in an even triplet state can. We wish therefore to suggest this interpretation, which is hardly in serious conflict with the calculations[14] based on a Hartree model, according to which the ^2D of B^{11} is only $\sim 2.5\ mc^2$ higher than the ^2P. According to this view the resonance reaction may contribute also to the short range α-particles, and the small yield from this reaction must be ascribed to the smallness of Γ_p for a p-proton at these low energies.

With the Li reactions, one point remains a little puzzling if one accepts the usual interpretation: since normal Li^7 is almost certainly odd, the long range α-reaction must be ascribed to the capture of a p-proton, the Be_B^8 to that of an s-proton. The fact that the long range α-reaction comes from p-capture may in part account[15] for the smallness of the α-particle yield compared to that of the reaction $Li^6+H^1 \rightarrow He^3+He^4$. One would now expect that if the Be_A^8 could be formed in a ^1D state, the corresponding α-particles should be distributed in angle with marked anisotropy; and the fact that the observed distribution[16] seems to be isotropic suggests that such states contribute little to Be_A^8 in the range of energies ($\sim$250 kv) investigated. This could then only be understood if the spacing of levels of different angular momentum in Be^8, even at the high excitation of 17 Mev, were still large compared to the very considerable breadth of these levels.

[14] Feenberg and Wigner, Phys. Rev. **51**, 95 (1937); Feenberg and Phillips, Phys. Rev. **51**, 597 (1937).

[15] Compare M. Goldhaber, Proc. Camb. Phil. Soc. **30**, 561 (1934).

[16] Kirchner, Physik. Zeits. **34**, 785 (1933); Giarratana and Brennecke, Phys. Rev. **49**, 35 (1936).

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Neutron Scattering Cross Section as a Function of Energy

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The study of scattering of neutrons of energy range from 0.02 to 80 volts from Fe, Ni, and Pb has been completed by measuring the activation of Ag, Rh, and CHI_3 detectors. The scattering of C neutrons was determined indirectly by two methods, and the results agreed closely. The scattering cross section for Ni fell off slowly with neutron velocity, that for Pb increased slightly, while that for Fe remained constant over the range from 0.02 to 80 volts. The directional distribution of neutrons emerging from the top of a paraffin cylinder containing a Ra–Be neutron source was investigated by placing detectors at various distances above the top of the paraffin. The results agreed well with those calculated for a cosine distribution law.

PART I. SCATTERING CROSS SECTION

A CONSIDERABLE amount of work has been done recently on the scattering of neutrons from various materials. Mitchell and Murphy[1-2] measured the scattering cross section for a number of elements, while Pontecorvo and Wick[3] measured the reflection of neutrons from several substances and calculated scattering cross sections for a few of these. Furthermore, various materials sensitive to neutrons of different energies have been used as detectors. We have extended our experiments on the scattering of slow neutrons using various detectors and filter combinations so that we now have data on the scattering cross section of neutrons of energies from 0.02 to 80 volts for several different scattering materials.

The method used was that previously described with certain modifications which we shall show to be unessential. A cylindrical block of paraffin, 15 cm in diameter and 17 cm high, contained a source of neutrons located 6 cm from its top surface. Ag, Rh, and CHI_3 were used as detectors of the various groups of neutrons.

[1] A. C. G. Mitchell and E. J. Murphy, Phys. Rev. **48**, 653 (1935); Mitchell, Murphy, and Langer, Phys. Rev. **49**, 400 (1936).

[2] Mitchell, Murphy, and Whitaker, Phys. Rev. **50**, 133 (1936).

[3] B. Pontecorvo and G. C. Wick, Ricerca Scient. **1**, 134, 220 (1936).

The detectors were 6 by 10 cm in area and were irradiated by placing them on the top of the paraffin block for a given length of time. The scattering material, in the present instance Fe, Ni, and Pb, in the form of metallic blocks the same size as the scatterer, was placed above the detector. After irradiation the detectors were counted with the help of a tube counter and recording mechanism. The percentage scattering was plotted as a function of the thickness of the scattering material, after suitable corrections had been made for absorption in the detector.[2]

The detectors used were metallic silver, thickness 0.105 g/cm^2, for neutrons of groups C and $A+B$; and metallic rhodium, thickness 0.124 g/cm^2, for neutrons of groups C and D. These detectors were used with and without a cadmium filter, thickness 0.218 g/cm^2, which completely absorbs neutrons of group C. The neutrons which affect iodine, group I, were detected with the help of CHI_3 deposited in paraffin and mounted between thin aluminum foils. The concentration of iodine was approximately 0.1 g/cm^2, but varied slightly among the detectors in the group. The iodine detectors were always used with Cd filtering so that only I neutrons were detected. Under these conditions the fraction of neutrons transmitted by the detector was 0.80. The fraction of neutrons transmitted by the other two detectors is tabulated in the previous paper.[2]

In the earlier work the neutron source consisted of a small glass bulb containing beryllium and radon in amounts up to 300 millicuries. In the present work the source consisted of 211 mg of radium, in the form of $RaCl_2$, mixed with 5 grams of beryllium powder, contained in a brass capsule 2 cm in diameter and 5 cm long. The capsule was placed in the paraffin with its axis parallel to the top surface and so that its center was on the axis of the paraffin cylinder. With the axis of the capsule 6 cm below the top surface of the paraffin, the activity of an Ag detector irradiated with the radium-beryllium mixture was compared with that obtained when a mixture of radon and beryllium, of known strength, was used under the same geometrical conditions. The activity per millicurie was found to be the same, to within 10 percent, in either case. Furthermore, certain scattering curves taken with the radon-beryllium source were redone with the radium-beryllium source and the results were in agreement.

Since the activity of the iodine detector was rather weak it was found necessary to place the neutron source closer to the top surface of the paraffin. A new cylinder of paraffin was prepared, having the same dimensions as the previous one, except that the neutron source was placed 4 cm below the surface. Since the relative scattering cross section depends on the geometry of the beam, corrections had to be made so that all cross sections would be on the same basis. This was accomplished by running a scattering curve for Fe with an Ag detector with Cd filtering, first with the arrangement in which the neutron source was 4 cm below the surface of the paraffin and second when it was 6 cm below. The results for the iodine detector were then corrected to standard conditions, i.e., source 6 cm below surface, by multiplying by the ratio.

Source 6 cm below surface/Source 4 cm below surface.

The scattering curves were similar to those previously published[2] and consisted of one portion in which the scattering for small thicknesses of scatterer, was proportional to the thickness, and another portion for larger thicknesses in which the scattering eventually became independent of the thickness. Over the linear portion of the curve the slope may be equated to $N\sigma$, where σ is the relative scattering cross section and N the number of scattering nuclei per cm^3. The relative scattering cross sections for the elements Fe, Ni, and Pb for neutrons affecting the various detectors are shown in Table I.

From Table I the scattering cross section for the C neutrons can be obtained in two ways: (1) From the scattering cross sections found with the Ag detector; and (2) from similar results with the Rh detector. The scattering cross section for neutrons of two groups x and y can be calculated from that for the separate groups from the relation

$$\sigma_{x+y}=\frac{n_x}{n_x+n_y}\sigma_x+\frac{n_y}{n_x+n_y}\sigma_y, \qquad (1)$$

where $n_x/(n_x+n_y)$ is the fraction of the activity of the detector due to group x. For the arrangements we have used we find that in the Ag detector the fraction of the activity due to group

TABLE I. *Relative scattering cross sections* $\times 10^{24}$ *cm*^{2}.

GROUP ELEMENT	$A+B+C$	$A+B$	D	I	$C+D$
Fe	10.5	11.6	10.0	10.8	9.3
Ni	18	13.4	11.9	12	17
Pb	7.7	12.3	6.6	13	—

C is 0.75 and that due to $A+B$ is 0.25; while for Rh we find 0.72 due to C and 0.28 due to D. Using this method in conjunction with the results shown in Table I we find:

For Fe

$$(\sigma_c)_{Ag}=10.2 \quad 10^{-24} \text{ cm}^2;$$

and

$$(\sigma_c)_{Rh}=9.1 \quad 10^{-24} \text{ cm}^2.$$

For Ni

$$(\sigma_c)_{Ag}=19.5 \quad 10^{-24} \text{ cm}^2;$$

and

$$(\sigma_c)_{Rh}=18.9 \quad 10^{-24} \text{ cm}^2.$$

The agreement is therefore quite good for σ_c calculated from two different detectors.

The scattering cross section is shown as a function of the energy of the neutrons in Table II. The values for the energy of the various groups are taken from the paper of Goldsmith and Rasetti,[4] who determined these energies from the absorption coefficient in boron.

It will be seen from Table II that, in the case of Fe, the scattering cross section is independent of energy. Ni shows a larger cross section for thermal neutrons than for those of higher velocities, while the reverse is true for Pb. It is known from the work of Breit and Wigner[5] that the scattering cross section will be affected by the positions and widths of the resonance levels of the scatterer. These factors are not known for the elements in question so that it is difficult to predict the dependence of scattering cross section on energy. It would appear that, since the scattering cross section in Pb is small in the region up to 3.5 volts, there are probably resonance levels giving rise to absorption in this region.

[4] H. H. Goldsmith and F. Rasetti, Phys. Rev. **50**, 328 (1936).
[5] G. Breit and E. Wigner, Phys. Rev. **49**, 519 (1936).

TABLE II. *Scattering cross section as a function of neutron energy.*

GROUP	ENERGY (VOLTS)	SCATTERING CROSS SECTION $\times 10^{24}$ cm^2		
		Fe	Ni	Pb
C	0.02	9.8	19.2	6.2
D	1.16	10.0	11.9	6.6
$A+B$	3.5	11.6	13.5	12.3
I	80	10.8	12	13

PART II. DIRECTIONAL DISTRIBUTION OF NEUTRONS EMERGING FROM PARAFFIN

Some time ago Mitchell and Murphy[1] reported experiments in which they attempted to measure the directional distribution of neutrons emerging from the top of the paraffin cylinder. Recently Amaldi and Fermi,[6] from measurements of the activity of detectors at small distances below the top surface of the paraffin cylinder, came to the conclusion that the thermal neutrons issued from the surface of the paraffin according to the law $\cos\theta+\sqrt{3}\cos^2\theta$. We have repeated the experiments of Mitchell and Murphy with the object of testing the above law, through measurements of the intensity of the neutron beam outside of the paraffin.

In the present experiments the top surface of the paraffin was covered with a sheet of Cd, 1 mm thick in the center of which there was a rectangular aperture 6×10 cm. Ag detectors, 6×10 cm, could be placed at various positions above the top surface of the paraffin. Arrangements were also made to place an additional Cd filter (0.218 g/cm^2) over the aperture so that the activity of the Ag detector due to C neutrons could be obtained by the difference in activity with and without the Cd filter. Furthermore, sheets of Ag 1 mm thick were placed on the top of the bucket covering the whole surface except the 6×10 cm opening. This was done to prevent neutrons issuing from the outer edges of the paraffin surface from being recorded by the Ag detector. Direct experiment showed that 1 mm Ag, used as an absorber, diminished the activity of an Ag detector irradiated with neutrons filtered through 0.218 g/cm^2 Cd to 46 percent of its original intensity.

[6] E. Amaldi and E. Fermi, Ricerca Scient. **1**, 11–12, p. 1 (1936); Phys. Rev. **50**, 899 (1936).

With the 211 mg radium-beryllium source, measurements were made with the Ag detector at several different distances above the paraffin surface both with and without the additional filter of Cd. The difference in the activity of the detector with and without Cd filtering (effect due to C neutrons) was plotted as a function of the distance above the top surface of the paraffin. A smooth curve was drawn through the points and the following points taken off the curve are shown in Table III together with points calculated for a theortical neutron distribution, which will be discussed below.

To compare our results with theory we made the following calculations: (1) The number of neutrons emerging from a rectangular aperture of area $dxdy$ and striking a parallel detector area $dx'dy'$ located r_0 cm above the aperture is given by

$$dn = n_0 \cos^2\theta \, dxdy \, dx'dy'/\pi r^2, \qquad (2)$$

where n_0 is the number emerging per unit area, r is the distance between $dxdy$ and $dx'dy'$, and θ is the angle between r and the normal to $dxdy$. The assumption here is that the neutron intensity falls off as the square of the distance and that the directional distribution follows the simple geometrical cosine law. This equation was integrated over the length and breadth of the aperture and the detector of the same size and shape. The resulting equation is omitted, but the results of the calculations are shown in column 3 of Table III. (Ratio of n/n_0.)

(2) According to Amaldi and Fermi, the distribution of neutrons differs from the cosine law, so that Eq. (2) should read

$$dn = n_0(\cos^2\theta + \sqrt{3}\cos^3\theta)dxdy\,dx'dy'/\pi r^2. \qquad (3)$$

We have also integrated this equation and find as may be expected that over relatively large detector and aperture areas there is almost no difference between the two resulting distributions. It is also to be expected that the Fermi and Amaldi distribution should give a relatively higher value of n/n_0 at small distances. This is confirmed by comparing the results in columns 3 and 4 of Table III, but the difference is seen to be far below the experimental error of measurement and therefore beyond observation.

Experiments were tried and calculations made for small apertures and large detectors. Because of the weak intensity of the neutron beam, the maximum predicted differences between the results for large and small apertures were of the same size as the experimental error.

The following conclusions can be drawn from these experiments: (1) The experimental results for detectors and apertures of the same size are in essential agreement with the cosine law of distribution. (2) The law of Amaldi and Fermi differs so little from the cosine law for large apertures and detectors that the experiments could not possibly differentiate between them.

Finally, in comparing curves for the total activity of the Ag detectors, activiated by neutrons of groups C, A and B (i.e. with no Cd absorber over the aperture) taken using a radon-beryllium source or the radium-beryllium source, it was found that the points fitted the same curve to better than 5 percent. Since the radon-beryllium mixture was contained in a small bulb about 1 cm in diameter and the radium-beryllium source in a cylinder of much larger dimensions, it follows that the distribution of neutrons issuing from the paraffin is dependent on the amount of paraffin present and the size of the aperture but does not depend critically on the size or shape of the neutron source.

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TABLE III. *Intensity of neutron beam as a function of distance from upper surface of paraffin.*

DISTANCE (cm)	OBSERVED	INTENSITY CALCULATED ($\cos\theta$)	CALCULATED ($\cos\theta + \sqrt{3}\cos^2\theta$)
0	1.000	1.000	1.000
1	—	0.776	0.787
2	0.590	0.615	0.625
3	0.461	0.488	—
4	0.361	0.400	—
5	0.290	0.322	0.322
6	0.250	0.265	—
7	0.215	0.222	0.227