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Inelastic Scattering of Fast Neutrons

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The radiation observed in the presence of a source of fast neutrons is found to be due chiefly to the excitation of gamma-rays in the lead block used in these experiments. The true absorption of fast neutrons in several elements is less than previous measurements had indicated, and hence an absorption process cannot account for the soft gamma-rays produced by the action of fast neutrons on matter. The capacity of fast neutrons to produce gamma-rays in lead and copper is considerably diminished as a result of their passage through various substances. Therefore the energy of the gamma-rays must be derived from the kinetic energy of the fast neutrons by a process of inelastic scattering.

INTRODUCTION

IT is found that most substances emit soft gamma-rays under the action of fast neutrons.[1–3] Aoki has reported that of forty-one elements bombarded by fast neutrons all but five produce some gamma-rays. It has often been supposed that these gamma-rays arise by inelastic scattering of the fast neutrons, but conclusive proof of this has been lacking. As an alternative explanation it may be supposed that the capture of a fast neutron occurs with the emission of the excess energy in a cascade process as a considerable number of low energy gamma-rays. If the apparent absorption of fast neutrons in several elements reported by Dunning, Pegram, Fink and Mitchell is a true absorption, such a process could easily account for the observed gamma-rays.[4] However, as pointed out by them, the results are more probably due in large part to large neutron energy losses through inelastic collisions. In this paper experiments will be described which show that inelastic scattering is responsible for practically all of the soft gamma-rays produced by fast neutrons (§§2–3).

In the following experiments a Geiger-Müller counter has been employed. Such a counter in the path of fast neutrons from which x- and gamma-rays and slow neutrons have been removed by the interposition of suitable absorbers gives a count much in excess of that due to unabsorbed gamma-rays. As it will be necessary to refer to this effect repeatedly in what follows it will be termed the "fast neutron effect." Section 1 of this paper is concerned with the identification of this effect.

§1. IDENTIFICATION OF THE "FAST NEUTRON EFFECT"

It is natural to suppose that this "fast neutron effect" arises from the interaction of fast neutrons with lead (which is usually present in these experiments) to form gamma-rays. In an early paper Lea reported finding such gamma-rays,[1] but repeated investigations of this matter by Kikuchi, Aoki and Husimi, using both a "deuteron-deuteron" and a Ra-Be source of neutrons had failed to confirm his results.[2, 5] More recently Kikuchi and co-workers have reported the detection of gamma-rays from the action of fast neutrons on lead, but of too small an intensity to account for more than a few percent of their rather large "fast neutron effect."[6] In order to account for this radiation, Kikuchi and co-workers have postulated a hitherto unknown direct interaction of fast neutrons with extra-nuclear electrons to produce beta-particles with a maximum energy of about 1 Mev.[6, 7] As alternative explanations, Kikuchi has suggested that the neutron may disintegrate spontaneously or in the neighborhood of a nucleus with the

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[1] Lea, Proc. Roy. Soc. (London) **A150**, 637 (1935).

[2] Kikuchi, Aoki, Husimi, Proc. Phys.-Math. Soc. Japan **18**, 115 (1936).

[3] Aoki, Nature **139**, 372 (1937).

[4] Dunning, Pegram, Fink and Mitchell, Phys. Rev. **48**, 265 (1935).

[5] Kikuchi, Aoki, Husimi, Proc. Phys.-Math. Soc. Japan **18**, 297 (1936).

[6] Kikuchi, Aoki, Husimi, Proc. Phys.-Math. Soc. Japan **18**, 727 (1936).

[7] Kikuchi, Aoki, Husimi, Nature **138**, 841 (1936).

emission of a beta-particle or a gamma-ray. Measurements to be described in §2 on the absorption of fast neutrons in matter prove that the latter of these processes cannot occur to a measurable extent, and measurements of Gilbert, Smith and Fremlin[8] failed to reveal any appreciable spontaneous disintegration of the neutron.

The possibility of explaining the effect in terms of a short-lived radioactivity in lead was eliminated as follows: A Geiger-Müller counter was enclosed in lead and operated near a "deuteron-deuteron" source of neutrons. This "deuteron-deuteron" source of neutrons used a 60-cycle a.c. accelerating voltage on the target which made it possible to look for an induced radioactivity of very short half-life. An induced radioactivity would produce counts during both halves of the accelerating voltage cycle. Actually, visual observation of the cathode-ray oscilloscope (which used the same 60-cycle a.c. for sweep voltage) showed that the kicks occurred during the negative half of the accelerating voltage cycle. Hence it is probable that no radioactivity of half-life greater than 0.01 second is induced in lead under these conditions.

As mentioned above, experiments performed by Kikuchi and co-workers in an effort to measure the intensity of the gamma-rays produced by the action of fast neutrons on lead, led them to the conclusion that such gamma-rays were entirely inadequate to account for their rather large "fast neutron effect." These measurements were complicated, however, by the possibility that a considerable amount of radiation might arise from the action of neutrons on the x-ray shield and walls of the room; consequently, it was thought desirable to measure the intensity of the gamma-rays produced by the action of fast neutrons on lead with a different arrangement in which the effects of stray radiations could be positively eliminated. In particular, it was desired to determine whether or not the intensity of the gamma-rays from lead was sufficient to account for the entire radiation observed under these conditions.

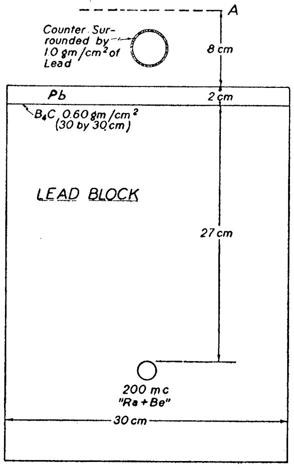

FIG. 1. Experimental arrangement for the detection of gamma-rays from the action of fast neutrons on lead.

This measurement was carried out with the arrangement shown in Fig. 1. A Ra-Be source of neutrons was encased in a lead block of sufficient size to absorb nearly all of the primary gamma-rays from the radium, and the assembly was mounted out-of-doors on a steel table 175 cm above the ground. A layer of B_4C (0.6 g/cm^2) was interposed, as shown, in order to absorb the few slow neutrons that might be coming from the source and from the ground below the source. Two centimeters of lead above the B_4C absorbed the gamma-rays which are known to be formed[9, 10] in small intensity when slow neutrons are captured by boron. A steel Geiger-Müller counter of dimensions 3.7 cm×12 cm with a wall thickness of 0.20 mm and filled with argon to a pressure of 15 cm Hg was surrounded with a lead foil (1.0 g/cm^2) and placed as shown. The absence of slow neutrons in the region above the counter was proved by the fact that a thin sheet of cadmium (0.4 mm×13×25 cm) placed at *A* in Fig. 1 caused no appreciable increase in the counting rate.

When the Ra-Be was introduced into the large lead block under these conditions the counting rate changed from the natural background of 65 per minute to 126 per minute. The primary gamma-rays coming directly from the Ra-Be source were responsible for about 3 per minute of this increase, as estimated by a method described in §3. The "fast neutron effect" is therefore $126-65-3=58$ counts per minute.

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[8] Gilbert, Smith, Fremlin, Nature **139**, 796 (1937).

[9] Kikuchi, Aoki, Husimi, Proc. Phys.-Math. Soc. Japan **18**, 188 (1936).

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

Additional "test lead" (in plates 15×30 cm) was placed above the counter (position A in Fig. 1) and produced a further increase in the counting rate. Fig. 2 gives this increased counting rate as the percentage increase over the fast neutron effect with no lead at A. Allowance has been made for the change in natural background of the counter caused by the addition of the lead at A.

The curve in Fig. 2 gives direct proof of the existence of gamma-rays produced by the action of fast neutrons on lead. The shape of the curve affords a rough estimate of the average energy of these gamma-rays, indicating a value somewhat less than 1 Mev. The largest thickness of lead at A gave an increase amounting to 21 percent of the fast neutron effect with no lead at A. Upon the assumption that the fast neutron effect was entirely due to gamma-rays from the action of fast neutrons on the large lead block in Fig. 1, it was determined that the increase caused by the test lead at A should be approximately 30 percent. Hence it follows that in these experiments roughly two-thirds of the fast neutron effect is due to gamma-rays excited in the large lead block.

The remainder of the fast neutron effect must arise in the lead foil surrounding the counter or in the counter wall or counter gas. It could not be identified with certainty, but there are several processes which could contribute to it. An appreciable part will be due to recoil argon atoms within the counter. Internal conversion of gamma-rays produced in the counter wall and in the lead foil surrounding the counter may also contribute to the unidentified radiation. If neutrons excite a hitherto undetected, very soft, gamma-radiation in lead, this could likewise be responsible for the residual effect. Although no figure is available for the ionization produced by fast neutrons traversing a gas, an upper limit of one ion pair in 3 meters' path of air at NTP has been set by Dee.[11] Since the production of one ion pair in 50 meters' path of argon at NTP would be sufficient to account for the remainder of the fast neutron effect in these experiments, the possibility that neutron primary ionization is contributing to the count cannot be eliminated. In view of these multifold possibilities it is impossible to say whether the process proposed by Kikuchi plays any part in this small residual count.

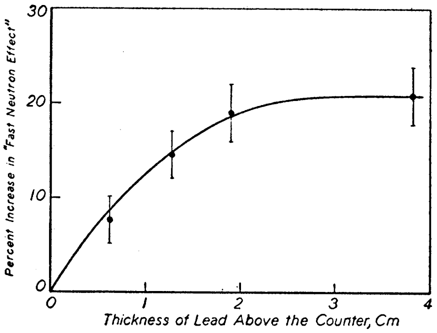

FIG. 2. Intensity of gamma-rays from the action of fast neutrons on "test lead" at A (Fig. 1) *vs.* thickness of lead.

In the experiments described in §§2–3 of this paper, however, the gamma-rays from lead or other elements always constitute the major part of the fast neutron effect. The conclusions to be drawn will not be affected by the presence of a small number of counts from any other process.

§2. Measurements on the Absorption of Fast Neutrons

When *slow* neutrons are absorbed in matter, the excess energy of the transformation is usually emitted as one or more gamma-rays. It is of interest to determine whether the gamma-rays produced by the action of fast neutrons on matter arise in a similar manner. The absorption of fast neutrons in several elements has been measured by Fleischmann[12] and by Dunning, Pegram, Fink and Mitchell.[4] Fleischmann used a method in which the loss of neutrons by scattering could not be avoided, whereas the results of Dunning and co-workers could be interpreted as being due either to absorption or to the slowing of the fast neutrons.

In the present work the absorption of fast neutrons has been measured with cylindrical absorbers to minimize the loss of neutrons by scattering and with a method of detection which made any change in the energy spectrum of the fast neutrons relatively unimportant.

The source of neutrons (Be+200 mg Ra) was mounted in the center of a cavity A (Fig. 3) within a large lead block. Measurements were

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[11] Dee, Proc. Roy. Soc. (London) **A136**, 727 (1932).

[12] Fleischmann, Zeits. f. Physik **97**, 265 (1935).

made alternately with and without cylindrical absorbers around the source at A. The fast neutrons were detected by slowing them in 5.7 cm of paraffin at B and counting by means of a Geiger-Müller counter the gamma-rays produced by the absorption of these slow neutrons in cadmium and lead. A screen of B_4C, (0.6 g/cm^2) used as a shutter, could be inserted as shown in the figure, and the difference in counting rate with and without the shutter gave directly a measure of the intensity of slow neutrons incident upon the counter system, and hence also a measure of the intensity of *fast* neutrons incident upon the paraffin at B.

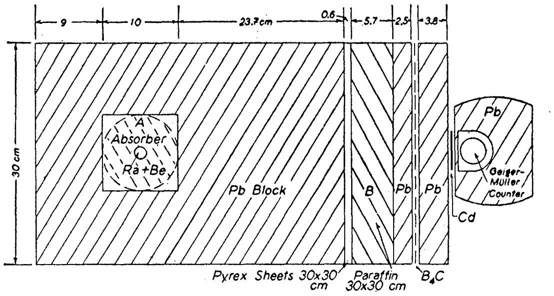

FIG. 3. Experimental arrangement for measuring absorption of fast neutrons in matter.

Pyrex glass at the left of the paraffin slabs (Fig. 3) served to prevent slow neutrons originating in or behind the source from reaching the counter system. The lead between the paraffin and counter absorbed the gamma-rays produced by the capture of slow neutrons in the paraffin. The entire assembly was mounted on a steel table 175 cm from the floor in the center of a large room. The Geiger counter was enclosed in a lead block in order to absorb gamma-rays produced in the floor and walls of the room by slow neutrons.

The absorbing cylinders used in these experiments were 17.8 cm long and approximately 10 cm in diameter. The exact thickness of the absorbing wall is stated for each element in Table I. Ideally, one should use a small spherical source of neutrons and spherical absorbers, but since the source of neutrons available was in the form of a cylinder 13 cm long and 1.8 cm in diameter, absorbers of the sort used were appropriate.

With the above arrangement, the results presented in Table I were obtained.

From Table I one sees that within the limitations of the experimental method no absorption outside of the probable error has been detected in the elements studied and that the calculated transmission of fast neutrons through several elements appears even to exceed one hundred percent. This excess may be attributed to the slowing of fast neutrons in the absorbers (§3). If the neutrons are slowed in the absorber without being captured there, the number of slow neutrons subsequently emerging from a layer of paraffin of a given thickness will be slightly increased. To this extent the method of detection used was evidently affected by changes in the energy spectrum of the fast neutrons as they traversed the absorbers.

Dunning and co-workers found considerable apparent absorption of fast neutrons in several elements, but as they have pointed out, a slowing of fast neutrons in the absorbers could also produce their experimental results.

The experiments described in §3 show that whatever real absorption may occur is not responsible for any important part of the gamma-rays produced by the action of fast neutrons. Hence a capture process followed by the emission of soft gamma-rays in a cascade cannot be the origin of the gamma-rays observed.

It is well known that fast neutrons produce induced radioactivity and other nuclear transformations in many elements. Thus it is certain that some absorption of fast neutrons occurs in these elements, but such absorption was evidently too small to have been measured by the method described above. The increase due to slowing in the number of slow neutrons emerging tends to compensate for the decrease due to true absorption within the material. Since these two factors cannot be separated by such experiments, and in view of the obtained precision, it is clear

TABLE I. *Measurements on the absorption of fast neutrons.*

ABSORBER	WALL THICKNESS (cm)	FRACTION TRANSMITTED
C	4.1	1.00±0.02
Al	4.2	1.03±0.02
S	4.0	0.99±0.02
CCl_4	4.0	0.98±0.02
Fe	4.0	1.02±0.02
Cu	3.4	1.05±0.02
Cd	4.3	1.00±0.02
Pb	4.2	1.04±0.02

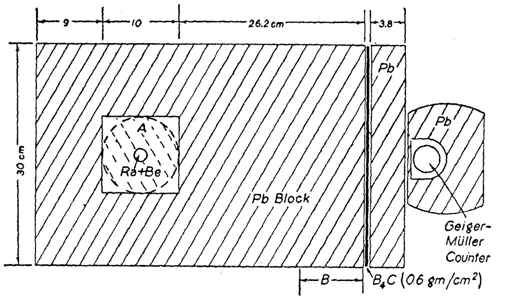

FIG. 4. Experimental arrangement for measuring the intensity of primary gamma-rays reaching the counter; also, arrangement for demonstrating inelastic scattering of fast neutrons.

that true capture cross sections of the order of 10^{-25} cm^2 are not ruled out.

§3. SLOWING AND INELASTIC SCATTERING OF FAST NEUTRONS

In the experiments of §1 and in the experiments to be described presently, an accurate knowledge of the intensity of primary gamma-rays penetrating the large lead block and tripping the counter is imperative. For this purpose a set of measurements was made in which the 200 millicuries of Ra-Be was replaced by 55 millicuries of pure radon. It was proved in this manner that scattered gamma-rays had been reduced to negligible proportions, and it was estimated that with 30 cm of lead between the Ra-Be source and the counter only 1.1±0.3 counts per minute could be attributed to gamma-rays from the radium itself. Another determination of this quantity has been made as follows. The experimental arrangement used is shown in Fig. 4. It is the same as that used for the experiments on inelastic scattering to be described below. The Ra-Be source of neutrons was in the center of the empty cavity A. The lead housing around the counter was surrounded by Pyrex glass in order to eliminate stray slow neutrons formed in the walls of the room. Counts were taken with various thicknesses of lead between the source and counter. The excess lead was removed at B.

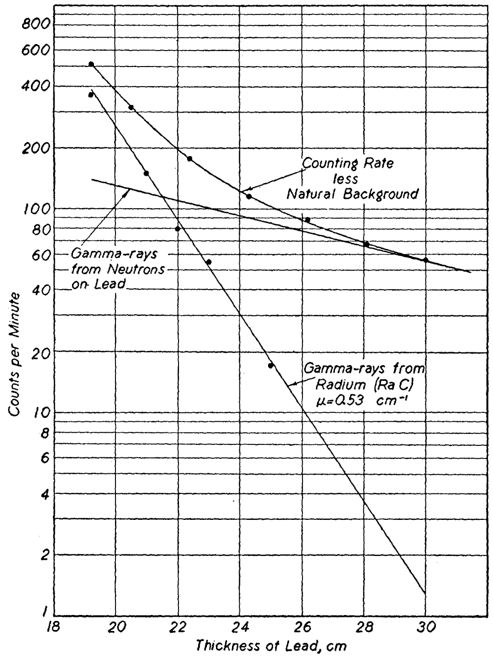

FIG. 5. Variation of counting rate with thickness of lead between source and counter. Straight lines show resolution of curve into its components.

The curve so obtained is plotted logarithmically in Fig. 5. It has been resolved into two straight lines by making use of the known absorption coefficient of RaC gamma-rays in lead. One line gives the intensity of such gamma-rays acting on the counter, the other gives the intensity of gamma-rays produced by the fast neutrons on the lead surrounding the counter. The slope of the latter curve is due partly to the loss of neutrons by scattering, and partly to the process of inelastic scattering next to be described. In all of the following work the corrections for the primary gamma-rays reaching the counter have been taken from Fig. 5.

The value obtained with pure radon referred to above (1.1±0.3 counts per minute) is in agreement with the curve in Fig. 5. With 30 cm of lead between the Ra-Be source and the counter the counts due to the primary gamma-rays amount to less than 3 percent of the fast neutron effect.

It was proved in the following manner that the soft gamma-rays excited by fast neutrons are the result of inelastic scattering. The experimental arrangement was again as shown in Fig. 4, but in these experiments the full thickness of lead remained at B. Measurements were made alternately with and without cylindrical absorbers at A. The counts recorded by the Geiger-Müller counter (after subtracting the natural background) were due chiefly to gamma-rays excited in the lead by fast neutrons as described in §1. When the cylindrical "absorbers" were placed around the source at A, a marked decrease in the counting rate was observed. The results so obtained are listed in Table II.

In order to show that these effects did not arise solely from changes in that part of the "fast neutron effect" which could not be positively identified (§1), the counter was removed from its lead housing and placed in a copper cylinder of 2.8 cm wall thickness. This assembly replaced the lead housing shown in Fig. 4. Because of its small gamma-ray absorption and large cross section for the production of gamma-rays under the action of fast neutrons, copper gives a much larger yield of gamma-rays than does lead. When the gamma-rays from copper were used as the detector, the counting rate was twice as great as in the measurements using the gamma-rays from lead, and hence it is certain that in this case nearly all of the counts were due to gamma-rays excited in the copper. The results of these experiments are also listed in Table II. The results obtained by the two methods of detection are nearly the same, although close agreement was not necessarily to be expected.

Although it was shown in §2 that nearly all of the fast neutrons are transmitted through the "absorbers" (except H_2O), the results presented in Table II show that the capacity of these neutrons to produce gamma-rays in lead or copper is considerably diminished as a result of their passage through the "absorbers." Since the neutrons are not absorbed, the energy of the gamma-rays must be derived from the kinetic energy of the fast neutrons. In producing these gamma-rays the neutrons must lose energy and be slowed down. The results show, however, that below a certain energy, perhaps 0.5 Mev, the neutrons are no longer capable of exciting gamma-rays, and hence no further slowing is to be expected.

TABLE II. *Measurements on the inelastic scattering and slowing of fast neutrons.*

ELEMENT	WALL THICKNESS	FRACTION TRANSMITTED		AVERAGE CROSS SECTION $\times 10^{25}$ CM^2
		PB γ-RAY DETECTION	CU γ-RAY DETECTION	
C ($\rho=1.3$)	4.1 cm	0.97 ± 0.02	0.96 ± 0.02	1.2 ± 0.8
Al	4.2	0.90 ± 0.02	0.94 ± 0.02	3.3 ± 0.9
S ($\rho=2.0$)	4.0	0.92 ± 0.02	0.91 ± 0.02	5.8 ± 1.4
Cl(CCl_4)	4.0	0.92 ± 0.02	0.94 ± 0.02	7.3 ± 2.1
Fe	4.0	0.78 ± 0.02	0.78 ± 0.02	7.4 ± 0.8
Cu	3.4	0.75 ± 0.02	0.78 ± 0.02	9.4 ± 0.9
Cd ($\rho=7.3$)	4.3	0.79 ± 0.02	0.81 ± 0.02	13.4 ± 1.5
Hg	3.9	0.82 ± 0.02	0.79 ± 0.02	14.0 ± 1.6
Pb	4.2	0.85 ± 0.02	0.83 ± 0.02	12.2 ± 1.7
H_2O	4.0	0.84 ± 0.02	0.86 ± 0.02	

It is demonstrated, therefore, that many of the collisions of fast neutrons with nuclei are inelastic, leaving the nuclei in an excited state. This process has recently been discussed by Bohr and others.[13, 14]

The cross sections given in the right-hand column of Table II have been calculated in a purely formal manner from the experimental mean free paths corresponding to the transmissions observed. No correction has been attempted for the small amount of real absorption that must occur, nor for the diffusion of neutrons throughout the lead block. The values so obtained are several times smaller than the scattering cross sections found by Dunning, from which one concludes that only a part (1/2–1/10) of the impacts of fast neutrons with nuclei are inelastic. The ratio of the inelastic to elastic scattering cross section is doubtless dependent upon the energy of the incident neutrons.

Fleischmann looked for the production of thermal neutrons by the action of fast neutrons on lead and found an effect just outside of his probable error.[12] In a more sensitive experimental arrangement, Fink has confirmed the fact that fast or residual neutrons passing through several elements produce a detectable number of thermal neutrons.[15] Wertenstein, Ehrenberg, and Collie and Griffiths have observed that when fast neutrons traverse various substances, their capacity to induce artificial radioactivity in silver and iodine is enhanced.[16–18] These observations are in accord with the results of this paper.

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[13] Bohr, Nature **137**, 344 (1936).

[14] Bethe and Placzek, Phys. Rev. **51**, 450 (1937).

[15] Fink, Phys. Rev. **50**, 738 (1936).

[16] Danysz, Rotblat, Wertenstein, Zyw, Nature **134**, 970 (1934).

[17] Ehrenberg, Nature **136**, 870 (1935).

[18] Collie and Griffiths, Proc. Roy. Soc. (London) **A155**, 434 (1936).

The inelastic scattering process gives rise to neutrons of low energy. A small fraction will have energies of a few hundred volts or less; of these an even smaller fraction will have energies within the cadmium resonance band. Owing to the extremely high efficiencies with which these two classes of neutrons can be detected, the production of both classes of neutrons has been observed.

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The Compton Effect with Gamma-Rays

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This paper summarizes the results of recent studies of the Compton effect using Geiger-Müller counters. The results show that no time lag as great as 10^{-4} second can exist in the Compton scattering process and that the angular relationship given by the photon theory is verified to within ±20°.

THE results of several recent experiments[1] have seemed to indicate that in the Compton scattering of x-rays or gamma-rays the recoil electron appears at the same instant that the quantum is scattered. The angular relationship predicted by the theory of Compton-Debye[2] between the directions of the recoil electron and scattered photon pairs is, however, more difficult to establish. The original cloud chamber experiments of Compton and Simon[3] made with hard x-rays scattered by air indicated an agreement with theory. More recently, the counter experiments of Bothe and Maier-Leibnitz[1] and the cloud chamber experiments of Crane, Gaerttner and Turin[4] have seemed consistent with the angular relationship predicted by theory. Some experiments by the present writer[5] which attempted to fix the angular relationship sharply, yielded results that did not support the theoretical predictions. The publication of these findings aroused an active interest in the subject which resulted in several new experiments[6] and theoretical discussions[7] that have added greatly to the knowledge of these phenomena.

An experiment to check the angular relationship between the paths of the recoil electrons and scattered photons has been made with the apparatus shown schematically in Fig. 1. The beam of gamma-rays is directed against the scatterer at S, which in this experiment is an aluminum foil of thickness 0.00165 cm. The source is a radon tube giving off the gamma-rays of Ra C which are filtered through 0.32 cm of lead. The collimating system consists of a series of lead shields surrouncing a brass tube 0.8 cm in diameter and 28 cm long. The end of this system as shown in Fig. 1 is designed to prevent most of the gamma-rays scattered from the brass tube from going

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[1] W. Bothe and H. Maier-Leibnitz, Zeits. f. Physik **102**, 143 (1936), Gött. Nachr. **2**, 127 (1936), Phys. Rev. **50**, 187 (1936); J. C. Jacobsen, Nature **138**, 25 (1936); W. E. Burcham and W. B. Lewis, Proc. Camb. Phil. Soc. **32**, 637 (1936); R. S. Shankland, Phys. Rev. **50**, 571 (1936), Phys. Rev. **51**, 1024 (1937).

[2] A. H. Compton, Phys. Rev. **21**, 483 (1923); P. Debye, Physik. Zeits. **24**, 161 (1923).

[3] A. H. Compton and A. W. Simon, Phys. Rev. **26**, 289 (1925).

[4] H. R. Crane, E. R. Gaerttner and J. J. Turin, Phys. Rev. **50**, 302 (1936).

[5] R. S. Shankland, Phys. Rev. **49**, 8 (1936).

[6] Ibid. also A. Piccard and E. Stahel, J. de phys. **7**, 326 (1936); E. J. Williams and E. Pickup, Nature **138**, 461 (1936).

[7] P. A. M. Dirac, Nature **137**, 298 (1936); N. Bohr, Nature **138**, 26 (1936); F. Cernuschi, Comptes rendus **203**, 777 (1936); M. Taketani, Kagaku, 6 (1936); B. Hoffmann, A. G. Shenstone and L. A. Turner, Phys. Rev. **50**, 1092 (1936); E. J. Williams, Nature **137**, 614 (1936); R. Peierls, Nature **137**, 904 (1936).