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Inelastic Scattering of Fast Neutrons by Fe, Pb, and Bi

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Measurements of inelastic scattering effects of $Ra-\alpha-Be$ and $Ra-\alpha-B$ neutrons in Fe, Pb, and Bi have been made. A U^{238} fission threshold detector was used. The method consisted in measuring the fission counting rate in the detector with and without the spherical scatterer surrounding the source. From the decrease in the counting rate caused by the presence of the scatterer, values of the cross section for inelastic scattering to below the U^{238} fission threshold were calculated for several assumed values of the elastic scattering cross section.

I. INTRODUCTION

THIS report describes some experiments performed by the authors in the early part of 1943 at the Metallurgical Laboratory of the University of Chicago under the auspices of the Manhattan District. The purpose of the experiments was to measure the cross sections of Fe, Pb, and Bi for inelastic scattering of fast neutrons. As sources of fast neutrons $Ra-\alpha-B$ and $Ra-\alpha-Be$ mixtures[1] were used. For detector, the fast fission of U^{238} with a threshold of about one Mev was employed. Because fast fission of U^{238} was used as detector, the experiment dealt only with that part of the neutron source spectrum which is above the threshold energy. More exactly, the inelastic scattering cross section measured is an average for all the energies in the neutron spectrum of the cross section for scattering of these neutrons to below the threshold.

II. EXPERIMENT

The experimental procedure is patterned after that used by Szilard and Zinn.[2] Figure 1 is a schematic diagram showing the experimental arrangement. A source of fast neutrons was placed at a given distance from a spherical uranium-coated ionization chamber. The chamber was connected in the conventional manner to a linear amplifier and scaling circuit for the purpose of counting fission pulses. The chamber was surrounded by Cd so that neutrons which may have been slowed down to thermal energies by collisions with the walls of the room would be prevented from causing fissions in the U^{235}. There were, possibly, some fissions in U^{235} resulting from epi-cadmium neutrons, but the number of these relative to the number of fast fissions in U^{238} must be small, since the relative amount of U^{235} in normal uranium is small, and the source emits no slow neutrons. The fission counting rate is then proportional to the fast neutron flux through the chamber. (A fast neutron in this report is defined to be one whose energy is above the U^{238} fission threshold.) The source is then surrounded by a sphere of scattering material and the measurement of the fission counting rate repeated. The ratio of counting rates, with to without scatterer, is thus determined. From this ratio the inelastic scattering cross section may be derived. Table I gives the measured values of this ratio, called F, for the various scatterers used.

III. INTERPRETATION

The ratio of fast fission counting rates, F, is equal to the ratio of fast fluxes through the fission chamber. From F it is possible to obtain the ratio, F', of the number of fast neutrons emerging from the scattering sphere to the number of fast neutrons emitted by the source. Since the presence of the sphere (and elastic scattering in the sphere) gives the emerging neutrons an angular distribution which no longer corresponds to a point source, F' and F are not precisely equal. An estimate of the upper limit of the difference between F and F' indicated that, for the small spheres and large source to

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[1] H. L. Anderson and B. T. Feld, Rev. Sci. Inst. 18, 186 (1947).

[2] Private communication.

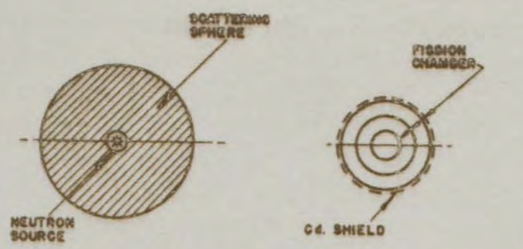

FIG. 1. Schematic diagram of experimental arrangement.

detector distances used in the experiments, the difference was always less than 1 percent. This correction has been applied in the interpretation of the data.

The simplest interpretation of the experiments assumes that the only possible process is one of inelastic scattering. For fast neutrons the capture cross section can be considered negligible in comparison. Thus, if λi is the mean free path for inelastic scattering in the sphere, the number of fast neutrons emerging is

$$F=e^{-t/\lambda i}, \tag{1}$$

where t is the thickness of the sphere (the radius minus the small amount cut out to accommodate the source).

This interpretation is satisfactory if: (1) the thickness of the sphere is small compared to the mean free path for total (elastic plus inelastic) scattering; (2) the elastic scattering cross section is small compared to the inelastic scattering cross section. The values for inelastic scattering cross section found in this approximation are given in column 6 of Table I.

Elastic scattering will cause a decrease in the number of fast neutrons emerging from the scattering sphere. For elastic scattering increases the path of the fast neutrons in the sphere and, thus, gives them a greater opportunity to suffer inelastic collisions. The larger the sphere, the more pronounced will be the effect of elastic scattering on the number of emergent fast neutrons. To calculate this effect we classify the neutrons as primary, first, second, etc., generation fast neutrons. A primary fast neutron is one which emerges from the sphere without having suffered any collisions; a first generation fast neutron has suffered one elastic but no inelastic collision, etc.

For one fast neutron starting out from the source, the number of primary fast neutrons emerging from the sphere is

$$f_0=e^{-t/\lambda}, \tag{2}$$

where t is the thickness of the sphere, λ is now the mean free path corresponding to both elastic and inelastic scattering.

The primary neutrons act as a source of first generation fast neutrons. The number of these produced in the sphere is $(1-f_0)(\sigma_{\mathrm{elastic}}/\sigma_{\mathrm{total}})$. The density of first generations neutron is proportional to

$$1/r^2e^{-r/\lambda},$$

where r is the distance from the center of the source in the sphere. The fraction of these emerging as fast neutrons from the sphere, f_1, can no longer be calculated as simply as though the source were at the center; however, it can be computed in a straightforward fashion by performing numerical integrations. The number of first generation neutrons emerging per primary fast neutron is then

$$F_1=(1-f_0)\frac{\sigma_{\mathrm{el}}}{\sigma_{\mathrm{total}}}f_1\equiv p_0f_1. \tag{3}$$

The number of second generation neutrons produced is $p_0(1-f_1)(\sigma_{\mathrm{el}}/\sigma_{\mathrm{total}})\equiv p_0p_1$. Of these, the fraction f_2 emerges fast from the sphere. f_2 may be calculated if we know the source distribution of second generation neutrons in this sphere. For the second and all further generations, we have assumed a neutron density proportional to $1/r^2$. Using this calculated $f_2=f_3=\cdots=f_n$, the number of second generation neutrons emerging from the sphere, F_2, is $p_0p_1f_2$ and the number of third generation neutrons produced is $p_0p_1p_2$. The number of third generation neutrons emerging from the sphere is $p_0p_1p_2f_2\equiv F_3$.

Calculating in this way the number of fast neutrons escaping for each generation, we have for the nth generation

$$F_n=p_0p_1p_2^{\,n-2}f_2. \tag{4}$$

The total number of fast neutrons escaping from

TABLE I. Pairs of σ_i and σ_{el} to give measured ratios, F.

Source	Scatterer	Radius of scatterer, cm	Thickness of scatterer, cm	F	σ_i in Barns $\sigma_{el}=0$	1	2	3	4
RaB	Bi	8.29	7.10	0.79 ± 0.02	1.18	1.12	1.08	1.05	0.97
		12.02	10.86	0.69 ± 0.02	1.21	1.14	1.05	0.97	0.90
	Pb	8.21	7.22	0.80 ± 0.02	0.94	0.88	0.83	0.77	0.72
		10.72	9.55	0.71 ± 0.02	1.12	1.04	1.00	0.88	0.80
	Fe	5.70	4.60	0.73 ± 0.02	0.88	0.78	0.69	0.60	0.49
		8.33	7.14	0.62 ± 0.02	0.82	0.71	0.60	0.47	0.35
Ra-Be	Bi	8.29	7.30	0.73 ± 0.02	1.56	1.48	1.38	1.29	1.20
		12.02	11.10	0.64 ± 0.02	1.44	1.35	1.24	1.14	1.06
	Pb	8.21	7.47	0.74 ± 0.02	1.26	1.19	1.11	1.04	0.95
		10.72	9.79	0.64 ± 0.02	1.42	1.34	1.23	1.12	1.00
	Fe	5.70	4.80	0.68 ± 0.02	1.05	0.92	0.80	0.71	——
		8.33	7.38	0.57 ± 0.02	1.00	0.83	0.72	0.62	——

the sphere is, thus,

$$F=\sum_{n=0}^{\infty} F_n=f_0+f_1p_0+f_2p_0p_1+f_2p_0p_1p_2+\cdots+f_2p_0p_1p_2^{n-2}, \quad (5)$$

$$F=f_0\left\{1+p_0\left[\frac{f_1}{f_0}+\frac{p_1}{1-p_2}\frac{f_2}{f_0}\right]\right\}. \quad (6)$$

The number which have suffered an elastic collision before escaping is obtained by summing all generations except the primary.

$$\sum_{n=1}^{\infty} F_n=p_0\left[f_1+\frac{p_1}{1-p_2}f_2\right]. \quad (7)$$

It is to these neutrons that the correction for angular distribution must be applied. A series of calculations has been carried out using the above formulae and different values of σ_{el}. From these, the values of σ_i, the inelastic scattering cross section, best fitting the experimental ratio have been found for a number of different values of σ_{el}. These are given in Table I.

IV. CONCLUSIONS

If the only effects taking place in the scattering spheres were those discussed above, and if the above outlined method of calculation of these effects were adequate, then there should be one combination of inelastic and elastic scattering cross sections leading to the measured F for the two different thicknesses of scatterer used for each type of material. A glance at the table serves to show that this is not the case.

One possible reason for the failure of the simple interpretation outlined above is that there is another effect which tends to decrease the inelastic scattering cross section (as measured in this experiment) as the size of the scattering sphere is increased. This effect is in the nature of

TABLE II. Inelastic scattering cross sections (barns).

Neutron source	Detector	Lead	Bismuth	Iron	Reference
Ra-Be	$Fe^{56}(n,p)Mn^{56}$	2.13 ± 0.24	2.32 ± 0.20		(3)
	$Al^{27}(n,p)Mg^{27}$	1.97 ± 0.16	1.98 ± 0.09		(3)
	$Cu(n,n\gamma)$	0.91 ± 0.08	0.63 ± 0.09	0.57 ± 0.05	(3)
	$Pb(n,n\gamma)$	0.73 ± 0.16		0.62 ± 0.07	(3)
Rn-Be	$Si(n,p)$	1.4	1.3		(4)
	$Al(n,p)$	1.8		1.1	(4)
	U^{238} fission	1.34	1.85		(5)
d-d	U^{238} fission	0.55	0.64		(6)

[3] D. C. Graham and G. T. Seaborg, Phys. Rev. 53, 795 (1938).
[4] C. H. Collie and J. H. E. Griffiths, Proc. Roy. Soc. A155, 434 (1936).
[5] J. Marshall and L. Szilard, priv. comm.
[6] W. H. Zinn and L. Szilard, priv. comm.

a "hardening" effect, arising out of the fact that the "cross section for inelastic scattering to below the U^{238} fission threshold" decreases with increasing neutron energy, so that the neutrons with energy close to the threshold are more rapidly removed from the fast neutron beam than those neutrons of energy far above the threshold. The sources emit a spectrum of energies going up (in the case of $Ra-\alpha-Be$) to about 12 Mev.

It should be stressed that what we call, for the purposes of this report, inelastic scattering is really only a special type of inelastic scattering wherein the original fast neutron loses enough energy to drop below the threshold of our detector. Strictly speaking, inelastic scattering is a process in which the scattering nucleus is left in any one of the (energetically) possible excited states; elastic scattering (except for "shadow" scattering) is a special case where the nucleus ends up in its ground state. Of all the possible states in which inelastic scattering can leave a nucleus, our method of measurement picks out only those scatterings in which the neutron loses enough energy to drop below the threshold. For neutrons of energy very much greater than 1 Mev, most inelastic scatterings will not be detected. Our experiment is most sensitive for neutrons close to the threshold. On the other hand, since more levels become available with increasing neutron energy, the true inelastic scattering cross section increases with energy until it reaches the value πR^2 (the cross section for formation of the compound nucleus).

Little is known about the energy spectra emitted by the sources used in this experiment beyond the fact that both emit a rather broad distribution of energies, with both the average and the maximum energy being greater for the $Ra-Be$ source.[7] Because we do not know the energy distributions, nor the details of the level schemes of the nuclei involved, none of the effects mentioned above could be calculated or even estimated for our experiment. Hence the uncertainty in the results, as indicated by the values in the table. For all three elements, however, the inelastic scattering is greater for $Ra-Be$ than for $Ra-B$ neutrons. For the three elements investigated the inelastic scattering increases with atomic weight.

What is really needed for a determination of details of the inelastic scattering process is a series of experiments involving the scattering of monoenergetic neutrons and measurements of the energy distribution of the scattered neutrons. This has been done in one instance.[8] In most cases other observers have also used non-monochromatic neutron sources and threshold detectors. Their results are equally difficult to interpret rigorously. A compilation of values of other observers is given in Table II.[9]

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[7] B. T. Feld, R. Scalettar, and L. Szilard, Phys. Rev. 71, 464 (1947).

[8] H. F. Dunlap and R. N. Little, Phys. Rev. 60, 693 (1941).

[9] Note added in proof: See also the recent work of H. H. Barschall, J. H. Manley, and V. F. Weisskopf, Phys. Rev. 72, 875 (1947), and H. H. Barschall, M. E. Battat, W. C. Bright, E. R. Graves, T. Jorgensen, and J. H. Manley, Phys. Rev. 72, 881 (1947).