Scattering of Slow Neutrons

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With the radioactivity produced in a silver foil as a detector of neutrons, the scattering of slow neutrons by the metals Fe, Cu, Pb, Sn and Hg has been investigated. Curves showing percentage scattering as a function of thickness are given, from which the relative cross section for scattering has been calculated.

INTRODUCTION

DUNNING, Pegram, Fink and Mitchell[1] and Amaldi, D'Agostino, Fermi, Pontecorvo, Rasetti and Segrè[2] have investigated the absorption of slow neutrons by various metals. Dunning[3] has also measured the absorption of fast neutrons by a large number of substances. In these experiments, an almost parallel beam of neutrons was incident on an ionization chamber containing hydrogen, or in the later experiments lithium, as a detector. The interposition of various metals caused a decrease in the number of neutrons entering the chamber. The number was found to decrease exponentially with the thickness of the absorber and from these data an absorption coefficient and hence a cross section for absorption could be obtained. In the experiments with slow neutrons, a sphere of paraffin, 6 cm in diameter, surrounded the neutron source, and the absorption of the slow neutrons was measured in the same manner as before. In the experiments of Fermi and his collaborators, however, the radioactivity produced by neutrons in a silver or rhodium sheet served as an indicator of the number of neutrons. The absorption was then obtained by noting the decrease in the activity of the silver or rhodium sample as a function of the thickness of absorber.

Dunning found a monatonic increase in cross section with increasing atomic weight of scatterer in the case of fast neutrons. For the slow neutrons, however, certain metals, notably cadmium and mercury, showed absorption cross sections considerably higher than they showed for fast neutrons. In the case of elements showing small cross sections, it was generally supposed that the absorption was due largely to scattering of neutrons out of the beam rather than to true absorption. The large cross sections to slow neutrons exhibited by some substances was attributed to capture of the neutrons by these metals.

Up to the present there have been very little data obtained for the scattering of neutrons by various metals. Indeed, it is difficult to devise an experiment for this purpose in which one is sure that multiple scattering and absorption are not playing a predominant role. The purpose of this paper is to report some experiments which throw some light on this problem and from which can be obtained relative scattering cross sections for some metals. A preliminary report on the scattering by iron and copper appeared at an earlier date,[4] and the present work confirms and amplifies this.

APPARATUS AND METHOD

The apparatus, shown in Fig. 1, consisted of a cylindrical bucket filled with paraffin, in which was placed a bulb, *S*, containing radon (250 millicuries to 60 millicuries) and beryllium. After passing through approximately 6 cm of paraffin, the neutrons struck a silver foil, 6×10 cm, and then were scattered from blocks of metal, the same size as the foil, placed above it. The scattering was measured by observing the increase in the radioactivity of the silver foil caused by the presence of various thicknesses of scatterer.

The activity of the foil was measured with the help of a Geiger-Müller tube counter. The

[1] J. R. Dunning, G. B. Pegram, G. A. Fink and D. P. Mitchell, Phys. Rev. **47**, 416 (1935).
[2] E. Amaldi, O. D'Agostino, E. Fermi, B. Pontecorvo, F. Rasetti and E. Segrè, Proc. Roy. Soc. **A149**, 522 (1935).
[3] J. R. Dunning, Phys. Rev. **45**, 586 (1934).
[4] A. C. G. Mitchell and E. J. Murphy, Phys. Rev. **47**, 881 (1935).

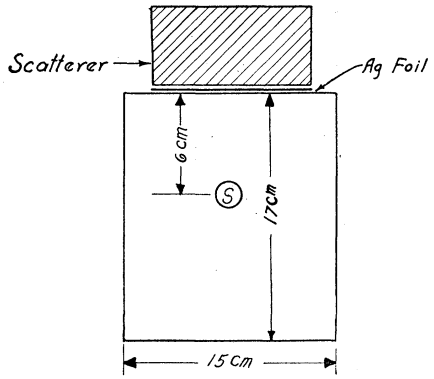

FIG. 1. Apparatus.

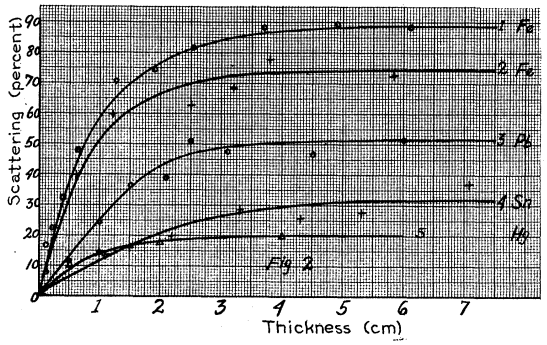

FIG. 2. Scattering of slow neutrons by Fe, Pb, Sn and Hg.

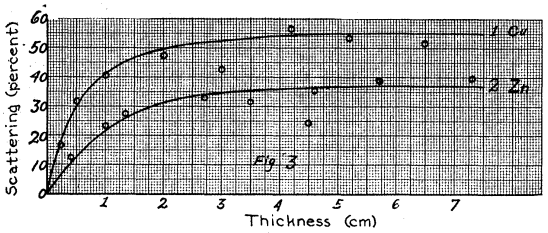

FIG. 3. Scattering of slow neutrons by Cu and Zn.

counters used in these experiments were made of thin-walled aluminum tubing and were filled with either argon or air. The potential was supplied to the case by a stabilized voltage source which kept the voltage constant to within 0.1 percent. The impulses from the counter were amplified and then fed into a thyratron "scale of two counter."

The usual procedure in carrying out the experiment was to irradiate the silver foil, with no scatterer present, for six minutes. The foil was then removed and wrapped around the tube counter. Counting was begun one minute after removing the foil from the source and continued until the end of the fifth minute. The total count in this interval, minus the natural background of the counter, was then recorded. In the scattering experiments blocks of metal of various thicknesses were placed directly above the foil, which was then irradiated and counted in the same manner as before. The percentage scattering was then obtained by subtracting the activity of the foil with no scatterer present, corrected for radon decay, from that with scatterer present and dividing by the activity of the foil alone. In this way a curve could be plotted in which the percentage scattering appeared as ordinate and the thickness of scatterer as abscissa.

RESULTS

The results of the experiments are shown in Figs. 2 and 3. All curves except curve 2 of Fig. 2 were taken under identical conditions. It should be noted that all the curves start out nearly linearly from the origin and then bend off gradually to a region in which the scattering is independent of thickness. This latter region is difficult to interpret since multiple scattering and absorption are probably playing a large role. On the other hand, in the initial part of the curves it is reasonable to suppose that single scattering is predominant, since the scattering is proportional to the thickness.

If single scattering obtains, the slope of the curves as they come out of the origin should be given by $N\sigma^2 c(\theta)$, where N is the number of atoms per cc, σ^2 the collision cross section for scattering, and $c(\theta)$ is a quantity which gives the fraction of neutrons which are scattered through an angle θ sufficiently great so that they will return and strike the foil. This quantity will depend on the angular scattering function, $f(\theta)$, which is supposed to be a constant for slow neutrons,[5] and the angle which the oncoming neutrons make with a plane through the detecting foil. This latter is not definitely known, as the neutrons probably have all directions

[5] H. A. Bethe and R. Peierls, Proc. Roy. Soc. **A149**, 176 (1935).

between nearly 0° and 180° with a line drawn in this plane parallel to the long direction of the foil. Experiments, in which the activity of the silver foil was measured as a function of the distance from the top of the paraffin, showed that the neutron beam was in effect not parallel. Furthermore, experiments were performed in which the foil was placed at 2.5 cm and 4.5 cm, respectively, from the top of the paraffin and scattering curves taken for iron, with the scatterer placed directly above the foil. The slopes of the curves became smaller as the distance from top of paraffin to foil increased. This is to be expected since the fraction of scattered neutrons which return to the foil becomes less as the angular divergence of the beam decreases. The geometry was, however, not simple enough to allow one to calculate $c(\theta)$. Since the same geometry was used for all scattering curves shown in Figs. 2 and 3, it will be sufficient to put $c(\theta)=1$ and calculate the *relative* scattering cross sections. The values thus obtained are given in Table I, along with the absorption cross sections given by Dunning and collaborators.[6]

It will be seen from the table that, with the exception of mercury, the scattering cross sections are of the same order of magnitude and have the same relative size for the elements iron to tin as the observed absorption cross sections.

The case of mercury is of particular interest since the absorption cross section has been shown to be extremely large by both Dunning and Fermi. The scattering experiments on mercury were carried out on the liquid, which was contained in a "tin" box, the scattering from which was previously found to be negligible. It will be seen from curve 5 of Fig. 2 that the scattering curve rises very slowly and that the total scattering is never greater than 20 percent.

TABLE I. *Relative scattering cross sections for slow neutrons.*

METAL	CROSS SECTION	
	Scattering	Absorption
Fe	9.9	12.0
Pb	7.2	8.6
Cu	7.7	7.5
Zn	3.4	4.7
Sn	3.8	4.0
Hg	4.4	380

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

The curve indicates that the scattering cross section is not anomalously large and, on account of the small scattering at thicknesses of 3 to 4 cm, that the absorption cross section is relatively big. This is in agreement with the idea that the large absorption cross section is due to capture.

Some experiments have been performed which were designed to show whether the velocity distribution of the neutrons is changed on scattering from various materials. For example, if some of the faster neutrons are slowed down on being scattered by a metal, they might cause a greater activity in the silver than if their velocity had not been changed. It was first ascertained that a sheet of cadmium 0.25 mm thick, placed between the paraffin and foil, decreased the total count given by the foil (no scatterer present) from 2600 in four minutes to 800. An additional 0.25 mm sheet only reduced the count to 700. Measurements were then made with a 0.25 mm cadmium sheet between the neutron source and foil, and readings were taken with the scatterer in place with and without a second cadmium sheet 0.25 mm thick between the silver foil and the scatterer. Within the limits of error the results showed that the count was the same with or without the second cadmium sheet for the scatterers iron, tin, lead and copper. In the case of zinc a somewhat smaller count was obtained with the second sheet of cadmium in place than without it. The effect was small, however, and lay just outside the limit of error. If the scatterers had been very effective in slowing down neutrons of the velocity range used, a considerable decrease should have been detected when the second cadmium sheet was in place, since it would have been very effective in removing the slower neutrons from the scattered beam. No large effect was found, however, and one should therefore conclude that, for neutrons that have passed through 6 cm paraffin, the metals investigated, with the exception of zinc, do not slow the neutrons down further.

Finally, a scattering curve for iron was taken in which the neutrons, issuing from the paraffin, had passed through a sheet of cadmium 0.65 mm thick, placed between the paraffin and the silver foil. The scatterer was placed above the foil in the usual manner. The results are shown in

curve 2 of Fig. 2. The neutrons striking the scatterer are presumably faster than if no cadmium had been present. It will be seen from the curve that the scattering from iron is less for these neutrons than for those which have not passed through cadmium. The cross section, calculated from the curve, is 8.1×10^{-24} cm^2.

We are indebted to Mr. Lawrence M. Langer for help in taking some of the readings and to Dr. C. B. Braestrup of the Physical Laboratory of the Department of Hospitals of the City of New York for many favors. We also wish to acknowledge our indebtedness to the American Association for the Advancement of Science for a grant to one of us (A. C. G. M.) with the aid of which apparatus has been purchased.

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The Spectrum of the Zinc Arc in Vacuum

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Sixty lines in the spectrum of the vacuum zinc arc have been observed in the wave-length range 2178A to 7799A. All known solar zinc lines, including two not hitherto listed, are included. A suitable source for obtaining weak lines in vacuum is described. The stronger lines of the following elements were observed: Pb, Cu, Cd, Ag, Sn, Na, K, Rb, Cs, Sr, Be. The observations were made by means of the F and P interferometer, and by various gratings and prisms.

THE spectrum of the zinc arc was observed with a view to obtaining accurate vacuum wave-lengths of all those lines which are now, or might soon be, of astrophysical importance. This object has perhaps been attained, since precise values have been measured for the lines which have been identified as zinc in the *Rowland Revision*.[1] Two additional solar lines, both weak, are probably due at least in part to zinc. These are λ4292A and λ7799A.

The derivation of precise values of the atomic levels of an element usually makes it possible to compute accurate wave-lengths of lines which cannot be easily observed, either because the lines are faint, or because they lie in an inaccessible region of the spectrum. In the case of our work on zinc, only two such lines can be computed; λ1404A and λ1457A. The combinations of the low singlet S with the odd triplet P terms give rise to lines in the Schuman region; these are undoubtedly quite faint. Other possible combinations give lines in the far infrared.

The source of the zinc spectrum of wave-length less than 3700A was an arc in vacuum between brass electrodes, operated at 4 amperes. In the longer region, special brasses containing up to 80 percent zinc[2] were used in addition to commercial brass. Whatever the initial percentage of zinc, after the arc had run five minutes the tips of the electrodes were reduced to that alloy which remains stable at the operating temperature, and this is very low in zinc.

The strong lines of zinc can be observed in sharp condition and with reasonable exposure times by using carbon electrodes which have been soaked in a solution of a zinc salt. To obtain satisfactory sharpness, the amperage must be low. Zinc sulphate packed into a thin-walled copper or silver tube proved to be a fairly satisfactory source. For the weak lines, requiring long exposure at high current, the most satisfactory source was a pool of molten zinc held in a large brass cup, and an upper electrode of sterling silver. The use of copper as an upper electrode caused the zinc to oxidize more rapidly than was the case when silver was used; this made it

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[1] St. John, Moore, Ware, Adams, and Babcock, *Revision of Rowland's Preliminary Table of Solar Spectrum Wavelengths* (1928).

[2] Kindly alloyed for us by Federated Metals Corporation.