold: (1) To obtain information concerning variations of neutron-nucleus collision cross sections of various elements for neutrons detected by means of the boron and lithium neutron capture reactions; (2) To investigate the neutron-nucleus interaction in some representative elements for neutrons not strongly absorbed by cadmium.

Disintegration by slow neutrons

When a neutron is captured by B^{10} or Li^6 the capturing nucleus is disintegrated[1, 2] in accord with the following reactions:[3]

$$_5B^{10}+{}_0N^1={}_3Li^7+{}_2He^4,$$
$$_3Li^6+{}_0N^1={}_2He^4+{}_1H^3.$$

These two reactions are almost unique, as nitrogen is the only other element known[4] to be disintegrated directly by slow neutrons. The energy of the heavy particles emitted is such that they produce sufficient ionization in air to be easily detected.

Apparatus

The detecting apparatus consists of an ionization chamber, linear amplifier, and thyratron actuated counter previously described.[5] The

[1] Amaldi, d'Agostino, Fermi, Pontecorvo, Rasetti and Segrè, Ricerca Scient. **2**, 282, 380 (1934); Proc. Roy. Soc. **A149**, 522 (1935).

[2] Chadwick and Goldhaber, Nature **135**, 65 (1935).

[3] Taylor and Goldhaber, Nature **135**, 341 (1935).

[4] Chadwick and Goldhaber, Proc. Camb. Phil. Soc. **31**, 612 (1935).

[5] J. R. Dunning, G. B. Pegram, G. A. Fink and D. P. Mitchell, Phys. Rev. **48**, 265 (1935).

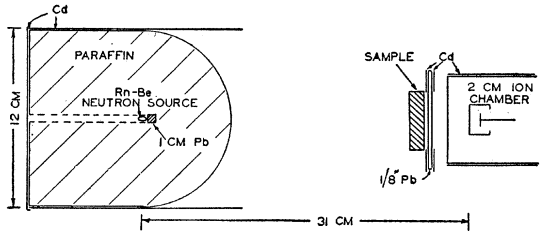

FIG. 1. Experimental arrangement for slow neutron absorption measurements.

chamber is lined with rolled lithium foil or coated with powdered boron with a little aquadag[6] as binder. The general arrangement of the source, absorber, and chamber is illustrated in Fig. 1.

Slow and Cd residual neutrons

Although most of the neutrons detected by these chambers are stopped by as little as 0.5 mm thickness of cadmium, many of the neutrons not so stopped—and in fact, those which pass through as much as 1.0 cm of cadmium—are detected. With the same chamber, the relative number of these residual (cadmium-penetrating) neutrons depends upon the amount of paraffin surrounding the source.[7] The size of the paraffin sphere shown in Fig. 1 is somewhat less than the optimum size to give a maximum number of slow neutrons that are within the strong absorption region of cadmium. With this arrangement, the residual neutrons represented about 19 percent of all neutrons detected with the boron chamber, and about 15 percent with a representative lithium chamber. Usually the collision cross section for these residual neutrons is much less than that of those neutrons which are stopped by cadmium. For this reason it has been our[8] custom to deduct this *residual neutron* count in all the determinations of *slow* neutron cross sections made in these laboratories.

Although it is probable that most of the neutrons referred to in the literature as "slow" do have energies approximating the thermal energy of the hydrogen in the material in which they were slowed down, the term has in general been applied to all neutrons having insufficient energy to produce measurable ionization by the projection of protons. Since an appreciable fraction of the residual neutrons detected by these chambers are sufficiently fast to project hydrogen nuclei, the word "slow" will be printed in italics when it is restricted to those neutrons which lie within the strong absorption region of cadmium.

Experiments with a chamber in which only the front was coated with a layer of lithium metal, 0.09 mm thick, also gave a residual of 15 percent. The effect of moisture in this lithium-lined chamber was demonstrated by breaking the seal, thereby permitting diffusion of air from the room into the chamber. Under these conditions, the residual ratio was more than doubled in two days.

This was probably due to a decrease in the efficiency of detection of *slow* neutrons due to the increased absorption of disintegration particles, from within the lithium, by the hydroxide on the surface, and an increase in the efficiency of detection of higher energy neutrons by the projection of hydrogen nuclei.

BORON *vs.* LITHIUM DETECTION

Slow neutrons are usually obtained from a source of high speed neutrons by multiple collision with hydrogen nuclei, so it is interesting to note first that the hydrogen collision cross section for *slow* neutrons detected by boron is somewhat less than for those detected by lithium. The value here obtained is 26 ($\times 10^{-24}$ cm^{-2}). For *slow* neutrons detected by lithium,[5] this value is about 35. Table I gives other collision cross sections as measured by boron and lithium detection.

TABLE I. *Nuclear collision cross section for neutrons stopped by 1 g/cm² of cadmium.*

MATERIAL	BORON DETECTION Transmission (Approximate)	BORON DETECTION Cross section ($\times 10^{24}$ cm²)	LITHIUM DETECTION Transmission (Approximate)	LITHIUM DETECTION Cross section ($\times 10^{24}$ cm²)
Al	0.7	2.0±0.3	0.75	1.5±0.2
C	.5	4.8± .4	.5	4.1± .4
Fe	.6	11.8± .6	.5	12± .5
HgO	.7	260±25	.6	360±40
Sm	.3	9000±25%	.5	5000±25%

Cadmium absorption

Although other elements such as gadolinium and samarium have been found[5] to have a larger absorption cross section for *slow* neutrons, cad-

[6] Acheson's Colloidal Graphite, National Carbon Co.
[7] J. R. Dunning and G. B. Pegram, Phys. Rev. **47**, 640 (1935).
[8] J. R. Dunning, G. B. Pegram, G. A. Fink and D. P. Mitchell, Phys. Rev. **47**, 416 (1935).

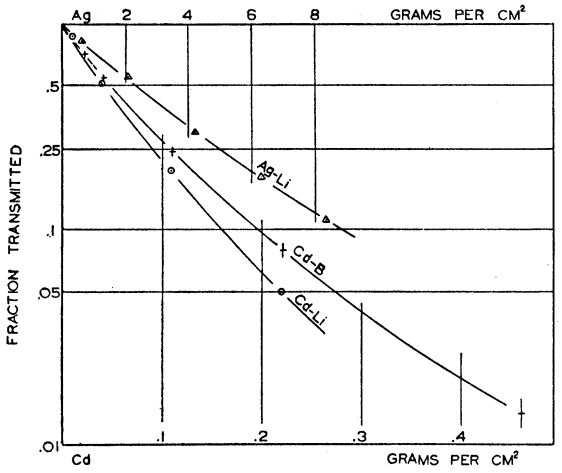

FIG. 2. Absorption of Ag by Li detection, of Cd by Li detection, and of Cd by B detection.

mium is particularly important because it is the most available for use in large quantities and is easily rolled into sheets of any desired thickness.

Fig. 2 shows that the absorption by cadmium of *slow* neutrons detected by boron is approximately exponential (the absorption coefficient changing not more than 20 percent for an intensity reduction of 90 percent), as was found[5] to be the case for *slow* neutrons detected by lithium.

Boron and lithium absorption

Investigators[9, 10] using radioactive detectors have found that in general the collision cross section for slow neutrons is largest for a given element when that element is used as a detector. Measurements of the absorption of a large range of thicknesses of both lithium and boron, when detected by their disintegration, indicate that the basic cross section of these elements is practically the same for *slow* neutrons detected by boron as for those detected by lithium. These data are shown in the accompanying plot, Fig. 3, of the logarithm of slow neutrons transmitted against the mass per square centimeter of the absorbing sample. In each case, the absorber was placed in front of the ionization chamber as in Fig. 1. The lithium was in lithium fluoride, and the boron in B_4C[11] mixed with talc. The *slow* neutron cross

[9] P. B. Moon and J. R. Tillman, Nature **135**, 904 (1935).
[10] Amaldi and Fermi, Ricerca Scient. **2**, 11–12 (1935).
[11] R. R. Ridgway (Norton Co.), Trans. Elect-Chem. Soc. **66**, 293 (1934).

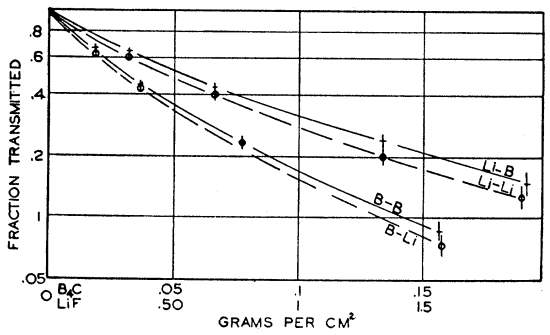

FIG. 3. Absorption of slow neutrons in Li and B measured with B and Li detectors.

section of the fluorine is 2.5×10^{-24} cm^{-2}, and the carbon as in Table I. The mass per unit area is the effective mass, account having been taken of the obliquity of part of the beam and the variation in intensity from different zones of the paraffin sphere. Such correction is very small, amounting to a maximum of about 3 percent for transmission of less than 0.1. The correction for the absorption of the talc in which the B_4C was mixed is only 7 percent.

The curvatures in Figs. 2 and 3 are, though small, an indication that the quality of the neutron beam is being changed by the filtering in the absorber itself. The change in cross section of the neutrons filtered out by the first layers of the absorber is more readily noticed by inspection of Table II. Here the cross sections are given as computed from measurements on the thin and thick samples of these absorbing materials. This effect is even less in silver than in cadmium—or, in other words, the absorption curve of silver for

TABLE II. *Effect of filtering on collision cross section for neutrons stopped by 1 g/cm² of cadmium.*

Material	Boron Detection			Lithium Detection		
	Transmission	Cross section ($\times10^{24}\times$cm²)	Decrease (%)	Transmission	Cross section ($\times10^{24}\times$cm²)	Decrease (%)
Ag				0.55	51	
				.11	47	8
Cd	0.55	2600		.52	2900	
	.07	2200	15	.07	2300	20
	.01	1800	30			
B	.65	510		.6	580	
	.08	370	27	.08	440	24
Li	.6	70		.6	70	
	.15	40	43	.13	50	29

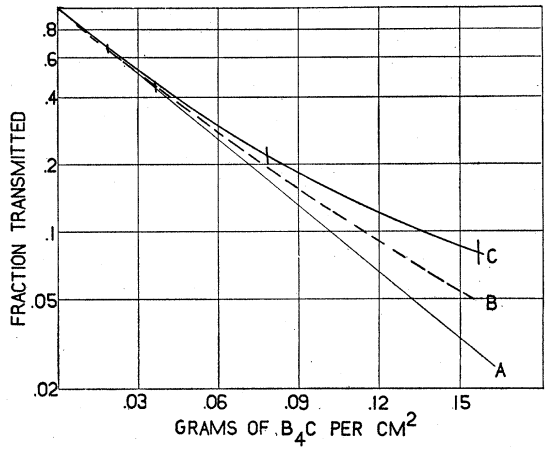

FIG. 4. A, the exponential form; B, the theoretical $1/V$ curve; C, absorption in boron observed with boron detector.

slow neutrons is more nearly exponential, as may be seen in Fig. 2.

Analysis[12] with a mechanical velocity selector has shown that the velocity distribution of slow neutrons that are highly absorbed by cadmium and detected by lithium, has a maximum closely coinciding with the maximum in a Maxwellian distribution; or, more specifically, the velocity distribution of these neutrons is approximately that to be expected if the neutrons are in thermal equilibrium in the paraffin from which they emerge. If the capture probability were, as currently[13] predicted, proportional simply to $1/V$, then the values of the integral

$$f(q)=\int_0^\infty e^{-q/V-V^2}V^3 dV$$

should represent a typical absorption curve for these slow neutrons.

As Mr. H. C. Torrey has computed the values of this integral, such a theoretical absorption curve has been plotted in Fig. 4 for comparison with one of the observed curves.

Cold neutrons

Another approach to the relation of the velocity of neutrons to the probability of capture has been made by several investigators, who observed the change in the efficiency of radioactive detectors when the temperature of the hydrogenic material in which the neutrons are slowed down is changed.

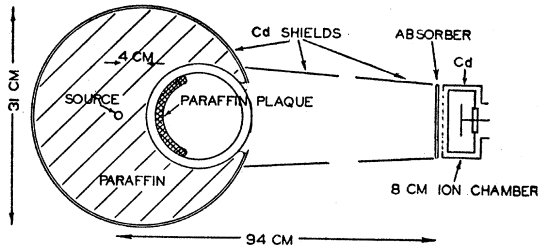

FIG. 5. Experimental arrangement for "cold" neutron absorption measurements.

Dunning, Pegram, Fink and Mitchell[14, 15] observed both a small increase in lithium detection efficiency and a small increase in the absorption of cadmium when the water through which the neutrons passed was lowered to the temperature of liquid air. Moon[9] and Tillman[16] observed a considerable increase in radioactivity induced in several substances when the paraffin used to slow down the neutrons was cooled from room temperature to 90°K.

Recently such experiments[17] have been made by Westcott and Miewodniczanski, who worked with temperatures of 77 and 20°K.

In the present experiment, the cold paraffin was in the form of a plaque 1 cm thick, so placed that neutrons already slowed down in paraffin at room temperature had to pass through this cold plaque before penetrating the absorber. The arrangement of the plaque in a soda glass Dewar partially surrounded by paraffin and Cd shields is shown in Fig. 5.

The cold paraffin was relatively thin, in order to avoid the high absorption of the very slow neutrons disclosed by the experimental work of Lukirsky and Zarewa.[18]

The results of the lithium detection measurements of the absorption in various materials of

[12] J. R. Dunning, G. B. Pegram, G. A. Fink, D. P. Mitchell and E. Segrè, Phys. Rev. **48**, 704 (1935).
[13] H. A. Bethe, Phys. Rev. **47**, 747 (1935).
[14] J. R. Dunning, G. B. Pegram, G. A. Fink and D. P. Mitchell, Phys. Rev. **47**, 796 (1935).
[15] J. R. Dunning, G. B. Pegram, G. A. Fink and D. P. Mitchell, Phys. Rev. **48**, 888 (1935).
[16] J. R. Tillman and P. B. Moon, Nature **136**, 66 (1935).
[17] Westcott and Miewodniczanski, Proc. Camb. Phil. Soc. **31**, 617 (1935).
[18] P. Lukirsky and T. Zarewa, Nature **136**, 681 (1935).

TABLE III. *Effect of cooling paraffin plaque in the path of slow neutrons. Lithium detection.*

MATERIAL	Ag	Cd	HgO	Pyrex	Rh
		FRACTION ABSORBED			
	Neutrons stopped by 1 g/cm² of Cd				
293°K	0.47	1.0	0.50	0.54	0.44
90	.51	1.0	.53	.54	.47
Ratio	1.09	1.00	1.06	1.00	1.07
	All neutrons detected				
293°K	0.38	0.78	0.39	0.41	0.38
90	.42	.79	.42	.44	.38+
Ratio	1.11	1.01	1.08	1.07	1.01

neutrons that have passed through the plaque in Fig. 5 are given in Table III. This table shows the fraction of *slow* neutrons absorbed when the plaque was at room temperature and when at liquid-air temperature, together with the increase in absorption in the latter case over the former, expressed as the ratio of the two absorption values. Investigators reporting similar experiments made with radioactive detectors have usually expressed such a ratio for all neutrons that affect the detector. For this reason, the second part of the table shows the absorption for all neutrons detected by lithium, instead of just those which are highly absorbed by cadmium.

The cadmium referred to in this table was that used to sort out the *slow* neutrons, and hence its absorption is 100 percent for those neutrons. Its absorption in the second part of the table indicates that the cadmium residual amounted to about 22 percent of all the neutrons detected. The precision of the "fraction absorbed," based upon the square root of the number of counts, is about ±2 percent. Differences such as those between the silver and mercury oxide are insignificant. Consistent with the earlier work[5] using lithium detection, the effect of cooling the neutron source under these conditions is notably less than that found with the radioactive detectors.

A velocity selector analysis, with lithium detection, of the velocity distribution of the *slow* neutrons from this "cold" source has shown[19] a much flatter distribution than the Maxwellian, for any particular temperature. This distribution appears consistent with the smallness of the ratios in Table III, but whether it is attributable to conditions at the source, to selective absorption in the intervening material, or to selectivity in the lithium reaction, is not yet clear.

Note added in proof: Recent experiments by Mr. Fink with the type of source described below in which the neutrons do not come through the walls of the Dewar and in which all the paraffin is cooled, have shown a much greater effect from cooling.

RESIDUAL NEUTRONS

The effects of self-filtering mentioned previously, shown in Table II, are of sufficient interest to demand further investigation. When thicker samples are used, the measurements with lithium detection can no longer be confined to those neutrons which are stopped by 1 gram per square centimeter of cadmium. The residual neutrons—or, more specifically, those which pass through such a cadmium absorbing screen—become of principal importance. As the neutrons penetrating such thick absorbers are relatively few in number, the large ionization chamber shown in Fig. 5 was again used, together with a source that was recently developed in these laboratories by Mr. George Fink. This new source, and the general arrangement used in the following experiments with residual neutrons, is shown in Fig. 6. With this arrangement the slow neutron yield from this source is about six times that from a 12-cm diameter paraffin sphere in the same position. Measurements were made of the absorption of cadmium ranging from 29 milligrams to 11½ grams per square centimeter. The results are shown in Table IV.

TABLE IV. *Absorption by Cd of residual neutrons through Cd.*

FILTER (g/cm²) ABSORBER (g/cm²)	None	0.029	0.89	1.78
	collision cross section (×10²⁴ cm²)			
0.029	2300			
.42	1200			
.89	600	31		
1.78	310	26	22	
3.55	160	17	12	7.5
7.1	82	12	9	7.0
11.5	51	8	6	4.7

The effect of self-filtering is very evident, as the cross section determined from the individual samples ranges from over 2000 down to about 50 (each of the values here stated should be multi-

[19] G. A. Fink, J. R. Dunning, G. B. Pegram and D. P. Mitchell, Phys. Rev. **49**, 103 (1936).

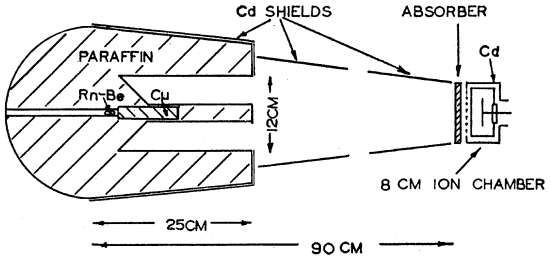

FIG. 6. Experimental arrangement for residual neutron absorption measurements.

plied by 10^{-24} cm^{-2}). The cross section in cadmium has really dropped to a much lower value for some of these neutrons. The additional columns in Table IV show the cross sections for neutrons that have filtered through cadmium screens of various thicknesses.

The continued decrease in cross sections with increased filtering probably indicates that the region of lithium detection includes neutrons which are well outside of the region of strong absorption in cadmium.

Other measurements of the absorption of cadmium, using those neutrons which pass through a boron carbide filter that contains 0.21 gram of boron per square centimeter, indicated a cadmium cross section of 60 when the cadmium absorbed 22 percent of the filtered neutrons, and of only 12 when enough cadmium was used to absorb 29 percent of these neutrons previously filtered through boron.

This indicates that the region of neutron energy most highly absorbed by cadmium is not the same as the energy band most highly absorbed by boron.

TABLE V. *Collision cross section for Cd residual and Cd absorbed neutrons.*

	Residual Neutrons			Cd Absorbed Neutrons	
Material	Absorber (g/cm²)	Transmission	Cross section (×10²⁴ cm²)	Cross section (×10²⁴ cm²)	Reference
Ag	2.07	0.86	13	51	21
Au	2.53	.80	29	88	5
B	.22	.77	22	535	22
Cd	3.55	.84	12	3300	5
HgO	.57	.94	39	360	5
Rh	.72	.78	59	115	5

Residual neutron absorption data for other elements is shown in Table V. The experimental arrangement was as in Fig. 6, and the residual neutrons are those that passed through a cadmium filter of 1 gram per square centimeter. For comparison, the absorption cross section for the usual *slow* neutrons is given in the fifth column.

An item of particular interest is that the cross section in mercury oxide, rhodium, and possibly gold is for these residual neutrons larger than that of boron and even cadmium.

These results add to the evidence that neutron absorption is selective and characteristic of the absorbing nuclei. The differences among neutrons that lead to selective absorption are most simply, and adequately so far as required by these experiments, ascribed to differences in neutron velocity. A somewhat similar result was recently reported by Szilard,[20] who, with an indium detector, found the absorption of cadmium-filtered neutrons to be much smaller in cadmium than in indium.

As Amaldi[10] and Fermi have recently reported results on selective absorption, using radioactive detectors, the following experiments were performed.

With a lithium detector, silver and mercury oxide absorbers, each of which transmitted about 50 percent of the neutron beam, were measured together, likewise a combination of rhodium and mercury oxide absorbers was measured. In each case the transmission of the two absorbers together was found to be equal to the product of their individual transmissions within the statistical error.

The author wishes to express his obligation to Professor George B. Pegram, who suggested the general problem; to Professor J. R. Dunning, for his assistance and friendly encouragement during the progress of this work; to Professor E. Segrè and Mr. George Fink for assistance in the laboratory.

[20] Szilard, Nature **136**, 950 (1935).
[21] D. P. Mitchell, J. R. Dunning, G. B. Pegram, Phys. Rev. **49**, 199 (1936).
[22] D. P. Mitchell, J. R. Dunning, E. Segrè, G. B. Pegram, Phys. Rev. **48**, 774 (1935).