A Cloud Chamber Study of the Compton Effect

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An experiment is described which is designed to test the photon theory of scattering in the energy region between 0.5 and 2.6 MEV. A small pencil of radiation from a thorium source is shot through a cloud chamber. A celluloid scatterer 0.8 mm thick is placed in the beam at the center of the chamber. Two thin lead sheets are placed parallel to, and on each side of, the primary beam, to absorb the scattered photons. A magnetic field is applied to determine the energies of the electrons. From the energy and direction of an electron ejected from the scatterer, the direction of the scattered photon expected from theory can be calculated, and is independent of any assumption about the energy of the primary photon. Out of 10,000 photographs taken, 300 electron-photon combinations were found. The angular and energy relations of these seem to indicate that the photon theory of scattering is valid. It is shown experimentally that the scattering of the electrons in the celluloid is of the right order of magnitude to account, at least in part, for the observed deviations of the results from theory.

INTRODUCTION

THE results recently published by R. S. Shankland[1] have incited a great deal of interest in the question of the validity of the Compton theory of photon scattering in the individual collision. Compton and Simon,[2] in 1925, performed an experiment with a cloud chamber, in which the angular relations of the secondary and tertiary electrons produced by 140 kilovolt x-rays were compared with the angles predicted by the theory. Although only a rather small amount of data was obtained the results appeared definitely to support the theory. All experiments reported subsequently were performed with Geiger counters. In 1925 Bothe and Geiger[3] performed an experiment with Geiger counters arranged in a coincidence circuit, designed to record the simultaneous appearance of the scattered photon and electron at the predicted angles. The primary photons were in this case obtained from a 70 kilovolt x-ray tube. Their results seemed to indicate that the Compton theory was valid.

Further work of this kind has been carried out at the University of Chicago since the experiments of Compton and Simon. R. D. Bennett,[4] and, later, J. A. Bearden[5] attempted to detect the simultaneous appearance of the scattered photon and the electron at the predicted angles by means of coincident Geiger counters. The results of both of their experiments were negative. The primary radiation used in these experiments was filtered x-rays. R. S. Shankland published, in January, 1936, the results of an experiment of essentially the type performed by Bennett and by Bearden. He used two sets of Geiger counters, one to record the electron and the other to record the scattered photon, placed in positions calculated from the Compton theory, and measured the rate at which coincident counts were obtained. Then, by placing the photon counter on the opposite side of the axis (at the same angle from the incident beam, but with opposite sign) he obtained a control count. He found the rate of coincidences to be the same for the two cases, which constituted evidence in direct contradiction to the predictions of the Compton theory. The fact that this experiment was done with the gamma-radiation from radon and its products, which was of much higher energy than that used in the previous experiments, invited theoretical speculation as to why the theory had so far appeared to be valid for x-rays but not for higher energy radiation.

EXPERIMENTAL METHOD

Following along the general lines of the Compton and Simon experiment, but with some modification, we have attempted to test the validity of the Compton theory for radiation between 0.5 and 2.6 MEV, especially insofar as

[1] R. S. Shankland, Phys. Rev. **49**, 8 (1936).
[2] A. H. Compton and A. W. Simon, Phys. Rev. **26**, 289 (1925).
[3] W. Bothe and H. Geiger, Zeits. f. Physik **32**, 639 (1925).
[4] R. D. Bennett, Ph.D. dissertation, University of Chicago, 1925.
[5] J. A. Bearden, Letter to A. H. Compton, quoted by Shankland (reference 1).

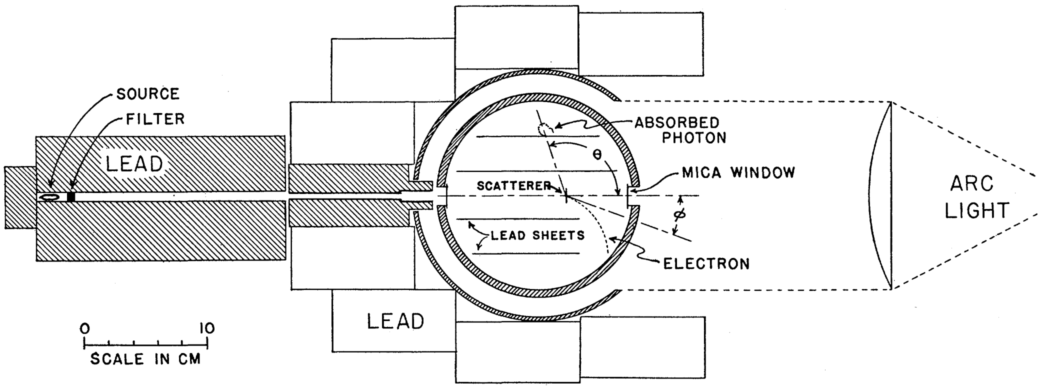

FIG. 1. Sketch of the experimental setup. Angles ϕ and θ are measured positively in the clockwise direction from the line of the gamma-ray beam; negatively in the anticlockwise direction.

the angular relationship of the electron and photon is concerned.

A thin pencil of gamma-rays was shot through a cloud chamber, as shown in Fig. 1, so as to pass through a scatterer suspended in its path. The intensity of the radiation was so adjusted that frequently a single electron appeared in the forward direction from the scatterer. Tracks of electrons of lower energy, presumably due to the absorption of scattered photons, were looked for near the four lead sheets indicated at the sides of the central gamma-ray beam. A magnetic field was applied normal to the chamber so that the energy of the electrons from the scatterer could be determined from their curvature. From the energy and the angle at which an electron was ejected, the angle of the scattered photon expected from the Compton theory could be calculated. In those photographs in which there also appeared evidence of the absorption of a scattered photon, the calculated and the observed photon angles were compared. In a similar manner, using the electron energy and the observed photon angle, the theoretical angle for the electron could be calculated and compared with the observed angle. The above calculations can be made *independently of any assumption whatever about the energy of the incident photon.* This is the important difference between the present experiment and previous experiments, in which it was always necessary to assume an energy for the primary photon.

Details of Apparatus

The cloud chamber used was 15 cm in diameter and 2.5 cm deep, filled with air and ethyl alcohol vapor at atmospheric pressure. A mica window 12 mm in diameter and 0.2 mm thick was provided in each side of the chamber to reduce the scattering of the gamma-ray beam on entering and leaving the chamber. A magnetic field of 880 gauss was produced by a pair of water cooled Helmholz coils. The strength of the field was determined by calculation from the geometry of the coils and the current, and also by measuring the spectrum of recoil electrons from the known 2.6 MEV gamma-ray line of Th C″. A sheet of parallel light about 1 cm in depth, obtained from a 200 ampere carbon arc was projected through the chamber, and photographs were taken with a Sept 35 mm movie camera, at f 3.5 and $\frac{1}{5}$ second exposure. The entire apparatus ran automatically, expansions occurring at 30-second intervals. This rather long expansion interval was found necessary on account of the large amount of material in the chamber in the form of absorbers, etc.

The scatterer used in obtaining most of the data was a piece of celluloid, 0.8 mm thick, although in a few runs at the beginning a 0.2 mm mica scatterer was used. The lead plates parallel to the beam were $\frac{1}{4}$ mm thick, and extended from the top to the bottom of the chamber. For a source of gamma-rays a small capsule containing mesothorium and its products of about 1 millicurie strength was placed at the end of a lead collimator 30 cm long and about 5 mm inside diameter. The walls of the collimator were 5 cm thick, and, for additional shielding, a number of lead blocks were placed around the sides of the cloud chamber, as shown in the diagram. The beam of radiation allowed to enter the chamber was filtered through about 6 mm of lead.

Results and Treatment of Data

About 10,000 photographs were taken, and the following procedure was employed in recording the data which they contained. The pictures were reprojected onto a screen, natural size. Before proceeding to each new picture, a black card was placed over the part of the field in which the recoil electrons appeared; namely, the part in front of, and to the right of, the scatterer. The angular position of any track in the chamber which was thought to indicate the absorption of a scattered photon was then recorded before the black card was removed. If a recoil electron track from the scatterer was found, its angle and energy were recorded. In this way the angle of an electron from the scatterer could not influence the choice or measurement of the "photon tracks." Some discrimination was permissible in dealing with the photon tracks, since in a few cases it was fairly certain that a track was due to the primary gamma-rays (if it was of very high energy), or that it had its origin in the path of the central beam. Such tracks were not counted. It is not probable that the position of the photon track could have influenced the measurement of the recoil electron from the scatterer, since these tracks were very distinct. All electron tracks were

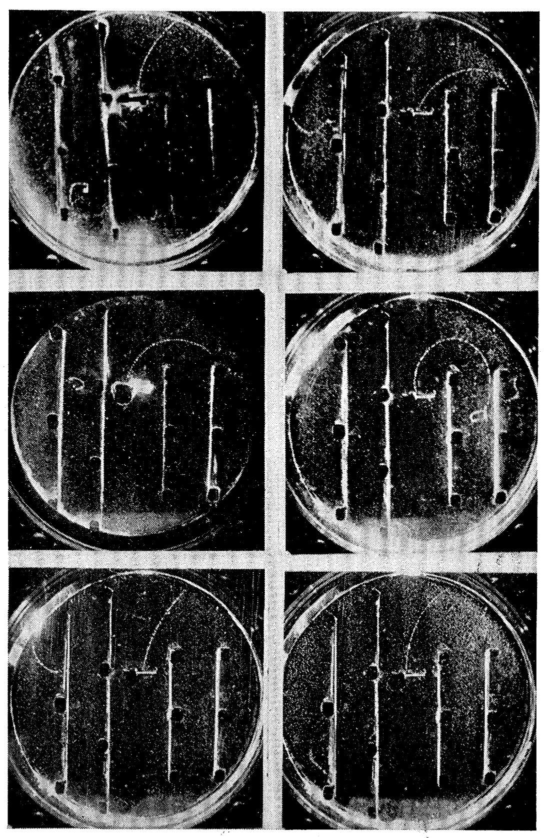

Fig. 2. Examples of cloud chamber photographs, each of which contains one recoil electron, together with evidence of the absorption of the scattered photon.

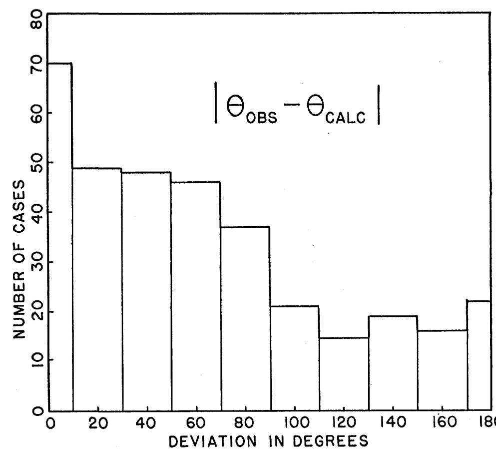

Fig. 3. Absolute values of the differences between the calculated and the observed angles of the scattered photons.

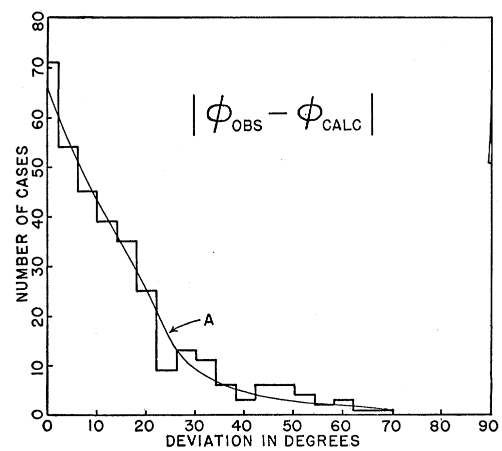

Fig. 4. Absolute values of the differences between the calculated and the observed angles of the recoil electrons.

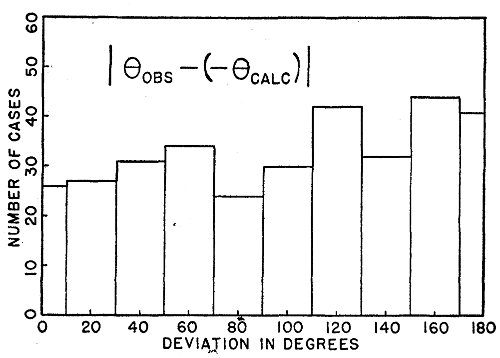

FIG. 5. Absolute values of the differences between the observed and minus the calculated angles of the scattered photons.

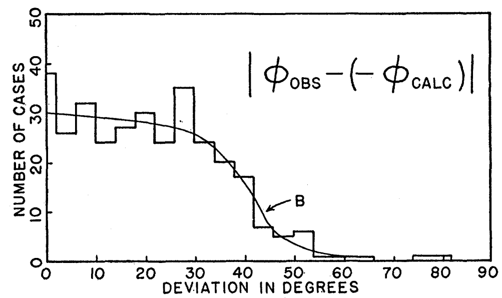

FIG. 6. Absolute values of the differences between the observed and minus the calculated angles of the recoil electrons.

measured which lay nearly enough in the plane of the light beam that an arc of about 90° was visible. After recording all the data in the manner described, only those electron-photon combinations were used which consisted of a single electron from the scatterer and a single absorbed photon. 300 such combinations were found in the 10,000 photographs. Each of the electron-photon combinations was treated as follows: (1) Using the angle and energy of the electron, the theoretical angle of the photon was calculated. (2) Using the energy of the electron and the angle of the photon, the theoretical angle of the electron was calculated. Fig. 3 shows these results plotted according to the absolute difference between the calculated and observed photon angles, and Fig. 4 shows a similar plot for the electron angles.

For the purpose of comparison, similar plots are shown (Figs. 5 and 6) of the absolute differences between the observed photon and electron angles and minus the corresponding calculated angles. These give control plots which are not influenced by asymmetry in the chamber, because spurious tracks have the same chance of appearing near the calculated angles as they have of appearing near minus the calculated angles. (See paragraph on symmetry considerations.)

Discussion of Results

The results of the present experiment may be expected to answer with fair certainty the general question of whether the Compton energy and angular relations are at all valid for the individual collision, or whether the correspondence which has been established by many x-ray scattering experiments is of an entirely statistical nature. The question of how closely the angles correspond in the individual collision to those predicted by theory is a more difficult one on the basis of the data obtained here, and only the vaguest kind of answer can be attempted.

If the Compton angular and energy relationship were assumed to hold only statistically, we would expect the plots of the photon angles in Figs. 3 and 5 to be alike. Actually, they seem to show a significant difference, in a direction which indicates that the predicted Compton angles are considerably favored. The broadness of the maximum, as will be shown later, can be accounted for at least partly by the scattering which the recoil electrons suffer in getting out of the celluloid scatterer. The small errors in the angle ϕ which come about in this way make correspondingly large errors in the theoretical angle θ, especially when ϕ is small, as can be seen readily from the Compton formulas. For 1 MEV electron energy, $d\theta/d\phi$ is about 6 for $\phi=5°$, 5 for $\phi=10°$, 4 for $\phi=15°$, which produces in the θ plots considerable amplification of the broadening effect of the electron scattering.

An indication that the Compton angles are favored can be obtained in a different way, simply by considering the signs of the angles ϕ and θ. In 209 of the 300 cases ϕ and θ were of opposite sign, meaning that the lateral components of momentum of the electron and photon were opposite in direction, while in only 91 cases they were in the same direction.

The plots of the deviations of the electron angles from those calculated, shown in Figs. 4

and 6, were made in order to obtain a curve which could be interpreted more directly in terms of electron scattering. We should point out at the beginning, however, that we should expect a maximum at zero degrees for both the ϕ plots, even if the distribution of photon angles were random. Because of (1) the predominance of forward electrons (Klein-Nishina distribution) and (2) the fact that large angular ranges for θ in the backward direction correspond to small angular ranges for electrons in the forward direction, we should expect many of the differences between ϕ and ϕ calc. to be small. This is apparent in Figs. 4 and 6, but the curve in Fig. 4 is much more peaked at zero than that in Fig. 6. These, again, should have the same form if there were no correspondence of the angles in the individual collision with those predicted from the Compton theory. The ratio of the two curves, shown in Fig. 7 should, provided the breadth is due to scattering, bear some resemblance to a scattering curve for the electrons, even though it does not give it directly.

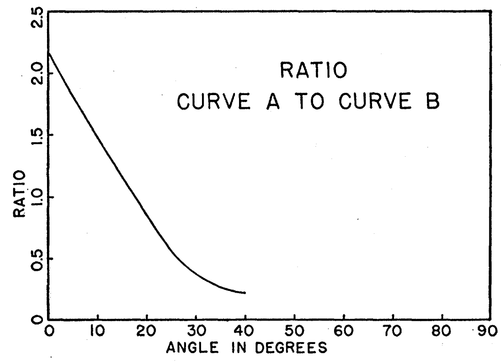

Fig. 7.

An experiment on the scattering of electrons

To determine, under the actual conditions of our experiment, whether the amount of scattering of the electrons is of the order of magnitude indicated by Fig. 7, the following experiment was performed: A sheet of celluloid of the same thickness as the scatterer used in the previous set-up was placed across the center of the cloud chamber. Recoil electrons produced by gamma-rays from the same source with the same filtration as above were allowed to pass through the celluloid, (without a magnetic field) and the angles through which they were deviated in the celluloid were measured. This gave only the projection in two dimensions of the scattering, but this is approximately the thing desired for comparison with Fig. 7, since in the other work all the angles were measured in two dimensions, and errors in the measured ϕ were due mainly to the component of scattering in the horizontal plane. The result is shown in Fig. 8. This is roughly in accord with theoretical estimates of the scattering. The fact that this curve is not as broad as that in Fig. 7 may be satisfactory, since it leaves room for some other errors in measurement, etc., which have broadening effects. From this rough indication of the extent of scattering, it seems reasonable to say that we are not compelled by the present results to look for any inherent breadth or uncertainty in the Compton angles to explain the breadth of the maxima observed. Better measurements of scattering may clarify this point.

Division of the data into energy groups

Because the suggestion has often been made that the scattering of quanta of energy large compared to mc^2 may be different from that for quanta of energy near mc^2 or below, we have analyzed the data more closely with regard to energy. The data shown in Figs. 4 and 6 were divided into groups according to the energies of the recoil electrons and plotted separately, as shown in Figs. 9 and 10. Although this was not strictly a separation according to the energy of the incident photon, it approximated it well enough for the present purpose, and placed a definite lower limit upon the photon energy. (See footnote.) The groups having electron energies from 0.3 to 0.55, 0.55 to 1.0, and 1.0 to 2.4 (photon energies above 0.5, 0.8, and 1.25 MEV, respectively), show no difference in character beyond the expected statistical fluctuations, and each group indicates that the Compton angles are favored. The numbers of cases in these groups are of course not large, but from this small amount of data, at least, there appears no reason to believe that the quanta in the low and the high energy groups are scattered differently.

The three groups in Figs. 9 and 10 automatically give some idea as to the composition of

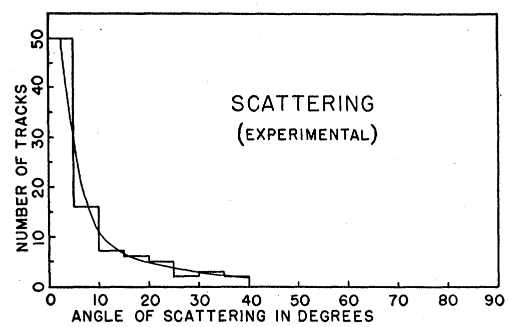

FIG. 8. Experimental curve for the scattering of electrons by 0.8 mm of celluloid.

the radiation from the mesothorium source used. This source was not old enough to have reached equilibrium with its products, and consequently there was present a larger proportion of low energy radiation than is usual with a mesothorium source. Figs. 9 and 10 show that roughly equal numbers of recoil electrons were due to quanta in the three energy regions indicated. In this the low energy component is of course accentuated, due to the larger absorption coefficient of celluloid for the lower energy radiation.

Probability of observing the scattered photon

Considering the total number of electrons and absorbed photons observed, and assuming that from $\frac{1}{2}$ to $\frac{1}{3}$ the observed electron-photon combinations are really associated, we estimate that roughly 1 photon in 50 which passed through the lead sheets was observed. This efficiency seems rather high, but several reasons can be suggested to account for it. (1) All measurable recoil electron tracks observed necessarily lie approximately in the plane of the chamber; therefore (if conservation of momentum holds) the path of the scattered photon also lies in the plane, and has a good chance of passing through one or two of the lead plates. Thus the fact that observations are restricted essentially to two dimensions does not appreciably affect the chance of observing the photon associated with an observed electron. (2) The greater majority of the photons were directed backward from the scatterer, because of the Klein-Nishina angular distribution, and were therefore of comparatively low energy (of the order of 0.25 MEV). This made them quite efficient at ejecting photoelectrons from the lead. (3) In addition to the eight lead surfaces, the top and bottom of the chamber were to some extent effective. Because of the magnetic field, electrons ejected from these surfaces had a 50 percent chance of executing a vertical helix through the visible part of the chamber.

Scattering material

Celluloid was chosen for the scattering material because of its low average atomic number and also because of its transparancy. Scattering of electrons of the energy dealt with here is mainly nuclear, and is about proportional to the square of the atomic number of the scattering material and inversely proportional to the square of the momentum of the electron. With the best lead shielding available around the chamber the background of spurious tracks is about constant, and independent of the scatterer. Too thin a scatterer will give too small a number of Compton collisions compared to the background, while too thick a scatterer gives rise to undue errors in ϕ through scattering of the recoil electrons. 0.8 mm proved to be not far from the optimum thickness.

Symmetry

The arrangement of the lead plates in the chamber was not symmetrical on the two sides of the gamma-ray beam. This had no effect on the result, however, since as many electrons were ejected having ϕ positive as having ϕ negative (by actual count). This was equivalent to interchanging the two halves of the chamber for half the data.

Simultaneity of appearance of photon and electron

The possibility of a difference in the times of appearance of the scattered electron and the photon has often been suggested to account for the failure of some of the Geiger-counter experiments to give positive results. The resolving time of a cloud chamber is about 1/25 of a second, and that of a coincidence Geiger-counter circuit of the order of 1/1000 of a second or less. If the results so far given by both the cloud chamber and the Geiger-counter technique are to be adhered to, one possible interpretation would of course be that the time difference lies somewhere between the resolving times of these two instruments. Exclusive of this argument, however, the one type of experiment seems but

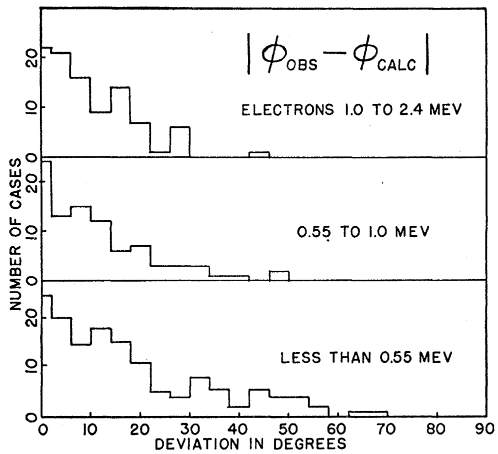

FIG. 9. The data of Fig. 4, plotted in three groups according to the energy of the recoil electrons.

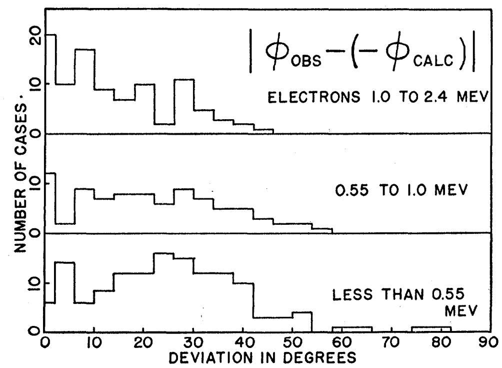

FIG. 10. The data of Fig. 6, plotted in three groups according to the energy of the recoil electrons.

little more satisfying than the other, since a time difference in the process may be imagined to lie anywhere in the large range between the above resolving time and 10^{-20} second or less. There seems at present a great likelihood that with further refinements in both methods of attack, the results of both methods will come into agreement. The desirability of further experiments along these lines can hardly be over-estimated.

This work was made possible by a grant from the Rackham Fund. The authors wish to express their appreciation for this support.

According to the Klein-Nishina formula most of the recoil electrons due to gamma-rays have nearly the maximum energy. Therefore a division of the data on the basis of electron energy seems permissible. Alternative ways of obtaining the energy of the primary gamma-ray quantum are: (1) Calculation from the energy of the recoil electron and the direction of the scattered photon. This is not satisfactory because the photon is really associated with the electron in only $\frac{1}{2}$ or $\frac{1}{3}$ of the cases. (2) Calculation from the energy and direction of the recoil electron. This is vitiated by scattering of the recoil electron. The result is rather sensitive to this.

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Disintegration of Beryllium, Boron and Carbon by Deuterons

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The energy distribution of the neutrons emitted when beryllium, boron and carbon are bombarded by 0.9 MEV deuterons has been investigated. The neutrons from beryllium are attributed to the reaction

$$_4\mathrm{Be}^9 + {}_1\mathrm{H}^2 \rightarrow {}_5\mathrm{B}^{10} + {}_0n^1 + Q_1. \quad (1)$$

The energy of disintegration Q_1 is 4.25 ± 0.2 MEV. Several lower energy neutron groups attributed to excited B^{10} nuclei were observed with Q's equal to 3.7, 2.1 and 0.8 MEV. The neutrons observed when boron is bombarded by deuterons are attributed to the reactions:

$$_5\mathrm{B}^{11} + {}_1\mathrm{H}^2 \rightarrow {}_6\mathrm{C}^{12} + {}_0n^1 + Q_2, \quad (2)$$

$$_5\mathrm{B}^{11} + {}_1\mathrm{H}^2 \rightarrow 3\,{}_2\mathrm{He}^4 + {}_0n^1 + Q_3, \quad (3)$$

$$_5\mathrm{B}^{10} + {}_1\mathrm{H}^2 \rightarrow {}_6\mathrm{C}^{11} + {}_0n^1 + Q_4. \quad (4)$$

The most probable of these is reaction (3); it gives rise to a group of neutrons with a continuous distribution of energies below 3 MEV. The disintegration energies observed from the other two reactions are:

$$Q_2^0 = 13.5 \pm 0.3 \text{ MEV}, \qquad Q_4^0 = 6.2 \pm 0.2 \text{ MEV},$$
$$Q_2^1 = 9.1 \pm 0.2 \text{ MEV}, \qquad Q_4^1 = 4.0 \pm 0.1 \text{ MEV}.$$

The neutrons observed when carbon is bombarded by deuterons are attributed to the reactions:

$$_6\mathrm{C}^{12} + {}_1\mathrm{H}^2 \rightarrow {}_7\mathrm{N}^{13} + {}_0n^1 + Q_5, \quad (5)$$

$$_6\mathrm{C}^{13} + {}_1\mathrm{H}^2 \rightarrow {}_7\mathrm{N}^{14} + {}_0n^1 + Q_6. \quad (6)$$

It is found that reaction (5) is responsible for approximately 99 percent of the neutrons from carbon and that reaction (6) is responsible for the remainder. The values of the disintegration energies are:

$$Q_5 = -0.37 \pm 0.05 \text{ MEV} \quad \text{and} \quad Q_6 = 5.2 \pm 0.4 \text{ MEV}.$$

The calculated value of the maximum energy of the positrons from N^{13} is 1.16 MEV which is lower than the Konopinski-Uhlenbeck extrapolated value of 1.45 MEV. A complete set of values of the masses of the light elements computed from disintegration data is given.

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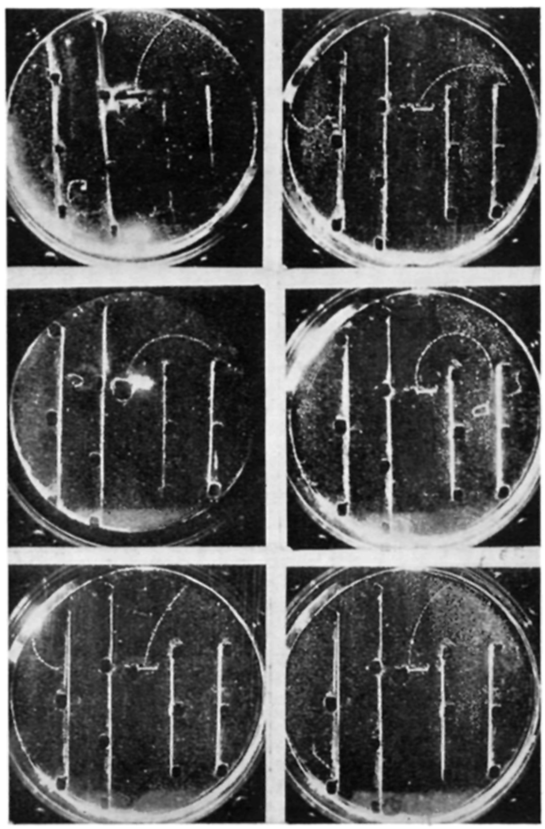

Fig. 2. Examples of cloud chamber photographs, each of which contains one recoil electron, together with evidence of the absorption of the scattered photon.