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## DIRECTED QUANTA OF SCATTERED X-RAYS

BY ARTHUR H. COMPTON AND ALFRED W. SIMON<sup>1</sup>

## ABSTRACT

**Relation between the direction of a recoil electron and that of the scattered x-ray quantum.**—It has been shown by cloud expansion experiments previously described, that for each recoil electron produced, an average of one quantum of x-ray energy is scattered by the air in the chamber. If the quantum of scattered x-rays produces a  $\beta$ -ray in the chamber, then a line drawn from the beginning of the recoil track to the beginning of the  $\beta$ -track gives the direction of the ray after scattering. Using a chamber 18 cm in diam. and 4 cm deep traversed by a carefully shielded narrow beam of homogeneous x-rays, with exploded tungsten wires as sources of light, nearly 1300 stereoscopic cloud expansion photographs were taken. Of the last 850 plates, 38 show both recoil tracks and  $\beta$ -tracks. The angles projected on the plane of the photographs were measured and it was found that in 18 cases, the direction of scattering is within  $20^\circ$  of that to be expected if the x-ray is scattered as a quantum so that energy and momentum are conserved during the interaction between the radiation and the recoil electron. This number 18 is four times the number which would have been observed if the energy of the scattered x-rays proceeded in spreading waves, that is if the direction of production of a  $\beta$ -ray was unrelated to the direction of the recoil track. The chance that this agreement with theory is accidental is about 1/250. The other 20  $\beta$ -rays are ascribed to stray x-rays and to radioactivity. This evidence seems a direct and conclusive proof that at least a large proportion of the scattered x-rays proceed in directed quanta of radiant energy.

**A**N increasingly large group of phenomena has recently been investigated which finds its simplest interpretation on the hypothesis of radiation quanta, proposed by Einstein to account for heat radiation and the photo-electric effect.<sup>2</sup> It has not been possible, however, to show that any of these phenomena necessarily demand this hypothesis for its explanation. Thus, for example, the photo-electric effect is not inconsistent with the view that the light energy proceeds from its source in expanding waves, if we postulate the existence within atoms of a

<sup>1</sup> National Research Fellow.

<sup>2</sup> An interesting summary of this work has been presented by K. K. Darrow in the *Bell Technical Journal* **4**, 280 (1925).

mechanism for storing energy until a quantum has been received. It is true that no such mechanism is known; but until our knowledge of atomic structure is increased it would be premature to assert that such a storing mechanism cannot exist. The change of wave-length of x-rays when scattered and the existence of recoil electrons associated with scattered x-rays, it is true, appear to be inconsistent with the assumption that x-rays proceed in spreading waves if we retain the principle of the conservation of momentum.<sup>3</sup> Bohr, Kramers and Slater,<sup>4</sup> however, have shown that both these phenomena and the photo-electric effect may be reconciled with the view that radiation proceeds in spherical waves if the conservation of energy and momentum are interpreted as statistical principles.<sup>5</sup>

A study of the scattering of individual x-ray quanta and of the recoil electrons associated with them makes possible, however, what seems to be a crucial test between the two views of the nature of scattered x-rays.<sup>6</sup> On the idea of radiation quanta, each scattered quantum is deflected through some definite angle  $\phi$  from its incident direction, and the electron which deflects the quantum recoils at an angle  $\theta$  given by the relation<sup>7</sup>

$$\tan \frac{1}{2}\phi = -1/[(1+a)\tan \theta], \quad (1)$$

where  $a = h/mc\lambda$ . Thus a particular scattered quantum can produce an effect only in the direction determined at the moment it is scattered and predictable from the direction in which the recoiling electron proceeds. If, however, the scattered x-rays consist of spherical waves, they may produce effects in any direction whatever, and there should consequently be no correlation between the direction in which recoil electrons proceed and the directions in which the effects of the scattered x-rays are observed

To make the test it is, of course, necessary to observe the individual recoil electrons and to detect the individual scattered quanta.<sup>8</sup> This we have done by means of a Wilson cloud expansion apparatus, in the manner shown diagrammatically in Fig. 1. In a recent statistical study,

<sup>3</sup> Cf A. H. Compton, *Jour. Franklin Inst.* **198**, 71 (1924).

<sup>4</sup> N. Bohr, H. A. Kramers and J. C. Slater, *Phil. Mag.* **47**, 785 (1924).

<sup>5</sup> It seems that there still remains a difficulty in accounting on this view for the intensity of scattered x-rays. See Y. H. Woo, *Phys. Rev.* **25**, 444 (1925).

<sup>6</sup> The possibility of such a test was suggested by W. F. G. Swann in conversation with Bohr and one of us in November 1923.

<sup>7</sup> Cf P. Deybe, *Phys. Zeits.* (Apr. 15, 1923); A. H. Compton and J. C. Hubbard, *Phys. Rev.* **23**, 444 (1924).

<sup>8</sup> A preliminary account of this work has been given in *Proc. Nat. Acad. Sci.* **11**, 303 (June, 1925).

we have found<sup>9</sup> that on the average there is produced about one recoil electron for each quantum of scattered x-rays. Each recoil electron produces a visible track, and occasionally a secondary track is produced by the scattered x-ray. When but one recoil electron appears on the same plate with the track due to the scattered rays, it is possible to tell at once whether the angles satisfy Eq. (1). If the photographs and the measurements can be made with sufficient definiteness, the experiment should thus give an unequivocal answer to the question whether the energy of a scattered x-ray quantum is distributed over a wide solid angle or proceeds in a definite direction.<sup>10</sup>

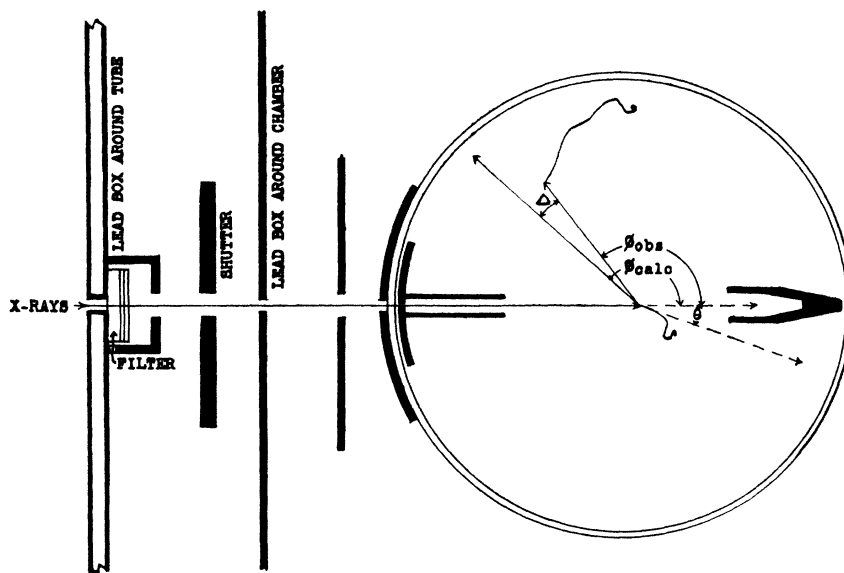


Fig. 1. Diagram of apparatus. On the hypothesis of radiation quanta, if a recoil electron is ejected at an angle  $\theta$ , the scattered quantum must proceed in a definite direction  $\phi_{calc}$ . In support of this view, many secondary  $\beta$ -ray tracks are found at angles  $\phi_{obs}$  for which  $\Delta$  is small.

*Experimental procedure.* In the final experiments we used a high voltage Coolidge x-ray tube excited by an unrectified alternating cur-

<sup>9</sup> A. H. Compton and A. W. Simon, Phys. Rev. **25**, 306 (1925).

<sup>10</sup> W. Bothe and H. Geiger have proposed (Zeits. f. Phys. **26**, 44, 1924) and carried out (Naturwissenschaften **20**, 440, May 15, 1925) a rather similar test. Using two point counters, one to receive the scattered x-rays and the other to receive the recoil electrons, they have found that many of the recoil electrons occur simultaneously with  $\beta$ -rays excited by the scattered x-rays. While such an experiment affords less definite evidence than does the present one regarding the directive nature of the scattered x-rays, it is equally incompatible with Bohr, Kramers and Slater's statistical view of the production of photo and recoil electrons.

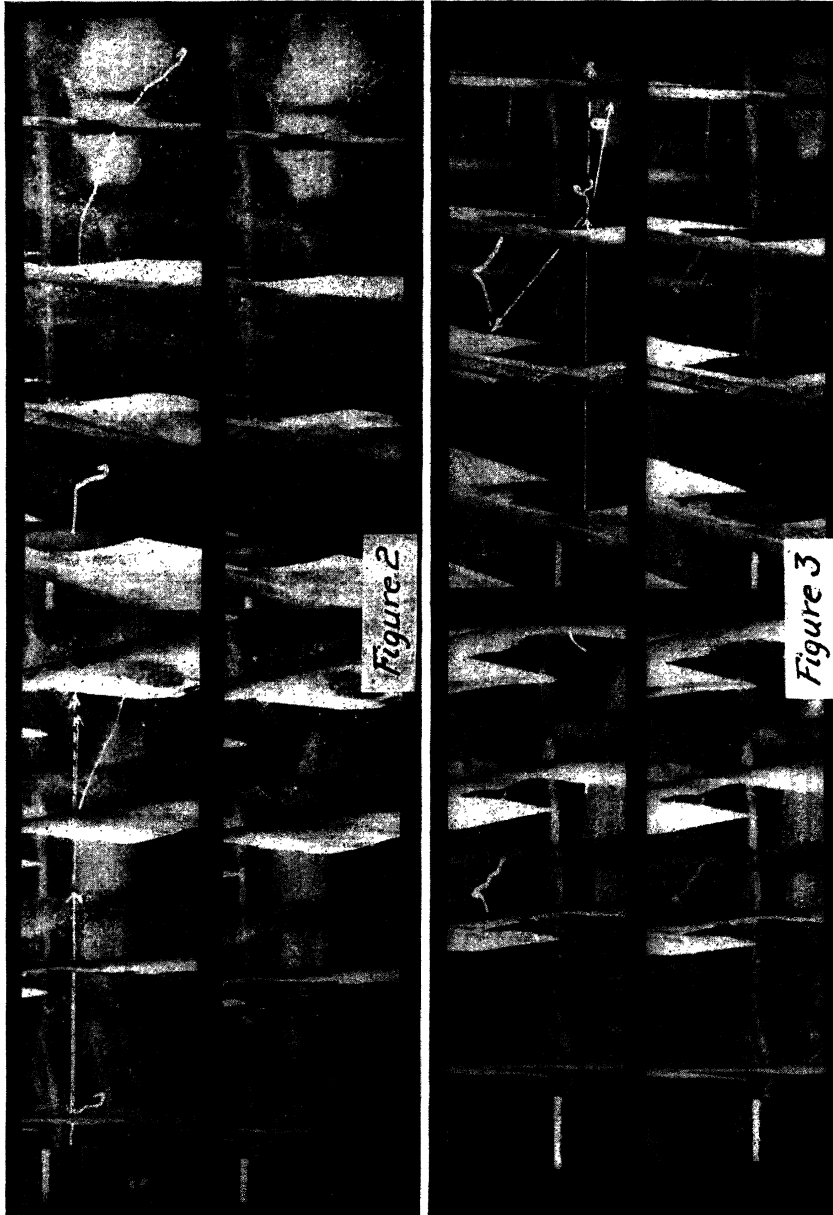


Fig. 2. A square hit. Plate 597. 1 recoil track, 1 secondary.  $\theta = -2^\circ$ ;  $\phi_{calc} = +175^\circ$ ;  $\phi_{obs} = +177^\circ$ ;  $\Delta = 2^\circ$ .

Fig. 3. Plate 560. 2 recoil tracks, 1 secondary.  $\theta = -25^\circ$ ;  $\phi_{calc} = +120^\circ$ ;  $\phi_{obs} = +120^\circ$ ;  $\Delta = 0^\circ$ . Recoil track (2) lies in wrong plane to be associated with secondary track.

rent at 140 peak kilovolts. Potentials as high as 250 kv were tried, but the resulting tracks of the recoil electrons were inconveniently long, and it was difficult to shield the expansion chamber adequately from the very penetrating direct rays. The x-rays were rendered approximately homogeneous by filtering through 6 mm of brass and about 2 mm each of copper and aluminium. Effects of stray x-rays were reduced to a minimum by surrounding the x-ray tube by a box of 9 mm lead, surrounding the expansion chamber with a box of 3 mm lead, and interposing suitable additional lead screens as shown diagrammatically in Fig. 1. The illumination was produced by exploding tungsten wires,<sup>11</sup> 0.1 mm in diameter and 14 cm long, by condenser discharges. The condenser, of about 0.1 microfarad capacity, was charged to about 70 kv by means of a separate transformer and "kenotron" thermionic rectifier. It was found necessary to surround this rectifier also with a box of 3 mm lead in order to avoid stray x-rays. The light entered the expansion chamber horizontally, at right angles to the primary beam, and the photographs were taken through the top of the expansion chamber in such a manner that the light was scattered by the water droplets at an angle of about 40°. We used an Ontoscope stereoscopic camera of 5.5 cm focal length, with the lenses stopped down to  $f/8$ . This gave ample exposure and a focus so deep that a  $\beta$ -ray track in any part of the chamber could be identified. Both the camera and the illuminating spark were enclosed within the lead box surrounding the expansion chamber.

In order to increase the probability that the scattered x-rays would produce  $\beta$ -ray tracks, a comparatively large chamber, about 18 cm in diameter by 4 cm high, was used. Diaphragms of thin lead foil were also suspended inside the chamber (see Figs. 2 to 5), so that the scattered x-rays might make themselves evident by ejecting photo-electrons. We allowed the primary rays to enter through a collimating lead tube, and absorbed them in a hollow lead cone. This eliminated almost completely the effect due to the scattering of the primary rays by the glass walls. When the expansion occurred, however, a slight blast of air proceeded from each of these lead tubes, and distorted the tracks for a distance of about 2 cm from the collimator and about 1 cm from the absorbing cone. It was accordingly possible to make accurate measure-

<sup>11</sup> The illumination obtained using the tungsten wires was roughly 10 times as brilliant photographically as that from a mercury spark at atmospheric pressure, using the same electrical energy.

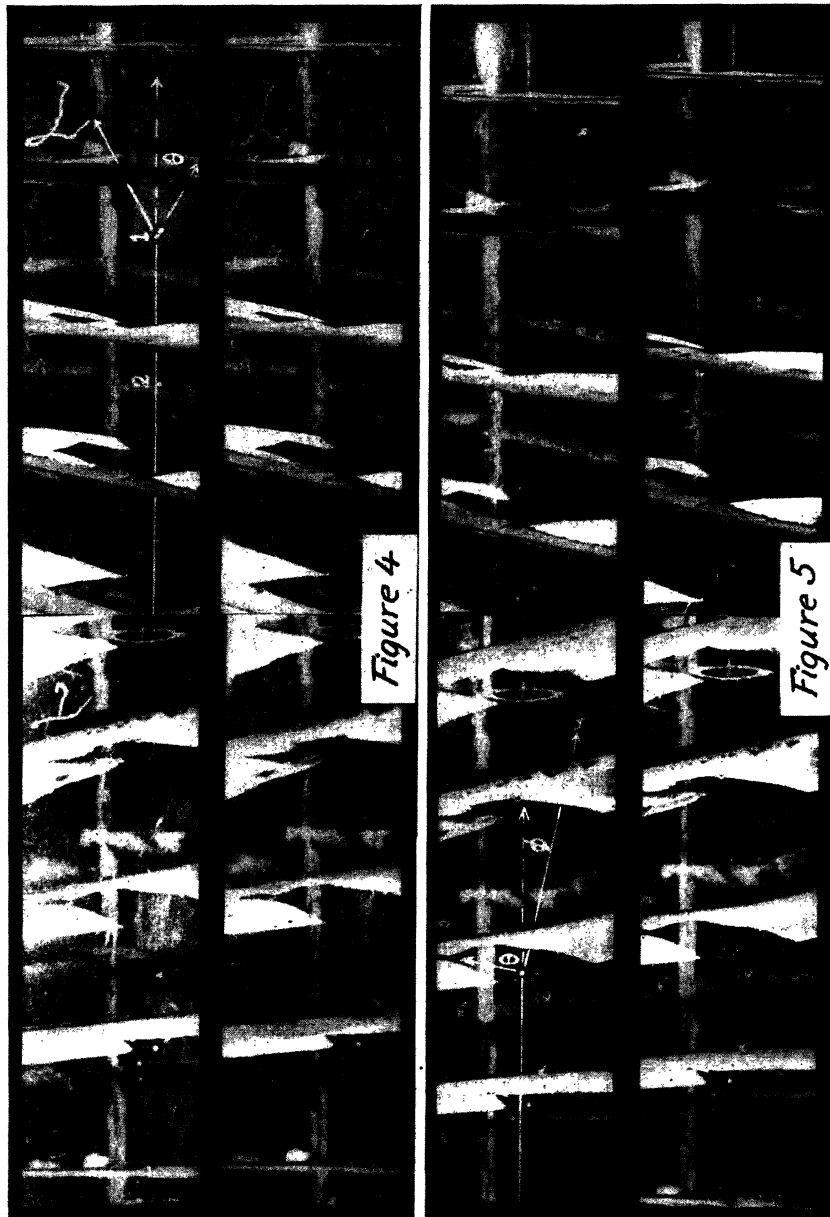


Fig. 4. Plate 1018. 2 recoil tracks, 1 secondary.  $\theta = -55^\circ$ ;  $\phi_{calc} = +59^\circ$ ,  $\phi_{obs} = +50^\circ$ ;  $\Delta = 9^\circ$ .  
 Fig. 5. A glancing blow. Plate 725. 1 recoil (sphere) track, 1 secondary.  $\theta = \pm 85^\circ$  as estimated from length of track;  
 $\phi_{calc} = \pm 8^\circ$ ,  $\phi_{obs} = -22^\circ$ ;  $\Delta = 14^\circ$  or  $30^\circ$ .

ments only on those recoil electrons which were ejected from a column of air about 4 cm long near the middle of the expansion chamber.

An examination of the photographs indicates that there was 1  $\beta$ -ray produced by x-rays scattered from this air column for about every 50 recoil electrons originating in this region, in satisfactory accord with a rough calculation based on the absorption coefficients of the x-rays and  $\beta$ -rays. There were in addition a considerable number of stray  $\beta$ -rays, due in part to stray x-rays and to radioactivity, as was shown by preventing the direct rays from entering the chamber, and probably in part also to the incompletely shielded scattered rays from the walls of the expansion chamber. The presence of these stray rays does not, however, present a serious difficulty in interpreting the photographs, since obviously there can be no correlation between their positions and the directions of ejection of the recoil electrons. Thus the effect of the scattered rays is a definite one superposed upon a random effect due to the stray  $\beta$ -rays.

*The photographs.* In making the preliminary adjustments and for auxiliary experiments we took about 140 photographs. The pictures which were useful in the final test were divided into three series. In the first series there were 302 plates. The second series of 338 plates and the third series of 511 plates were taken under improved conditions of x-ray shielding, thus reducing the number of stray  $\beta$ -ray tracks. There appear on the average two or three recoil tracks in each picture.

Typical photographs in which the secondary tracks appear are shown stereoscopically ( $\times 1.3$ ) in Figs. 2, 3, 4 and 5. In each case a retouched photograph with arrows marking the direction of the primary, recoil and scattered rays is placed above the untouched photograph. Unfortunately there appear on these plates also other marks due to water drops, pieces of lint, bubbles in the glass, etc. While these mar the beauty of the photographs, they do not impair their value, since such marks can always be identified by comparing successive plates.

*Analysis of the photographs.* An angular scale was placed on top of the expansion chamber and photographed with the camera raised half the height of the chamber. A transparency print of the resulting photograph was superposed on the negative of the tracks to be measured. By this means we measured the angles approximately as they would be projected on the plane of the top of the cylindrical chamber. We did not find it possible by means of the stereoscopic effect to make reliable estimates of angles in a plane including the line of sight. The

measurements were made on the original negatives, using a stereoscope with lenses of the same focal length as those of the camera.

When only one recoil electron and one secondary electron appeared on a photograph, the procedure was to record first the angle  $\theta$  at which the track of the recoil electron begins. The end representing the origin was rarely doubtful, since these tracks started within a narrow cylinder of air only about 1 mm in diameter. The angle between the incident ray and the line joining the origin of the recoil track and the origin of the secondary track was noted (when the origin of the secondary track

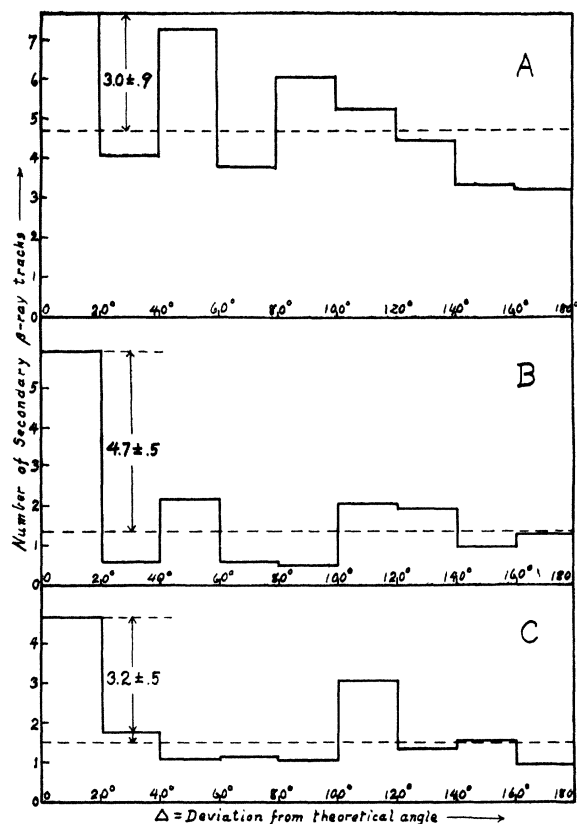


Fig. 6. The weighted number of secondary tracks at different angles  $\Delta$  from the theoretical position. The exceptionally large number between 0 and  $20^\circ$  indicates that many secondary tracks are due to rays scattered as directed quanta. Curve A: Some stray x-rays present. Curves B and C: Most of stray rays eliminated by lead screens.

could not be identified the measurement was made to a point midway between its two ends). The difference between this angle and the angle  $\phi$  calculated from  $\theta$  by equation (1) was called  $\Delta$ , and this value of  $\Delta$



was assigned a weight of unity. When a number  $n$  of recoil tracks appeared on the same plate with a secondary track, the value of  $\Delta$  was thus determined for each recoil track separately, and assigned a weight  $1/n$ . Following this procedure there are values of  $\Delta$  which are distributed approximately at random between 0 and  $180^\circ$  due to the  $n-1$  recoil electrons which are not associated with the secondary track. This is in addition to the random values of  $\Delta$  resulting from the presence of occasional stray tracks. We discarded the plates on which more than 3 recoil tracks appeared.

The results of this analysis are summarized in Figs. 6 and 7. Figure 6A shows the results for the first 302 plates, in which there appeared about 1 stray track for every 4 photographs. As will be seen, this was almost enough to hide the presence of the comparatively rare tracks due to scattered rays, which nevertheless show themselves by the exceptional concentration of  $\Delta$  values between 0 and  $20^\circ$ . Figs. 6B and

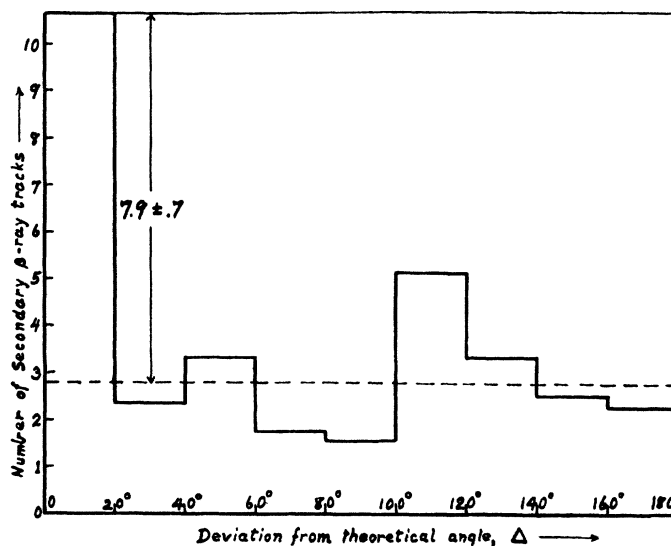


Fig. 7. Sum of curves 6B and 6C.

6C represent respectively the second and third series of plates, in which, by improving the lead shielding, the total number of secondary tracks was reduced to about 1 for every 20 plates. It will be seen that the result of this is to lower the general level of the random  $\Delta$  values and thus to exhibit much more prominently the concentration of these values at small angles. It is just such a concentration which is to be expected if Eq. (1) holds, that is if individual quanta are scattered in definite

directions from individual electrons. In Fig. 7 we have collected the results of the second and third series of plates. This figure shows the distribution of 38 secondary  $\beta$ -rays observed on these plates, 18 of which originate within  $20^\circ$  of the position anticipated from one of the recoil tracks present. The number 18 is about 4 times as many as would be expected if the distribution of the secondary tracks were a matter of chance. An idea of the degree of definiteness of the results can be obtained by calculating the probable variation from the mean of each of the 8 values between  $20^\circ$  and  $180^\circ$  by the usual formula,  $\pm .67\sqrt{\sum\delta^2/(n-1)}$ , where  $\delta$  is the deviation of each value from the mean, and  $n$  is the number (8) of values. Thus we find that the number of pairs occurring with values of  $\Delta$  less than  $20^\circ$  is greater than the mean value for the other angles by  $7.9 \pm 0.7$ . The probability that so great an accidental deviation would occur in the positive direction is accordingly  $(1/2) \times (.7^2/7.9^2) = 1/250$ . It is thus highly improbable that so many pairs of tracks should as a matter of chance have been found to fit Eq. (1) satisfactorily.

Two other possibilities remain, (1) that the observed coincidences are the result of an unconscious tendency to estimate the angles falsely, making consistently favorable errors in measurement, and (2) that the agreement with Eq. (1) is real. Regarding the first possibility, we may note that using our methods of measurement it was hardly possible to make an error in determining the angle of ejection of the recoil electron of more than  $10^\circ$  nor in the angle at which the secondary electron appeared of more than  $5^\circ$ . It will be seen that errors of this magnitude could not alter the general form of the curve. The evidence therefore seems unescapable that Eq. (1) describes to a close approximation the angles at which many of the secondary electrons appear.

The question arises, does the presence in Fig. 7 of the considerable number of values of  $\Delta$  greater than  $20^\circ$  indicate the existence of scattered rays which do not obey the quantum law? It can be shown that about half of these random values of  $\Delta$  are to be expected merely from the fact that in most of the cases where Eq. (1) describes accurately the relation between the position of the secondary electron and the direction of motion of one recoil electron, there are one or two other recoil electrons which are in no way associated with the secondary  $\beta$ -ray. We are unable to assign definitely the origin of the remaining half of the random  $\Delta$  values. Undoubtedly some are due to stray x-rays which could not be completely eliminated and some are probably due to  $\beta$ -rays of radioactive origin. Our experiments cannot therefore be taken to

afford any evidence for the production of  $\beta$ -rays by scattered x-rays which do not conform to the quantum rule described by Eq. (1).

It is our conclusion, therefore, that at least a large part of the scattered x-rays under investigation produce  $\beta$ -rays at an angle connected by equation (1) with the angle of ejection of an associated recoil electron.

Since the only known effect of x-rays is the production of  $\beta$ -rays, and since the meaning of energy is the ability to produce an effect, our result means that there is scattered x-ray energy associated with each of these recoil electrons sufficient to produce a  $\beta$ -ray and proceeding in a direction determined at the moment of ejection of the recoil electron. In other words, at least a large part of the *scattered x-rays proceed in directed quanta of radiant energy.*

Since other experiments have shown that these scattered x-rays can be diffracted by crystals, and are thus subject to the usual laws of interference, there is no reason to suppose that other forms of radiant energy possess an essentially different structure. It thus becomes highly probable that all electromagnetic radiation is constituted of discrete quanta proceeding in definite directions. It is not impossible to express this result in terms of waves if we suppose that a wave train possessing a single quantum of energy can produce an effect only in a certain predetermined direction.

These results do not appear to be reconcilable with the view of the statistical production of recoil and photo-electrons proposed by Bohr, Kramers and Slater. They are, on the other hand, in direct support of the view that *energy and momentum are conserved during the interaction between radiation and individual electrons.*

RYERSON PHYSICAL LABORATORY,  
UNIVERSITY OF CHICAGO.  
June 23, 1925.

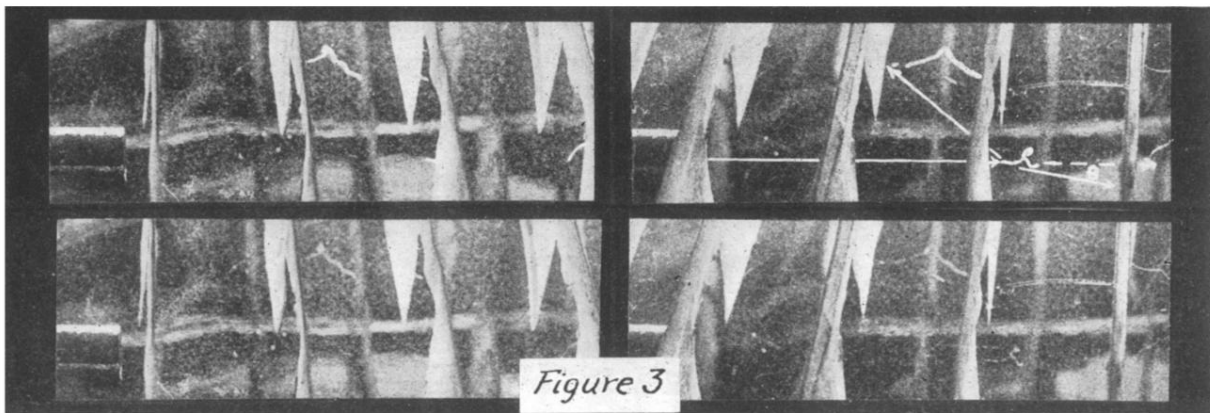
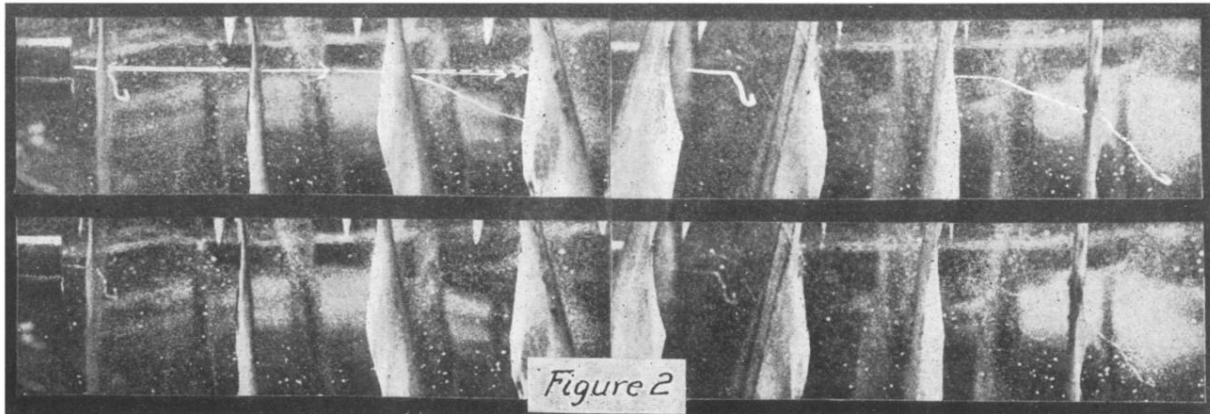


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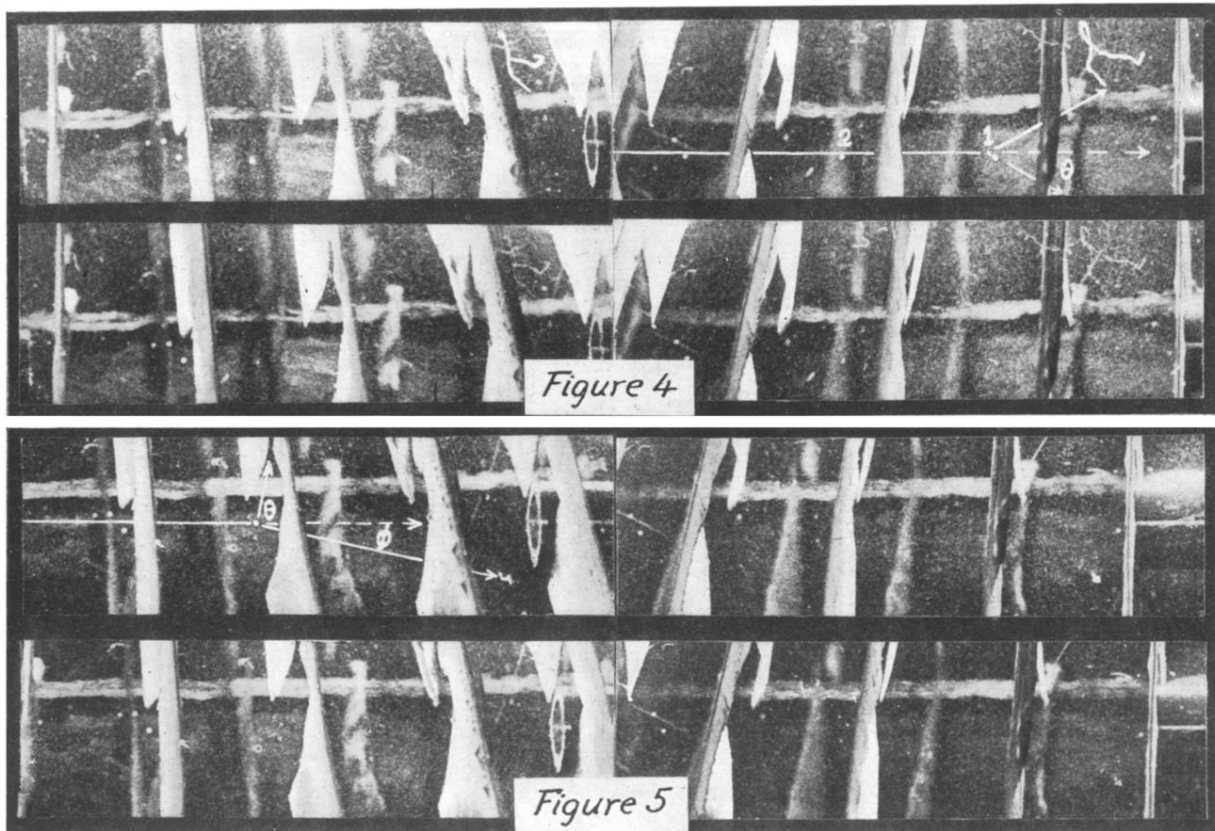


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