Scattering of Slow Neutrons. II

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The scattering of slow neutrons from various materials has been measured with several different detectors. The scattering cross section for a number of elements has been determined and the results given in a table. With suitable filters, the scattering curves for several of the Fermi groups have been investigated. The differences between the groups show up most markedly when the scatterer is itself a good absorber of one of the groups. The effect of temperature on the activation of In has been investigated, and the temperature ratio $J_{90}=\frac{\text{activity at liquid air temperature}}{\text{activity at room temperature}}$ found to be 1.08 for the D neutrons and 1.21 for the C neutrons.

1. INTRODUCTION

IN several recent papers[1, 2, 3] we have reported on some investigations of the scattering of slow neutrons by various metals. The experiments were originally designed to see whether the elements showing large "absorption cross sections" also showed large scattering cross sections, since the original theories of interaction[4] predicted such an effect. Experiments on the metals Ag, Cd and Hg as scatterers failed to show any large scattering and indeed the shape of the scattering curves indicated that the large absorption cross section was due to capture, the scattering cross section being normal. These facts are in agreement with the theory of Breit and Wigner[5] who show that scattering and capture are complementary.

Further experiments[3] with Rh and In detectors showed marked differences in the scattering curves for the same metal with various detectors. A large part of these differences can be accounted for by absorption in the detector, since many substances have been shown to exhibit marked absorption bands by Fermi and his collaborators.[6] In other cases, discussed below, we have been able to show marked differences in the form of the scattering curves due to the various groups discussed by Fermi.

Finally, using the method of Moon and Tillman[7] and Rasetti and Fink,[8] we have investigated with an indium detector the temperature coefficient of the C and D neutrons.

2. APPARATUS AND METHOD

The apparatus used was the same as that previously employed.[1] A cylindrical block of paraffin, 15 cm in diameter and 17 cm high, contained a Ra-Be bulb located on the axis 6 cm from the top surface. The detectors were thin sheets of the metals Ag, Rh and In of dimensions 6 by 10 cm. These were placed on top of the paraffin cylinder and the scatterer, usually blocks of metal the same size as the detector, were placed on top of the detector. In some cases a sheet of Cd metal, containing 0.218 g/cm^{-2}, was interposed between the paraffin and the detector. This served as a filter to cut out neutrons of the C group. After irradiation for a given length of time the detectors were placed around a Geiger-Müller tube counter and the activity obtained with the help of a thyratron "scale of two" recording system. In some experiments a "scale of four" counter was also used and gave results in substantial agreement with those obtained with the "scale of two" counter. In the previous communications the percent scattering, defined as the percentage ratio of the activity of the detector with a thickness x of scatterer minus the activity without scatterer divided by the activity without scatterer, was plotted as a function of the thickness of the scatterer.

In view of the rather large variations in

[1] A. C. G. Mitchell and E. J. Murphy, Phys. Rev. **48**, 653 (1935).
[2] A. C. G. Mitchell, E. J. Murphy and L. M. Langer, Phys. Rev. **49**, 400 (1936).
[3] A. C. G. Mitchell, E. J. Murphy and M. D. Whitaker, Phys. Rev. **49**, 401 (1936).
[4] H. A. Bethe, Phys. Rev. **47**, 747 (1935); E. Amaldi, O. d'Agostino, B. Pontecorvo, F. Rasetti and E. Segrè, Proc. Roy. Soc. **A149**, 522 (1935); Perrin and Elsasser, Comptes rendus **200**, 450 (1935).
[5] G. Breit and E. Wigner, Phys. Rev. **49**, 519 (1936).
[6] E. Amaldi and E. Fermi, Ricerca Scientifica; (VI) **2** (1935).
[7] P. B. Moon and J. R. Tillman, Proc. Roc. Soc. **A153**, 476 (1936).
[8] F. Rasetti and G. A. Fink, New York meeting, Phys. Rev. **49**, 642A (1936).

absorption coefficient for the various groups of slow neutrons exhibited by the several detectors which we used, we measured their absorption. This was accomplished by using the actual detectors as absorbing sheets and measuring the fraction transmitted with the help of a detector of the same material. In certain cases a Cd filter ($0.218\,g/cm^{-2}$) was used to absorb the C neutrons. The time of irradiation of the materials was the same as that used in the scattering experiments (see below). The results of the absorption experiments are given in Table I.

To get the true scattering fraction from the curve of percentage scattering, as defined above, it is necessary to correct the results for absorption in the detector. If y is the fraction of neutrons absorbed, then $1-y$ is the fraction getting through to the scatterer. If $a(x)$ is the fraction of these scattered from a thickness x of scatterer, then the number of these recorded by the detector is $a(x)y(1-y)$. The percentage scattering as it is defined above, and has been used in our previous papers is $a(x)(1-y)\cdot 100$. Hence to get the true fraction of neutrons scattered the results must be divided by $(1-y)$, the fraction transmitted by the detector. All curves published in this paper have been corrected and a corrected table of relative cross section is also given.

The time of irradiation depended on the period of the detector used and was also governed to some extent by practical considerations. The In (54-minute period) detectors were irradiated for 15 minutes and readings were taken at 1, 5 and 9 minutes after the end of irradiation. The Ag (22 sec., 2.2 min.) was irradiated 6 minutes and readings were taken at 1 and 5 minutes after irradiation; while the Rh (44 sec., 3.9 min.) was irradiated 5 minutes and readings taken at 1 and 5 minutes also at 2 and 6 minutes after irradiation.

In order to test whether there was a difference in the scattering as detected by the different periods of Ag, the following experiments were performed. The detector was irradiated for 10 seconds and counting began 30 seconds after removal of the foil. In this manner scattering curves were run for Ni and C and gave substantially the same results as were obtained for the combined periods. Furthermore, one run was made to measure the scattering of a certain thickness of Ni, in which the Ag detector was irradiated 6 minutes and the counting was not started until 6 minutes after irradiation, so that the activity of the thirty second period had practically disappeared. This point lay on the curve determined by the other groups of measurements. The scattering from the metals Ni and C, with an Ag detector, is, therefore, independent of the period used in the detection. This is probably also true for the other scatterers with the possible exception of Ag.

TABLE I. *Absorption measurements.*

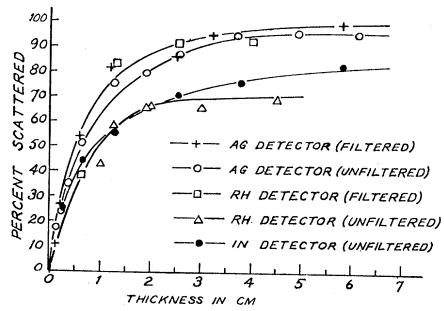
DETECTOR	THICKNESS (g/cm^{-2})	FRACTION TRANSMITTED
Ag	0.105	0.93
Ag (filtered)	0.105	0.73
Rh	0.124	0.80
Rh (filtered)	0.124	0.55
In	0.109	0.82

3. RESULTS

Figs. 1, 2, 3 and 4 show the scattering curves obtained for the elements Fe, Ni, Cu and C using the several detectors as shown. The form of the curves is such that they rise rapidly out of the origin and eventually reach a saturation value. This form of curve can be explained on greatly simplified assumptions as follows. Assuming that a plane parallel beam of neutrons falls on a scatterer of thickness x, then the fraction of neutrons scattered back to the detector will be, if one assumes a combination of single scattering and capture,

$$\frac{n}{n_0}=\frac{Na\sigma_s}{2Nb(\sigma_s+\sigma_c)}\left[1-e^{-2Nb(\sigma_s+\sigma_c)x}\right],$$

where N is the number of atoms/cm^3 of the scatterer, σ_s and σ_c the scattering and capture cross sections, respectively, and a and b quantities which come in because of the solid angles involved. The quantity $N(\sigma_s+\sigma_c)$ is the usual absorption coefficient, and the factor 2 arises since the neutrons traverse the scatterer twice. Such a simple picture does not, of course, correspond to the facts since the source does not give a plane parallel beam of neutrons, and integration over the various angles involved will eventually have to be carried out. The calculation does show, however, that the slope of the curve for small thicknesses is proportional to $N\sigma_s$ and the saturation value is governed by



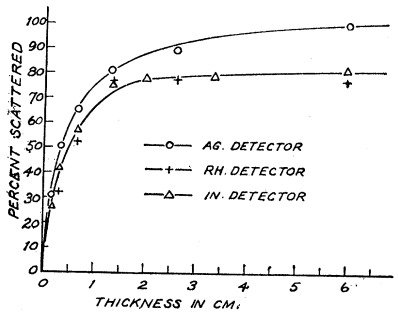
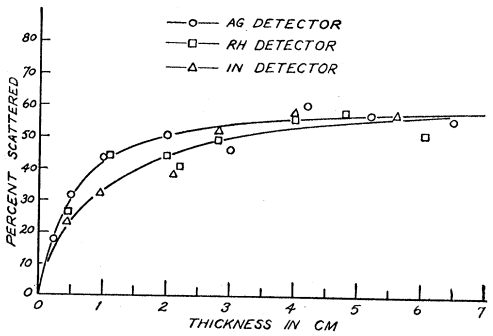


FIG. 1. (*upper*) Scattering of neutrons from iron.
FIG. 2. (*lower*) Scattering of neutrons from nickel.



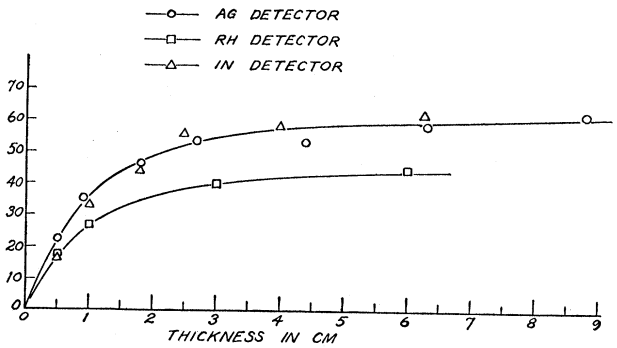


FIG. 3. (*upper*) Scattering of neutrons from copper.
FIG. 4. (*lower*) Scattering of neutrons from carbon.

$\sigma_s/(\sigma_s+\sigma_c)$. Thus the relative scattering cross section can be obtained and some idea as to the ratio of scattering cross section to total cross section. The values of the scattering cross sections of various scatterers, obtained with a Ag detector, together with the saturation value of the curve is given in Table II.

The curves of Fig. 1 show the scattering by Fe with Ag, In and Rh detectors with and without filtering through Cd. The curves for neutrons filtered through 0.218 g/cm² of Cd should represent the scattering of the *A* and *B* neutrons (Ag detector) and the *D* neutrons (Rh detector). It will be seen that these groups are scattered equally well from the iron. The curves for the unfiltered neutrons lie below those obtained when Cd filtering was employed and in the order of the number of C neutrons detected—Ag (50 percent C, 25 percent A, 25 percent B), In (60 percent C, 40 percent D), Rh (72 percent C, 25 percent D). This seems to indicate that the *C* neutrons have a somewhat smaller ratio of scattering cross section to total cross section in iron than do the other groups. The above explanation holds, of course, only in the case that the velocity distribution of the neutrons is not changed on scattering from the iron. Such an effect in Fe does not appear to occur to any appreciable extent.[1]

The curves for the scattering from Ni (Fig. 2) show that the results with Rh and In detectors are the same, whereas the curve for the silver detector shows greater scattering. In the case of scattering by Cu (Fig. 3) the curves for Ag, Rh

TABLE II. *Relative scattering cross section of various elements for slow neutrons (Ag detector).*

ELEMENT	AT. NO.	$\sigma_s \times 10^{-24}$ cm²	MAX. % SCATTERING
C	6	3.4	61
Mg	12	3.0	37 (at 6 cm)
Al	13	1.0	21 (at 6 cm)
S	16	0.9	18 (at 6 cm)
Cr	24	1.4	13
Mn	25	2.2	17
Fe	26	10.6	95
Ni	28	18	100
Cu	29	8.3	59
Zn	30	3.7	40
Ag	47	6.3	9
Cd	48	(1.2)	(2.4 at 4 mm)
Sn	50	4.1	34
Hg	80	4.7	21
Pb	82	7.7	56
Bi	83	10.2	43

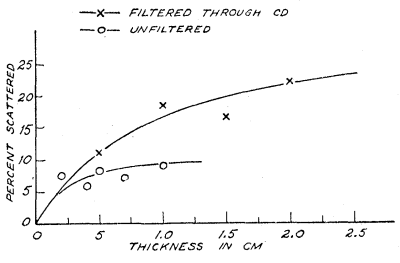


FIG. 5. Scattering of neutrons from silver. (Ag detector.)

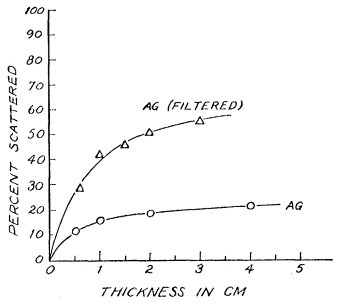


FIG. 6. Scattering of neutrons from mercury.

and In detectors give approximately the same results. For the experiments on the scattering by *C*, the curves for the Ag and In detectors are the same whereas the scattering curve using a Rh detector lies lower. No definite explanation of the differences in these scattering curves can at present be given on account of the complicated nature of the phenomena. Collisions with carbon atoms are known to cause a change in the velocity distribution of the neutrons,[9] and this will probably be the governing factor in the explanation.

The scattering from Ag and Hg present interesting cases. Both of these metals are good absorbers of "slow" neutrons. The cross sections for absorption in the whole range of the "slow region" have been found to be[10] for Ag 55×10^{-24} cm^{-2}, and for Hg 380×10^{-24} cm^{-2}. Furthermore, it is known that Ag shows marked selective absorption.

We have measured the scattering from Ag with an Ag detector with and without filtering through 0.218 g/cm^{-2} Cd. The curves are shown in Fig. 5. It will be seen that when no filter is used the scattering is small, about 9 percent, and the curve reaches saturation quickly. This indicates that the ratio of scattering to total cross section is small, most of the neutrons being absorbed in the scatterer before getting back to the detector. When the Cd filter is employed, on the other hand, the maximum observed scattering is 25 percent and the slope of the curve indicates a larger ratio of scattering to total cross section. The neutrons responsible for this scattering are probably the *B* group since the *C* group is absorbed in the Cd and the *A* group in the Ag scatterer.

The scattering from Hg with an Ag detector with and without filtering is shown in Fig. 6. When no filtering is employed the maximum scattering is 20 percent showing that a large fraction of the neutrons are absorbed in the scatterer. For those neutrons which have been filtered through Cd, however, a marked difference in the form of the curve exists. The maximum observed scattering is 55 percent and the curve is still rising at this point. The curve shows that the ratio of scattering to absorption cross section is larger in the case of the filtered neutrons (presumably groups *A* and *B*) than for the unfiltered. It is apparent, therefore, that the absorption coefficient is large in the region of thermal velocities (*C* region) and is not so large at those points in the higher energy region which correspond to the *A* and *B* group. This does not mean, of course, that the absorption may not be large in some other region of the spectrum not registered by a silver detector.

4. Temperature Effect for the Neutrons Which Effect Indium

We have measured the temperature effect on the neutrons which effect In by the method of Moon and Tillman[7] and Rasetti and Fink.[8] A block of paraffin 22 cm in diameter and 15 cm high was hollowed out so that a Dewar flask could be placed along the axis of the block. Inside of the Dewar there was located a cylinder of paraffin of 1 cm wall thickness, on the inside of which a cylindrical In detector could be placed. Arrangements were also made to interpose a cylinder of Cd (0.410 g/cm^{-2}) between the detector and the small paraffin cylinder of paraffin. The neutron source was embedded in

[9] E. U. Condon and G. Breit, Phys. Rev. **49**, 229 (1936). G. A. Fink, J. R. Dunning and G. B. Pegram, Phys. Rev. **49**, 340 (1936).

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

TABLE III. *Effect of liquid air temperatures.*

ARRANGEMENT	COUNTS
Liquid air, no Cd.	52,816
Liquid air, Cd filter	8,027
No liquid air, no Cd	44,309
No liquid air, Cd filter	7,473

the large block 9 cm off the axis so that the thickness of paraffin in a direct line between the source and the Dewar was 4 cm. The detector was activated when the inner paraffin cylinder was at liquid air temperature and when it was at room temperature, with and without the Cd filter. The In was irradiated 45 min. and counting was carried out from the fifth to the eightieth minute after irradiation. The results are shown in Table III.

Dividing the results obtained at liquid air temperature by those obtained at room temperature, when the Cd filter was present, gives the temperature ratio for the *D* group. This value turns out to be 1.08, and is the same as that obtained by Rasetti and Fink using Rh as a detector. The differences between the counts obtained with and without the Cd filter give that part of the activity due to the *C* group. The ratio of the activities due to the *C* group is 1.21.

Recently Rasetti, Fink, Goldsmith and Mitchell[11] have determined the energy of the various groups of neutrons with boron absorption. They showed that the energy of the *D* group activating Rh is approximately 0.6 ev, while the energy of those neutrons accounting for that part of the activity of In which is not effected by Cd filtering is about 0.35 ev. This small difference in energy between the two classes of neutrons would presumably now show up in the measurement of the temperature effect.

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Note Added with the Proof. R. Fleischmann[12] has recently published experiments in which he obtains much lower results for the scattering of slow neutrons from Fe and Cu than we do, and criticizes our results on the following grounds. He supposes that in our neutron beam there are a considerable number of fast neutrons which do not affect a silver detector on their way from source to scatterer. These fast neutrons are then supposed to be scattered in the Fe or Cu, return through the detector to the paraffin, and there suffer reflection with a loss of velocity which makes them capable of activating the silver detector on their second trip toward the scatterer. That this effect is playing no predominant role in our experiments can be shown by several experiments which we have already published but which we shall discuss again, in more detail, to allay this criticism.

In a group of experiments, described in our first communication,[13] we showed that, using an Ag detector, 4.3 cm of Cu as scatterer caused an increase of 52 percent in the activity of the detector. In a second experiment, a sheet of Cd 1 mm thick (0.86 g/cm²) shielded the neutron source from the detector. With this arrangement about 25 percent as many counts were obtained with Cd as without. A thickness of 4.3 cm of Cu caused an increase of about 50 percent in the count.

In another series of experiments the Ag foil was not shielded by Cd from the source, but a sheet of Cd 1 mm thick was placed on top of the foil. With this arrangement no change of activity of the detector was noted. With 4.3 cm of Cu placed above the Ag and Cd there was only an 11 percent increase instead of the 52 percent obtained without Cd. To be explicit we can use the following figures, taken directly from experiment, calculating the activity of the detector to be 1000 (the actual count was 1043):

Arrangement	Activity	Percent Scattering
Source, Ag	1000	—
Source, Ag, 4.3 cm Cu	1540	54
Source, Cd, Ag	253	—
Source, Cd, Ag, 4.3 cm Cu	392	55
Source, Ag, Cd	1000	—
Source, Ag, Cd, 4.3 cm Cu	1100	11

From the results of the experiments with and without the Cd between source and detector, one can calculate the result to be expected if the Cd is placed between detector and scatterer, assuming that the second reflection in the paraffin is negligible. It has been shown that, for those neutrons which activate Ag, the fraction transmitted by Cd is constant beyond 0.3 g/cm²,[6, 1] so that the only absorption to be considered takes place when the neutrons pass through the Cd on their way to the scatterer. The absorption on the way back to the detector may be neglected. Using the figures given above one would expect an activity of 1000+139=1139 for the arrangement (source, Ag, Cd, Cu), or an increase of 12.5 percent in substantial agreement with experiment.[14] If, on the other hand, a large number of fast neutrons were scattered from the Cu, returned to the paraffin, and were reflected back to the detector at a lower velocity, one would expect a much greater activity for the above arrangement than was actually found.

[11] F. Rasetti, G. A. Fink, H. H. Goldsmith and D. P. Mitchell, Washington meeting, Phys. Rev. **49**, 869A (1936).

[12] R. Fleischmann, Zeits. f. Physik **100**, 307 (1936).

[13] A. C. G. Mitchell and E. J. Murphy, Phys. Rev. **47**, 881 (1935).

[14] That no appreciable change of velocity takes place on scattering by Cu has been shown by us. (See ref. 1, p. 655.)