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The Scattering of X Rays as Particles*

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The experimental evidence and the theoretical considerations that led to the discovery and interpretation of the modification of the wavelength of x rays as a result of scattering by electrons are reviewed, as is the controversy between Duane and the author that took place in 1923–24. The confirmatory evidence obtained by Bothe, Geiger, Simon, and Compton is summarized.

I HAVE been asked to say something about how the study of the scattering of x rays has led to the concept of x rays acting as particles.

In the interest of conserving time I shall summarize the first part of the story by noting that, beginning in 1917, I spent five years in an unsuccessful attempt to reconcile certain experiments on the intensity and distribution of scattered x rays with the electron theory of the phenomenon that had been developed by Sir J. J. Thomson. Then a series of experiments that I performed at Washington University, beginning in 1922, confirmed an observation by J. A. Gray[1] of Queen's University of Kingston, Ontario, that the secondary rays produced when x rays pass through matter are in fact of the nature of scattered rays, showing the same polarization and approximately the intensity predicted by Thomson's electron theory and, further, that in the process of scattering, these rays are in some way altered to increase their absorbability. From my absorption measurements I was able to estimate that over a wide range of wavelengths of the primary rays the increase in the absorbability of scattered rays was what it should be if their wavelength was increased by about 0.03 A over the wavelength of the primary ray. This result I checked with an x-ray spectrometer, measuring an increase in the wavelength of approximately 0.02 A.

At this point I found myself engaged, as a member of a committee of which William Duane of Harvard was the chairman, in preparing a report for the National Research Council on secondary radiations produced by x rays. When it came to publication of the report, Duane objected to including my revolutionary conclusion that the wavelength of the rays was increased in the scattering process just described because he felt that the evidence was inconclusive. At the insistence of A. W. Hull, however, this portion of my report was included in the publication.[2]

At this point I paused in my experiments in order to concentrate on their theoretical interpretation. I found at once that the change of wavelength that I observed for scattering at 90° was what should be expected if the scattering electrons were moving in the direction of the primary beam at about half the speed of light, which would mean that each electron had a momentum equal to that of a quantum of energy of the frequency of the primary x rays. It was obvious, however, that not all of the electrons in the scattering material, which was fixed in my apparatus, could be moving forward at such a velocity; yet according to the theory all of the electrons should participate in the scattering

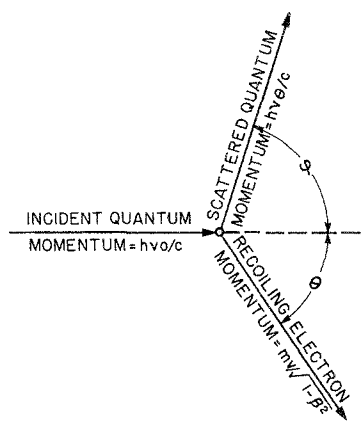

FIG. 1. Recoil of an electron upon scattering of an x-ray photon.

* Paper delivered as part of a program on "Topics in the history of modern physics" on February 3, 1961, at a joint session of the American Physical Society and the American Association of Physics Teachers during their annual meetings in New York City.

[1] J. A. Gray, J. Franklin Inst. **189**, 643 (1920).

[2] A. H. Compton, Bull. Natl. Research Council, No. 20, 19 (1922).

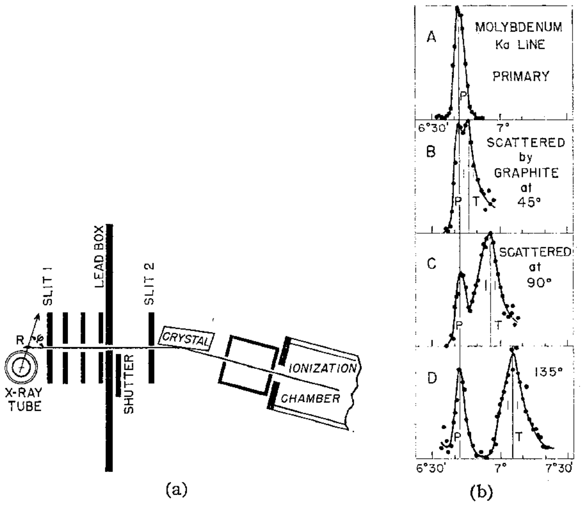

FIG. 2. (a) Schematic arrangement of the apparatus for determination of the spectrum of the scattered x rays. (b) Experimental results.

process. This led me to examine what would happen if each quantum of x-ray energy were concentrated in a single particle and would act as a unit on a single electron. Thus I was led to the now familiar hypothesis, illustrated in Fig. 1, of an x-ray particle colliding with an electron and bounding elastically from it with reduced energy, the lost energy appearing as the recoil energy of the electron. This idea, of an x-ray quantum losing energy by collision with an electron, must have been already in the mind of Peter Debye, then working at Zürich, for immediately upon the appearance of my report in the Bulletin of the National Research Council, he published a paper[3] in the Physikalische Zeitschrift in which he presented an explanation of the change in wavelength of the scattered rays identical in principle with my own hypothesis, and appearing in print only a few days after my first full publication.[4]

Assuming that the energy and the momentum of the incident quantum and of the electron are conserved in this collision process, one is led to a group of three expressions representing a change of wavelength, the energy of the recoil electron, and the relation between the angle of recoil and the angle of scattering of the photon. Each of these formulas, expressed in Eqs. (1)–(3), is subject to precise experimental test.

[3] P. Debye, Physik. Z. **24**, 161 (1923).
[4] A. H. Compton, Phys. Rev. **21**, 484 (1923).

$$\delta\lambda=\lambda'-\lambda=(h/mc)(1-\cos\phi), \qquad (1)$$

$$E_{kin}=2\alpha\cos^2\theta/(1+\alpha)^2=\alpha^2\cos\theta, \qquad (2)$$

$$\cot\theta=(1-\alpha)\tan(\phi/2), \qquad (3)$$

where

$$\alpha=h\nu/mc^2.$$

The change in wavelength I measured repeatedly at Washington University. Figure 2 shows the results of one series of these experiments.

The results, confirming accurately the theoretical predictions, immediately became a subject of the most lively scientific controversy that I have ever known. I reported the results shown in Fig. 2 before the American Physical Society in April, 1923. At the meeting of the American Physical Society during the Christmas holidays of that year there was arranged a rather formal debate between Duane and myself on the validity of the results. Having frequently repeated the experiments I entered the debate with confidence, but was nevertheless pleased to find that I had support from P. A. Ross of Stanford and M. de Broglie of Paris, who had obtained photographic spectra showing results similar to my own. Duane at Harvard with his graduate students had been able to find not the same spectrum of the scattered rays, but one which they attributed to tertiary x rays excited by photoelectrons in the scattering material. I might have criticized his interpretation of his results on rather obvious grounds, but thought it would be wiser to let Duane himself find the answer. Duane followed up this debate by visiting my laboratory (at that time in Chicago) and invited me to his laboratory at Harvard, a courtesy that I should like to think is characteristic of the true spirit of science. The result was that neither of us could find the reason for the difference in the results at the two laboratories, but it turned out that the equipment that I was using was more sensitive and better adapted than was Duane's to a study of the phenomenon in question.

During the following summer at Toronto there occurred a meeting of the British Association for the Advancement of Science, with Sir William Bragg presiding over the physics section. In the previous decade Sir William, as also Ernest Rutherford, had been greatly impressed by the forward momentum of the secondary electrons ejected from matter by both x rays and gamma rays and had been led thereby to defend a corpuscular theory of the scattering of the rays. This interpretation, however, he had abandoned following the experiments by von Laue and by himself on the reflection of x rays by crystals, which had given him confidence in the wave interpretation of x rays. At this Toronto meeting a full afternoon was set aside for a continuation of the debate. The result was inconclusive. It was summarized by Sir C. V. Raman by this statement to me privately after the meeting. "Compton," he said, "you are a good debater, but the truth is not in you." Nevertheless, it seems to have been this discussion that stimulated Raman to the discovery of the effect which now bears his name. Duane followed up this meeting by a new interpretation of the change in wavelength which he attributed to what he called a "box" effect, explaining that surrounding the scattering apparatus with a lead box had in some way altered the character of the radiation. This interpretation I answered by repeating the experiment out of doors with essentially the same results, and at the same time Duane and his collaborators in a repetition of their own experiments began to find the spectrum line of the changed wavelength in accord with my collision theory. At the next meeting of the American Physical Society they reported a very good measurement of this change in wavelength.

In the meantime other experimenters had not

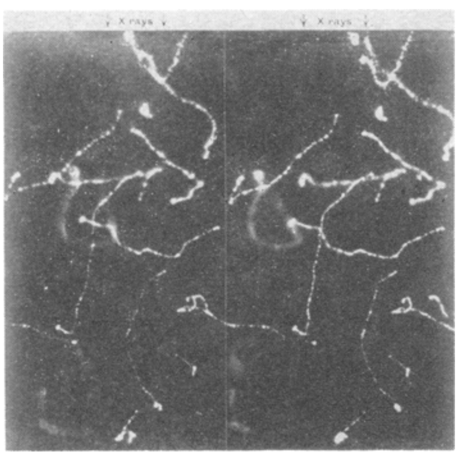

FIG. 3. Cloud chamber tracks produced by recoil electrons (after C. T. R. Wilson).

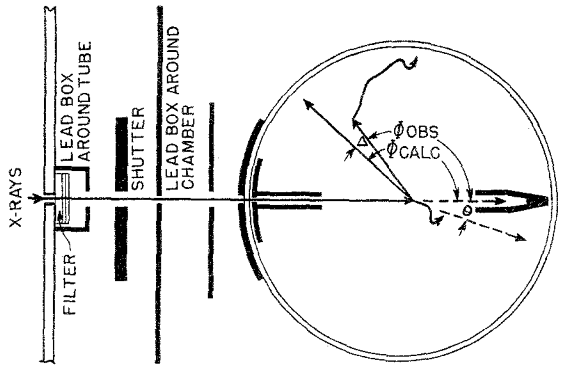

FIG. 4. Apparatus for measurement of scattering angle.

been idle. Within a few months after my first paper C. T. R. Wilson at Cambridge and W. Bothe in Germany had found the recoil electrons predicted by the corpuscular theory. Figure 3 shows one of C. T. R. Wilson's photographs of the cloud tracks left by these electrons in air traversed by x rays. The appearance of the trails led Wilson to call them "fish" tracks, with their tail toward the x-ray tube and their head pointed in the direction of the beam. A. W. Simon and I, repeating these experiments, showed that the number of the tracks and their ranges were just what should be expected according to the theory that each recoiling electron was the result of the impact of one photon of x rays that it scattered.[5] I had the opportunity to show some of these fish tracks in a cloud chamber to S. K. Allison, who was at that time working in Duane's laboratory. It is possible that it was these tracks, rather than the evidence of the x-ray spectra, that convinced Duane of the validity of the corpuscular theory. In any case, since that time no one seems to have questioned the correctness of our experimental results.

Immediately following their observation of the recoil electrons, Bothe and Geiger reported an observation of coincidences of recoil electrons and associated scattered photons as observed in a pair of counters. Simon and I were engaged in checking the angles at which the recoil electron and the associated scattered photon would occur. The apparatus that we used is shown diagrammatically in Fig. 4. According to the theory, associated with an electron recoiling at an angle θ, any effect of the associated scattered photon

[5] A. H. Compton and A. W. Simon, Phys. Rev. 25, 309 (1925).

should occur in the direction of ϕ, as given by Eq. (3). With a specially designed cloud chamber, out of 850 photographs 38 showed a β particle resulting from the photon associated with the recoil electron.[6] Figure 5 shows a typical photograph.

This result is of especial interest because it shows that it is possible to follow the path of an x-ray particle or photon by examining the secondary electrons that it ejects along its way. It is clear that the x rays thus scattered proceed in direct quanta of radiant energy; in other words, that they act as photon particles. This test of the relation between the angles θ and ϕ is a crucial test of the conservation of energy and momentum as related to the process of the scattering of photons by electrons. The results of Simon and myself have accordingly been reexamined and refined by a number of experimenters, as summarized recently by Robert Shankland in his *Atomic and Nuclear Physics*.[7] The net result is a full confirmation of the angular relation given by Eq. (3).

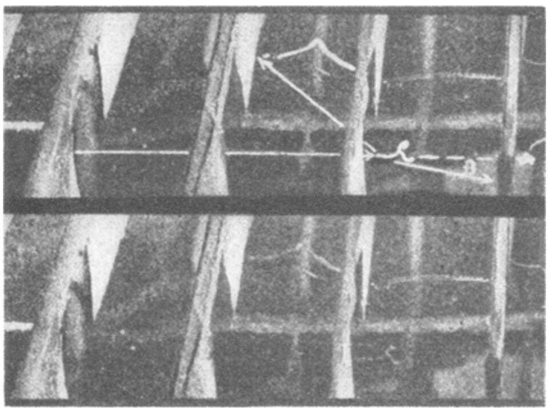

FIG. 5. Typical cloud chamber photograph of recoiling electron track.

Time does not permit me to review the evidence that was accumulating in the meantime that gave full support likewise to the electromagnetic wave character of the x rays: complete polarization of x rays scattered at 90°, the diffraction of x rays from ruled gratings, as well as from crystals, interference phenomena, and refraction phenomena, precisely analogous to results obtained with light. It became evident that though x rays moved and did things as particles, they nevertheless have also the characteristic optical qualities that identify them as waves. Thus we were introduced to the concept of light as having the nature of waves and particles as having a kind of reality, a difficult concept to which L. de Broglie was, however, at the same time giving a theoretical meaning.

It may be fair to say that these experiments were first to give, at least to physicists in the United States, a conviction of the fundamental validity of the quantum theory.

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

[7] Robert Shankland, *Atomic and Nuclear Physics* (The Macmillan Company, New York, 1960), 2nd ed., p. 204.