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# THE SPECTRUM OF SCATTERED X-RAYS[1]

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ABSTRACT

**The spectrum of molybdenum K$\alpha$ rays scattered by graphite** at 45°, 90° and 135° has been compared with the spectrum of the primary beam. A primary spectrum line when scattered is broken up into two lines, an "unmodified" line whose wave-length remains unchanged, and a "modified" line whose wave-length is greater than that of the primary spectrum line. Within a probable error of about 0.001 A, the difference in the wave-lengths $(\lambda-\lambda_0)$ increases with the angle $\theta$ between the primary and the scattered rays according to the quantum relation $(\lambda-\lambda_0)=\lambda(1-\cos\theta)$, where $\lambda=h/mc=0.0242$ A. This wave-length change is confirmed also by absorption measurements. The modified ray does not seem to be as homogeneous as the unmodified ray; it is less intense at small angles and more intense at large angles than is the unmodified ray.

**An x-ray tube of small diameter and with a water-cooled target** is described, which is suitable for giving intense x-rays.

THE WRITER has recently proposed a theory of the scattering of x-rays, based upon the postulate that each quantum of x-rays is scattered by an individual electron.[2, 3] The recoil of this scattering electron, due to the change in momentum of the x-ray quantum when its direction is altered, reduces the energy and hence also the frequency of the quantum of radiation. The corresponding increase in the wave-length of the x-rays due to scattering was shown to be

$$\lambda-\lambda_0=\gamma(1-\cos\theta) \qquad (1)$$

where $\lambda$ is the wave-length of the ray scattered at an angle $\theta$ with the primary ray whose wave-length is $\lambda_0$, and

$$\gamma=h/mc=0.0242 \text{ A}$$

where $h$ is Planck's constant, $m$ is the mass of the electron and $c$ the

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[1] A report on this work was presented before the American Physical Society, Apr. 21, 1923 (Phys. Rev. **21**, 715, 1923).

[2] A. H. Compton, Bull. Nat. Res. Coun., No. 20, p. 18 (October 1922); Phys. Rev. **21**, 207 (abstract) (Feb. 1923); Phys. Rev. **21**, 483 (May, 1923).

[3] Cf. also P. Debye, Phys. Zeitschr. **24**, 161 (April 15, 1923)

velocity of light. It is the purpose of this paper to present more precise experimental data than has previously been given regarding this change in wave-length when x-rays are scattered.

*Apparatus and method.* For the quantitative measurement of the change in wave-length it was clearly desirable to employ a spectroscopic method. In view of the comparatively low intensity of scattered x-rays, the apparatus had to be designed in such a manner as to secure the maximum intensity in the beam whose wave-length was measured. The arrangement of the apparatus is shown diagrammatically in Fig. 1. Rays proceeded from the molybdenum target $T$ of an x-ray tube to the graphite scattering block $R$, which was placed in line with the slits 1 and 2. Lead diaphragms, suitably disposed, prevented stray radiation from leaving the lead box that surrounded the x-ray tube. Since the slit 1 and the diaphragms were mounted upon an insulating support, it was possible to place the x-ray tube close to the slit without danger of puncture. The x-rays, after passing through the slits, were measured by a Bragg spectrometer in the usual manner.

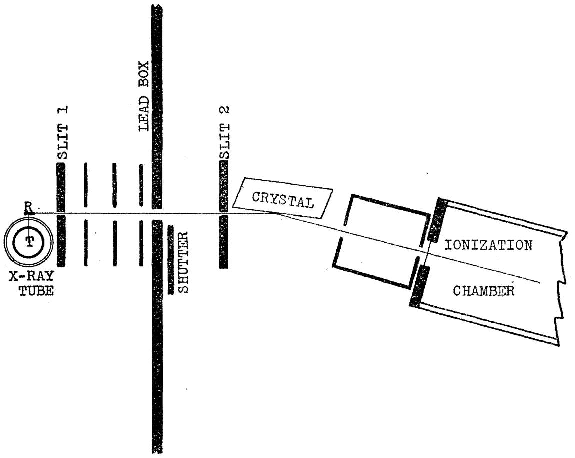

Fig. 1. Measuring the wave-length of scattered x-rays.

The x-ray tube was of special design. A water-cooled target was mounted in a narrow glass tube, as shown in Fig. 2, so as to shorten as much as possible the distance between the target $T$ and the radiator $R$. This distance in the experiments was about 2 cm. When 1.5 kw was dissipated in the x-ray tube, the intensity of the rays reaching the radiator was thus 125 times as great as it would have been if a standard Coolidge tube with a molybdenum target had been employed. The electrodes for this tube were very kindly supplied by the General Electric Company.

In the final experiments the distance between the slits was about 18 cm, their length about 2 cm, and their width about 0.01 cm. Using a crystal of calcite, this made possible a rather high resolving power even in the first order spectrum.

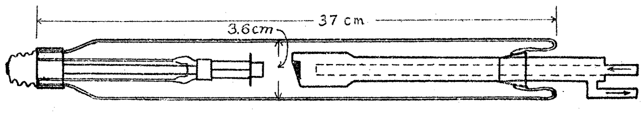

Fig. 2. X-ray tube.

*Spectra of scattered molybdenum rays.* Results of the measurements, using slits of two different widths, are shown in Figs. 3 and 4. Curves A represent the spectrum of the Kα line, and curves B, C and D are the spectra of this line after being scattered at angles of 45°, 90° and 135° respectively with the primary beam. While in Fig. 4 the experimental

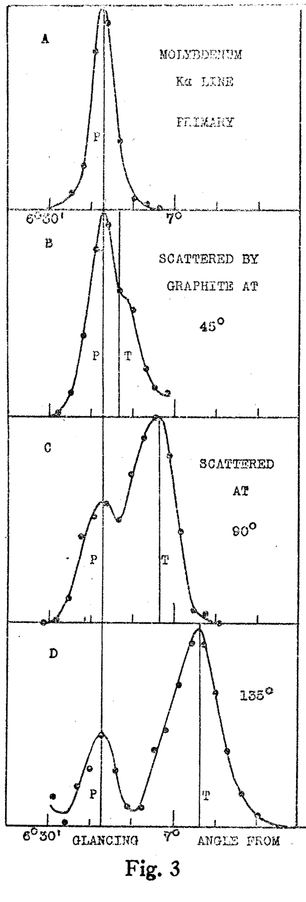

Fig. 3

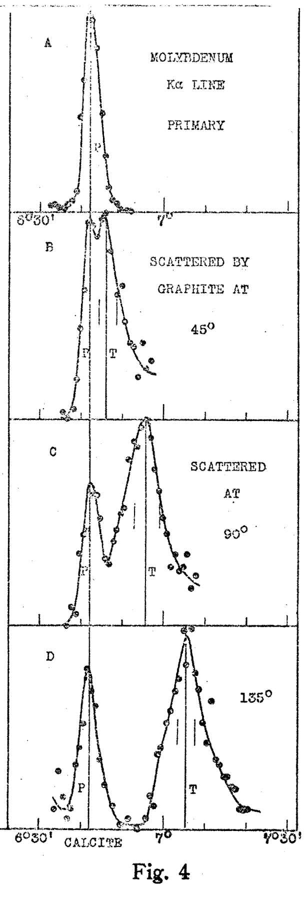

Fig. 4

points are a little erratic, it may be noted that in this case the intensity of the x-rays is only about 1/25,000 as great as if the spectrum of the primary beam were under examination, so that small variations produce a relatively large effect.

It is clear from these curves that when a homogeneous x-ray is scattered by graphite it is separated into two distinct parts, one of the same wave-length as the primary beam, and the other of increased wave-length. Let us call these the *modified* and the *unmodified* rays respectively. In each curve the line $P$ is drawn through the peak of the curve representing the primary line, and the line $T$ is drawn at the angle at which the scattered line should appear according to Eq. (1). In Fig. 4, in which the settings were made with the greater care, within an experimental error of less than 1 minute of arc, or about 0.001 A, the peak of the unmodified ray falls upon the line $P$ and the peak of the modified ray falls upon the line $T$. The wave-length of the modified ray thus increases with the scattering angle as predicted by the quantum theory, while the wave-length of the unmodified ray is in accord with the classical theory.

There is a distinct difference between the widths of the unmodified and the modified lines. A part of the width of the modified line is due to the fact that the graphite radiator $R$ subtends a rather large angle as viewed from the target $T$, so that the angles at which the rays are scattered to the spectrometer crystal vary over an appreciable range. As nearly as I can estimate, the width at the middle of the modified line due to this cause is that indicated in Fig. 4 by the two short lines above the letter $T$. It does not appear, however, that this geometrical consideration is a sufficient explanation for the whole increased width of the modified line, at least for the rays scattered at 135°. It seems more probable that the modified line is heterogeneous, even in a ray scattered at a definite angle.

The unmodified ray is usually more prominent in a beam scattered at a small angle with the primary beam, and the modified ray more prominent when scattered at a large angle. A part of the unmodified ray is doubtless due to regular reflection from the minute crystals of which the graphite is composed. If this were the only source of the unmodified ray, however, we should expect its intensity to diminish more rapidly at large angles than is actually observed. The conditions which determine the distribution of energy between these two rays are those which determine whether an x-ray shall be scattered according to the simple quantum law or in some other manner. I have studied this distribution experimentally by another method, and shall discuss it in another paper;[4] but the reasons underlying this distribution are puzzling.

*Experiments with shorter wave-lengths.* These experiments have been performed using a single wave-length, $\lambda = 0.711$ A. In this case we find for the modified ray a change in wave-length which increases with the angle of scattering exactly in the manner described by Eq. (1). While these experiments seem conclusive, the evidence would of course be more complete if similar experiments had been performed for other wave-lengths. Preliminary experiments similar to those here described have been performed using the K radiation from tungsten, of wave-length about 0.2 A. This work has shown a change in wave-length of the same order of magnitude as that observed using the molybdenum $K\alpha$ line. Furthermore, as described in earlier papers,[5] absorption measurements have confirmed these results as to order of magnitude over a very wide range of wave-lengths. This satisfactory agreement between the experiments and the theory gives confidence in the quantum formula (1) for the change in wave-length due to scattering. There is, indeed, no indication of any discrepancy whatever, for the range of wave-length investigated, when this formula is applied to the wave-length of the modified ray.

Washington University,
Saint Louis,
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[4] A. H. Compton, Phil. Mag. (in printer's hands)

[5] Cf. e.g., A. H. Compton, Phys. Rev. **21**, pp. 494–6 (1923)