Elastic and Inelastic Scattering of Fast Neutrons

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Cross sections for the combined processes of absorption+inelastic scattering of fast neutrons ($E \gtrless 4.5$ Mev and $E \gtrless 7$ Mev) have been measured for a number of elements by the use of absorbing cylinders and aluminum or iron detectors. A smooth increase with increasing atomic number is found. For neutrons of energies $\gtrless 7$ Mev the ratio of these cross sections to the cross sections for absorption+total scattering (Dunning) is nearly constant at a value of about 0.4. The existence of a scattering of fast neutrons in which little or no energy is lost has been demonstrated experimentally and approximate cross sections for the process have been obtained. Cross sections for an "effective absorption" of medium fast neutrons have also been determined. These cross sections, which are smaller than those obtained for the faster neutrons mentioned above, show a maximum at about $Z=50$ and a marked decrease for the heaviest elements. The cross sections obtained by Aoki and Lea from experiments on the yield of gamma-rays from the action of fast neutrons on matter are in agreement with the present results.

Introduction

The absorption scattering cross sections of atomic nuclei for fast neutrons have been measured for a considerable number of elements by Dunning.[1] These cross sections are the sum of the cross sections for three types of interaction of fast neutrons with nuclei: (a) absorption (transmutations due to simple capture, proton emission, double neutron emission, or alpha-emission), (b) elastic scattering, and (c) inelastic scattering. Experiment has not yet shown decisively what fraction of the total cross section is due to each of the three named processes. In the present investigation two series of experiments have been performed which yield cross sections of atomic nuclei for the combined processes of absorption and inelastic scattering for fast neutrons having energies greater than 4 and 7 Mev, respectively. As Weisskopf has pointed out,[2] the results of experiments on the inelastic scattering of such fast neutrons are especially suitable for theoretical investigation because the number of excited states in which the nucleus may be left when the neutron is reemitted will be large enough to make statistical considerations valid. Effective absorption cross sections for medium fast neutrons (so called in order to distinguish them from the faster neutrons used in the first-mentioned experiments) were reported in a previous paper.[3] These measurements have been repeated and extended to include a greater number of elements. Interesting comparisons can now be made between the results obtained with neutrons of different energies, and the conclusions thus reached are of assistance in interpreting the measurements of Aoki[4] and Lea[5] on the intensities of the gamma-rays excited by fast neutrons in various substances.

Scattering of Fast Neutrons

The considerations of Bohr[6, 7] have shown that the phenomena which occur upon the impact of a neutron (or other heavy particle) with an atomic nucleus must be treated as two independent processes, namely the formation and eventual breaking up of an intermediate metastable compound nucleus. Frenkel made the suggestion that the compound system formed by the impact of a fast neutron with a nucleus may reemit a neutron with an energy corresponding to the "temperature" of the residual nucleus, in a manner analogous to an ordinary evaporation process.[8] This process of inelastic scattering was treated in a quantitative manner by Weisskopf[2] who applied statistical methods to the case

[1] Dunning, Phys. Rev. **45**, 586 (1934).
[2] Weisskopf, Phys. Rev. **52**, 295 (1937).
[3] Seaborg, Gibson, Grahame, Phys. Rev. **52**, 408 (1937).
[4] Aoki, Proc. Phys.-Math. Soc. Japan **19**, 369 (1935).
[5] Lea, Proc. Roy. Soc. (London) **A150**, 637 (1935).
[6] Bohr, Science **86**, 161 (1937).
[7] Bohr and Kalckar, Vidensk. Selsk. Math.-fys. Medd. **14**, 10 (1937).
[8] Frenkel, Physik. Zeits. Sowjetunion **9**, 533 (1936).

of collisions of fast neutrons ($E>3$ Mev) with heavy nuclei ($A>100$). He found that the reemitted neutrons should have, on the average, energies much less than the energies of the incident neutrons. For example, neutrons with an energy of 10 Mev will be reemitted with a Maxwellian distribution having a mean energy of about 2 Mev. The nucleus is left in an excited state as a result of this energy loss by the neutrons and subsequently returns to the ground state by the emission of one or more gamma-rays.

A study of the cross sections for absorption and inelastic scattering of this kind for fast neutrons may be made by using the radioactivity induced in aluminum or iron. These substances become radioactive under the action of fast neutrons through the reactions:[9, 10]

$$Al^{27}+n\rightarrow Mg^{27}+p \qquad Mg^{27}\rightarrow Al^{27}+e^- \text{ (10.3 min.)}$$
$$Fe^{56}+n\rightarrow Mn^{56}+p \qquad Mn^{56}\rightarrow Fe^{56}+e^- \text{ (2.6 hr.)}$$

In each case the final stable nucleus is identical with the initial nucleus. From the upper energy limits of the emitted electrons[11–14] and the heights of the potential barriers for protons of the nuclei formed,[15] one may estimate the least energy required for the neutron to produce an observable radioactivity. From such considerations one estimates that neutron energies of about 4.5 and 7.0 Mev are required to activate aluminum (10.3-min. period) and iron, respectively.

The effective absorption of such fast neutrons was measured by observing the decrease in activity of an aluminum or iron detector caused by surrounding a source of neutrons (200 mg Ra+Be) with a cylinder of any one of a number of elements. If the inelastically scattered neutrons have a Maxwellian distribution of energies, the fraction having energies greater than 7.0 Mev probably will not exceed a few percent. Hence we may state that fast neutrons which have been inelastically scattered by the Bohr process will not, in general, retain enough energy to induce radioactivity in an iron detector. That this is also approximately true for an aluminum detector may be inferred from the fact that the results obtained with iron and aluminum detectors were found to be nearly the same. The success of the method probably also depends, in part, upon the fact that even those neutrons which retain sufficient energy to induce radioactivity in the detector after an inelastic scattering process must be expected to have a reduced probability for doing so as a result of their diminished energy.

The quantity measured in these experiments is the total cross section for all processes by which the neutron loses a large fraction of its energy or is absorbed. The values called absorption+inelastic scattering cross sections in the text are therefore more strictly cross sections for absorption+inelastic scattering with large energy losses. If a form of inelastic scattering occurs in which only a small fraction of the energy is lost, the experiments will not detect the process to any marked extent.

The cylindrical absorbers used in these experiments were 17.8 cm long and approximately 10 cm in diameter. The source of neutrons (13 cm long and 1.78 cm in diameter) was placed centrally in a 1.78 cm hole through the axis of the cylinder. Flexible targets of iron or aluminum (made of small strips held together with Cellophane tape) fitted around the curved surface of the cylinders. The radioactivity induced in these targets was measured with a thin-walled steel Geiger-Müller counter. In the measurements made without the absorbers, the geometrical conditions were accurately preserved by the use of identical blanks. When aluminum targets were used, measurements were made alternately with and without the absorbing cylinders in order to eliminate the effects of any changes in the sensitivity of the counter. When the longer (2.6-hr.) period induced in iron was used, the sensitivity of the counter was checked regularly during the measurements.

The results of these measurements are presented in Table I and plotted in Fig. 1 together

[9] Fermi, Amaldi, d'Agostino, Rasetti, Segrè, Proc. Roy. Soc. (London) **A146**, 483 (1934).

[10] The small amounts of Na^{24} and Al^{28} produced in aluminum under the experimental conditions adopted have been taken into consideration. Iron detectors have the advantage that Mn^{56} is the only radioactive element known to be formed by the action of neutrons on iron.

[11] Henderson, Phys. Rev. **48**, 855 (1935).

[12] Brown and Mitchell, Phys. Rev. **50**, 593 (1936).

[13] Gaerttner, Turin, Crane, Phys. Rev. **49**, 793 (1936).

[14] Alichanow, Alichanian, Dzelepow, Nature **136**, 257 (1935).

[15] Bethe, Rev. Mod. Phys. **9**, 172 (1937). See Table XXXIII.

with Dunning's cross sections[1] for the total scattering+absorption of fast neutrons.

The cross sections σ in Table I have been calculated from the fraction transmitted T by use of the relation $T=e^{-N\sigma t}$, where N is the number of nuclei per cm^3 and t is the average path length of the neutrons in the absorbers. The probable errors given refer to the errors in the measurements only and are not intended to include systematic errors inherent in the method. Under the experimental conditions here used the average length of path of a neutron originating on the axis of the cylinder and passing in a straight line through the absorber and detector is 24 percent greater than the wall thickness stated in column 2 of Table I. (This 24 percent is a weighted average which takes account of the obliquity of the path of the neutron in both the absorber and the detector.)

Two corrections to the cross sections in Table I must be considered. Neutrons which are scattered in the absorber with negligible energy losses will have, on the average, longer paths through the absorber than the calculations take into account. An approximate calculation of this correction may be made by assuming isotropic scattering and neglecting scattering processes after the first. Dunning's scattering cross sections have been used for Al, Zn, Sn and Pb, and interpolated values have been taken for Sb and Bi. It is assumed from Table II that 40 percent of the collisions are inelastic with large energy losses. (The calculation is not very sensitive to this quantity.) The result of such a calculation indicates that the cross sections in Table I should be reduced by about 13 percent (15 percent for Zn) to account for the effect of single scattering in the absorber. For scattering processes after the first the calculation becomes very complex, but a careful consideration of the problem suggests that a complete correction for single and multiple scattering would reduce the calculated cross sections by about 20 percent (23 percent for Zn).

TABLE I. *Measurements of absorption+inelastic scattering cross sections for fast neutrons.*

Element	Wall Thickness cm	Fraction Transmitted: $Fe^{56}(n,p)Mn^{56}$ Detection $E\geq 7$ Mev	Fraction Transmitted: $Al^{27}(n,p)Mg^{27}$ Detection $E\geq 4.5$ Mev	Cross Section $\times 10^{25}$ cm^2
Al	4.2	0.75 ± 0.03		9.3 ± 1.3
Zn	4.2	0.59 ± 0.03		15.4 ± 1.5
Sb	4.2	0.73 ± 0.03		17.9 ± 2.3
Pb	4.2	0.69 ± 0.03		21.3 ± 2.4
Bi	4.2	0.71 ± 0.02		23.2 ± 2.0
C	4.3		0.83 ± 0.02	4.2 ± 0.5
Al	4.2		0.78 ± 0.02	7.8 ± 0.8
Zn	4.2		0.58 ± 0.02	15.9 ± 1.0
Sn	4.1		0.72 ± 0.02	17.1 ± 1.5
Sb	4.2		0.74 ± 0.02	17.6 ± 1.5
Pb	4.2		0.71 ± 0.02	19.7 ± 1.6
Bi	4.2		0.74 ± 0.01	19.8 ± 0.9

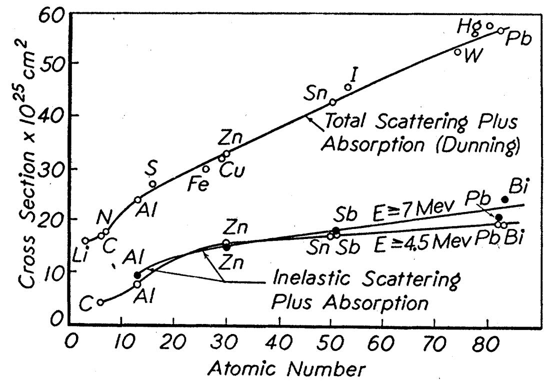

FIG. 1. Upper curve, total scattering+absorption cross sections for fast neutrons (Dunning). Lower curves, inelastic scattering+absorption cross sections for fast neutrons as measured with iron detectors ● or with aluminum detectors ○.

The second correction to be considered is that which arises from the increased obliquity in the detector of those neutrons which have been scattered in the absorber with negligible energy losses. The magnitude of this correction may be estimated from a calculation similar to the first by which it is found that the average path through the detector is 6 percent greater than it would be in the absence of the absorber. On account of the exponential nature of the calculation of the cross sections, this correction will amount to 16 percent of the total cross section (13 percent for Zn) and acts to increase the cross sections over the values given in Table I. Since these corrections act in opposite directions, the net result of both corrections is a correction smaller than the probable error of the measurements themselves, except possibly in the case of zinc.[15a]

[15a] A corrected value for the cross section of zinc with iron detection gives $\sigma=14.1\times10^{-25}$ cm^2. This value corresponds to a sticking probability of 0.43 for Table II instead of the value 0.47 there reported.

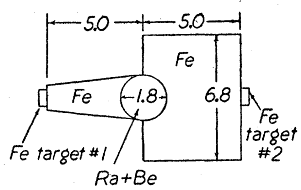

FIG. 2. Experimental arrangement for demonstrating scattering of fast neutrons with small energy losses (elastic or inelastic).

Collie and Griffiths[16] made measurements of the effective absorption of fast neutrons in spherical absorbers of several elements, and their results are in fair agreement with comparable values in Table I. Ehrenberg[17] measured the effective absorption of fast neutrons in a silver cylinder using aluminum and silicon detectors. His results yielded a cross section for silver somewhat larger than that expected from the curves in Fig. 1. However, Ehrenberg used the wall thickness of his silver cylinder for the path length of the neutrons in the silver. Since the average path length of the neutrons was presumably greater than the wall thickness, it is reasonable that his result should have been too large. The magnitude of the correction involved cannot be estimated from his published data.

Figure 1 shows a gradual increase in the cross sections for absorption+inelastic scattering from the lightest to the heaviest elements. No large differences were observed between the results obtained with aluminum and with iron detectors, although the results do suggest slightly larger cross sections for the neutrons detected by iron ($E \geq 7$ Mev) than for the neutrons detected by aluminum ($E \geq 4.5$ Mev), at least in the case of the heavier elements. The cross section given for carbon is doubtless too large because here elastic scattering may cause a neutron to lose nearly one-third of its energy in a single collision.

The cross sections listed in Table I give the sum of the cross sections for absorption and for inelastic scattering with large energy losses. Theoretical considerations lead one to expect that for any but the lightest elements the true absorption cross sections for fast neutrons will be small compared to the cross sections for inelastic scattering.[18] Thus one may say to a good approximation that the cross sections given in Table I refer to the single process of inelastic scattering with large energy losses.

One infers that the differences between the cross sections for inelastic scattering+absorption as given in Table I and Dunning's cross sections for total scattering+absorption give at once the cross sections for elastic scattering or for inelastic scattering with *small* energy losses. This procedure assumes that the absolute magnitudes of both sets of cross sections are correct. Dunning's cross sections were determined under good geometrical conditions, and none of the disturbing factors would tend to make his cross sections too large in any event. The values in Table I cannot be sufficiently in error to alter the conclusion that a large difference exists between the two sets of values. Thus it appears that the difference between these results and those of Dunning is real and attributable to elastic scattering or to inelastic scattering with small energy losses.

It is to be noted that a form of inelastic scattering of fast neutrons may occur in which there is a less complete amalgamation of the incident neutron with the nucleus and which might be designated by the term surface scattering. Such a process might often give rise to small energy losses.

Since no direct evidence for scattering with small energy losses (either elastic or inelastic) has been reported, experiments were carried out to give qualitative proof that such scattering does occur. A view of the apparatus used is given in Fig. 2. Two iron targets (composed of thin strips stacked together) were activated simultaneously in the positions shown, and the intensity of their activities compared. If a neutron may be scattered and still retain sufficient energy to induce radioactivity in iron, then target No. 1 (Fig. 2) will be less active than target No. 2 because in the latter case the mass of iron not directly between the source and the target may scatter into the target neutrons that would otherwise be lost. The activity observed in target No. 2 was 25±5 percent greater than that observed in target No. 1. This result is in qualitative agreement with the supposition that

[16] Collie and Griffiths, Proc. Roy. Soc. (London) **A155**, 434 (1936).
[17] Ehrenberg, Nature **136**, 870 (1935).
[18] Bethe, Rev. Mod. Phys. **9**, §65 (1937).

the difference between Dunning's curve and the lower curves in Fig. 1 gives the cross section for scattering of fast neutrons with small energy losses (elastic or inelastic).

Additional evidence for such scattering was obtained as follows: An aluminum detector in the form of a cylinder surrounded the source of neutrons, and measurements were made with and without a large iron block (back-scatterer) entirely surrounding this assembly. When the iron back-scatterer was in place, the 10.3-min. activity in aluminum was increased 4.5 ± 1.0 percent by the action of neutrons scattered from the iron block into the detector.

Table II shows, in column 2, cross sections for scattering of fast neutrons with small energy losses (elastic or inelastic) obtained by difference from Dunning's values for absorption+total scattering and the values in Table I for absorption+inelastic scattering as measured with iron targets. Column 3 gives the ratio of the absorption+inelastic scattering cross section to Dunning's cross section for the same elements. This ratio, which is nearly constant at a value of about 0.4, represents the fraction of the neutron-nucleus collisions which are inelastic with large energy losses. This ratio is the sticking probability, ξ, as defined by Bethe[18] in the equation $\xi = \sigma/\pi R^2$, where σ is the absorption+inelastic scattering cross section and where, in this case, Dunning's cross sections are used for πR^2.

Scattering of Medium Fast Neutrons

In a previous paper[3] cross sections for the combined processes of absorption and inelastic scattering were reported for medium fast neutrons; these measurements have now been repeated under improved experimental conditions and have been extended to include a greater number of elements. In these experiments a

TABLE II. *Cross sections for scattering with small energy losses and sticking probabilities for fast neutrons ($E \geq 7$ Mev).*

Element	Cross Section $\times 10^{25}$ cm^2	Sticking Probability (see text)
Al	15	0.39
Zn	18	0.47
Sb	26	0.41
Pb	37	0.37
Bi	39	0.39

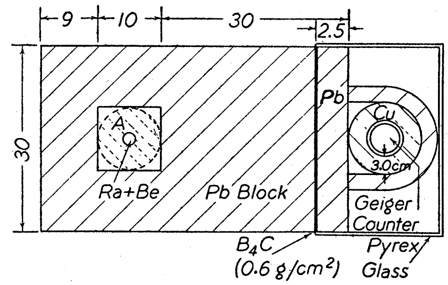

FIG. 3. Experimental arrangement for measuring effective absorption of medium fast neutrons.

source of fast neutrons was enclosed within a lead block of such dimensions that the neutrons to be studied passed through 30 centimeters of lead before reaching the detector. The detector used was a Geiger-Müller counter surrounded by copper. Neutrons which impinge upon the copper nuclei may undergo inelastic scattering, and the gamma-rays resulting from this process are detected by the counter. In order to be detected in this manner, the neutron must have an energy not less than the energy of the first excited state of the copper nucleus. Since this method of detection certainly detects neutrons with energies less than a million volts, the average energy of the neutrons to which it responds will be much less than that of the aluminum and iron detectors used in the previous section. Such neutrons will be called medium fast neutrons in order to distinguish them from the faster neutrons employed in the experiments described above.

The exact experimental arrangement used was a modification of that described in the previous paper and is shown in Fig. 3. The source of fast neutrons (200 mg Ra+Be) was mounted at the center of the cavity A within the lead block, which was large enough to absorb nearly all of the gamma-rays emitted by the radium source in the direction of the counter. The counter used was made from a steel tube (12.5 cm$\times$3.8 cm, 0.13 mm wall thickness) and was filled with a mixture of argon and ethyl alcohol vapor (10 cm A+0.3 cm C_2H_5OH).[19] Boron carbide and Pyrex glass surrounded the copper detector, as shown, to prevent slow neutrons from the source, or neutrons slowed in the floor and walls of the room from acting on the detector system. The entire assembly was mounted on a steel table well

[19] Trost, Zeits. f. Physik **105**, 399 (1937).

removed from neighboring walls or other hydrogenous material.

When the radium-beryllium source was introduced at the cavity A (Fig. 3), the counting rate increased from the natural background of 35 per minute to 160 per minute. This increase in counting rate was due chiefly to the gamma-rays produced by fast neutrons in the detector.[3] A small fraction of the increase caused by the radium-beryllium source will, of course, be due to the incomplete absorption in the large lead block of the primary gamma-rays from radium and its decay products. The magnitude of this effect was determined by methods previously described,[3] but another and more accurate determination has been made by replacing the radium-beryllium source by 150 millicuries of pure radon.[20] With the arrangement shown in Fig. 3, the effects due to primary gamma-rays were found to be very small; however, in the work which follows, the appropriate corrections have been made in every case.

TABLE III. *Measurements of effective absorption cross sections for medium fast neutrons.*

Element	Wall Thickness cm	Fraction Transmitted: Cu(n, $n\gamma$)Cu Detection	Fraction Transmitted: Pb(n, $n\gamma$)Pb Detection	Cross Section $\times 10^{25}$ cm^2
C($\rho=1.7$)	4.3	0.959±0.015		1.1±0.4
Al	4.2	0.933±0.015		2.7±0.6
S($\rho=2.0$)	4.0	0.918±0.015		5.7±1.1
Cl(CCl_4)	4.3	0.944±0.015		5.1±1.5
Fe	4.1	0.817±0.015		5.7±0.5
Cu	3.5	0.823±0.015		6.5±0.6
Zn	4.2	0.833±0.015		6.7±0.6
Cd($\rho=7.7$)	4.1	0.855±0.015		9.2±1.0
Sn	4.1	0.886±0.015		7.8±1.1
Sb	4.2	0.864±0.015		10.5±1.2
I($\rho=4.5$)	4.1	0.922±0.015		9.2±1.7
Hg	3.9	0.851±0.015		10.0±1.1
Pb	4.2	0.881±0.010		9.1±0.8
Bi	4.2	0.927±0.010		6.3±0.9
C($\rho=1.3$)	4.1		0.98±0.02	0.6±0.6
Al	4.2		0.92±0.02	3.4±0.8
S($\rho=2.0$)	4.0		0.93±0.02	5.0±1.4
Cl(CCl_4)	4.0		0.92±0.02	8.3±2.1
Fe	4.0		0.80±0.02	6.2±0.7
Cu	3.5		0.77±0.02	8.9±0.9
Cd($\rho=7.3$)	4.3		0.82±0.02	12.1±1.4
Hg	3.9		0.86±0.02	9.4±1.5
Pb	4.2		0.90±0.02	7.3±1.6

[20] The radon was enclosed in soft glass. Such a gamma-ray source gives a small intensity of neutrons from the action of alpha-particles on the constituents of glass. Their presence was easily demonstrated by the use of a BF_3-filled proportional counter and their effect was allowed for in this determination.

The effective absorption cross sections for medium fast neutrons were measured by surrounding the source at A with cylindrical absorbers and observing the decrease in counting rate of the Geiger-Müller counter. Those neutrons which have been inelastically scattered in the absorber with large energy losses will have a greatly diminished probability of exciting gamma-rays in the detector by a second inelastic collision. Experimentally, this will manifest itself as an effective absorption of the neutrons. The results of such measurements are presented in Table III together with results obtained in a similar manner by using lead instead of copper as the detector. Figs. 4a and 4b show both sets of data graphically. The cross sections given have been calculated from the mean free paths determined by the transmissions observed. The suitability of this method of calculation has been checked by showing that the absorption is approximately exponential with thickness of absorber. The values given are somewhat smaller than those reported in the previous paper because of a more accurate determination of the intensity of primary gamma-rays reaching the counter from the radium source.

The curves in Figs. 4a and 4b show a gradual rise with atomic number up to about $Z=50$ and a small decrease in cross section for the heaviest elements studied. In particular, the cross section for bismuth (Fig. 4a) is certainly much smaller than those for lead and mercury. A marked decrease for lead and bismuth has been observed by Aoki in experiments on the intensity of the gamma-rays excited in various elements by 2.4 Mev ($D+D$) neutrons.[4] The values obtained by Aoki give a direct measure of the relative cross sections for inelastic scattering, provided that the number of gamma-rays emitted by the participating nuclei and the efficiency of their detection remain the same from element to element. Aoki's results for the elements here studied are presented for comparison in Fig. 4c. The general agreement between the three sets of values shows that the small cross sections observed in the heavy elements must be real. These low cross sections for heavy nuclei indicate that medium fast neutrons either lack the energy necessary to undergo inelastic scattering with a high probability or, more likely, undergo inelastic scattering with much smaller energy losses. The experiments already described with more energetic neutrons (Table I) do not show this decrease in the cross sections for the heavy elements.

The absolute values of the cross sections in Table III are very much smaller than those obtained in Table I for more energetic neutrons. This result is undoubtedly due in large part to the fact that neutrons which are inelastically scattered in the absorbers may still retain enough energy to be detected by the copper or lead detector. It may also indicate that medium fast neutrons which are inelastically scattered lose on the average a smaller fraction of their energy than the faster neutrons employed in the first experiments, in agreement with the calculations of Weisskopf who showed that the energy of the inelastically scattered neutrons should be approximately proportional to the square root of the energy of the incident neutrons.[2] In addition it is not improbable that the sticking probability of fast neutrons increases with increasing energy of the neutrons as a result of the more closely spaced levels associated with higher energies of excitation in the compound nucleus.

Measurements on the intensity of gamma-rays produced by the action of fast neutrons on matter have been made by Lea[5] as well as by Aoki. The results of the two workers differed markedly for the heavier elements. Lea found a continual increase in the cross sections with atomic number, even up to lead and bismuth, whereas Aoki found a falling off for these elements as already shown (Fig. 4*c*). Moreover the yield of gamma-rays seemed to be larger in the experiments of Lea than in those by Aoki. These differences are evidently attributable to the higher energies of the neutrons used by Lea. He used fast neutrons from the interaction of polonium alpha-particles with beryllium (without the interposition of lead or other substances which would have slowed down the neutrons by inelastic scattering), whereas Aoki used the less energetic (2.4 Mev) neutrons from the action of deuterons on deuterium.

Several investigations have dealt with the intensity of gamma-rays produced by radium-beryllium neutrons acting on lead.[3, 21–23] In such experiments it has always been necessary to pass

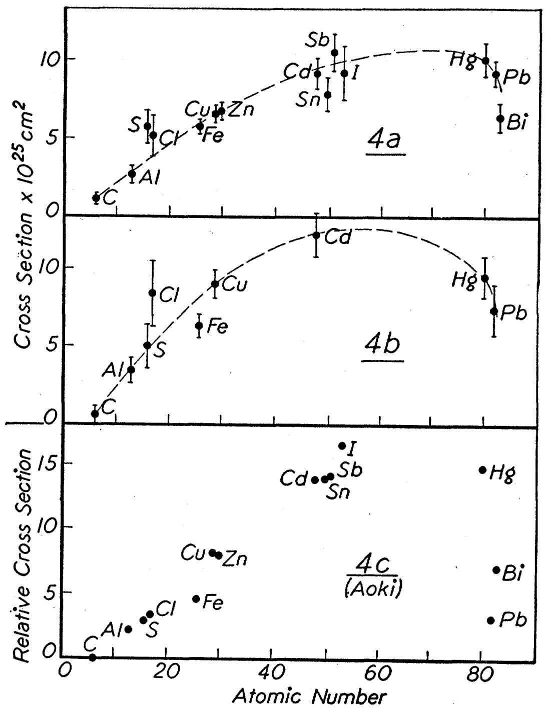

FIG. 4. *a*, Effective absorption cross sections for medium fast neutrons as measured with a Cu detector; *b*, same, measured with a Pb detector; *c*, relative cross sections for the production of gamma-rays by 2.4 Mev neutrons (Aoki).

the neutrons through large thicknesses of some dense substance in order to absorb the primary gamma-rays, and hence the neutrons emerge with reduced energies, as already pointed out. This fact is adequate to explain fully the fact that Lea, with his more energetic neutrons, observed large yields of gamma-rays from lead whereas Kikuchi and co-workers failed in their earlier experiments to find any gamma-rays whatsoever from the process.

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[21] Kikuchi, Aoki, Husimi, Proc. Phys.-Math. Soc. Japan **18**, 297 (1936).
[22] Gibson, Seaborg, Grahame, Phys. Rev. **51**, 370 (1937).
[23] Takeda, Proc. Phys.-Math. Soc. Japan **19**, 835 (1937).