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THE DISTRIBUTION OF ENERGY BETWEEN THE MODIFIED AND THE UNMODIFIED RAYS IN THE COMPTON EFFECT

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ABSTRACT

Intensity ratio of modified to unmodified scattered x-rays as a function of scattering angle.—Using small tubes of the Compton type and Soller collimators, reliable measurements of the intensity of scattered x-rays were obtained from five radiators—*paraffin, wood, carbon (graphite), aluminium and sulfur*. An ionization spectrometer (ethyl bromide) with a large calcite crystal was employed. Since the wave-length range investigated was small, the relative energy of each spectrum was obtained, to a close approximation, by integrating with a planimeter the area under the ionization curve which represented the line. The results of this measurement are as follows:

φ	R(paraffin)	R(wood)	R(carbon)	R(aluminium)	R(sulfur)
60°	2.29	1.19	1.08	0.46	....
75	3.10	1.85	1.31	0.74	0.25
90	4.69	2.73	1.45	0.91	0.42
105	5.16	3.21	1.82	1.23	0.67
120	5.49	4.57	2.26	1.45	....
135	6.52	5.38	3.42	2.11	....
150	6.98	6.21	4.05	2.52	....
165	7.47	7.00	4.86	....	....

where φ represents the scattering angle and R the intensity ratio of the modified to the unmodified line. The values of R increase with angle of scattering for a given element in the general manner predicted by Jauncey's theory, but the numerical values given by the theory are 20 to 50 percent too large. For a given angle, the values of R increases as the atomic number decreases, being greatest for paraffin which contains relatively more hydrogen than does wood. Experiments were also performed with a *lithium* radiator kept in a lead cell filled with hydrogen, on which two mica windows (about 0.005 mm in thickness) were provided so that one of them allowed the primary ray to fall on the scatterer and the other permitted the secondary ray to pass into the collimator. With a scattering angle of 110°, the unmodified line was practically absent, certainly less than 4 percent of the modified. This seems to prove that the Compton effect cannot be attributed to anything other than true scattering. This also favors the hypothesis, suggested by A. H. Compton, that the unmodified line occurs when the energy imparted to the electron during the process of scattering is insufficient to eject it from the atom.

IN connection with the study of the Compton effect in the scattered x-radiation it is important to measure the relative intensity of the modified and unmodified lines. Once such measurements have been made with some accuracy, they may throw some light upon the question of how the orbital electrons take part in the scattering effect.

Method and Apparatus

For the measurement of the intensity of the secondary radiation a spectroscopic method was employed. The arrangement of the apparatus was similar in general character to that employed by Compton[1] for measuring the spectrum of the secondary x-rays scattered from carbon and is diagrammatically shown in Fig. 1.

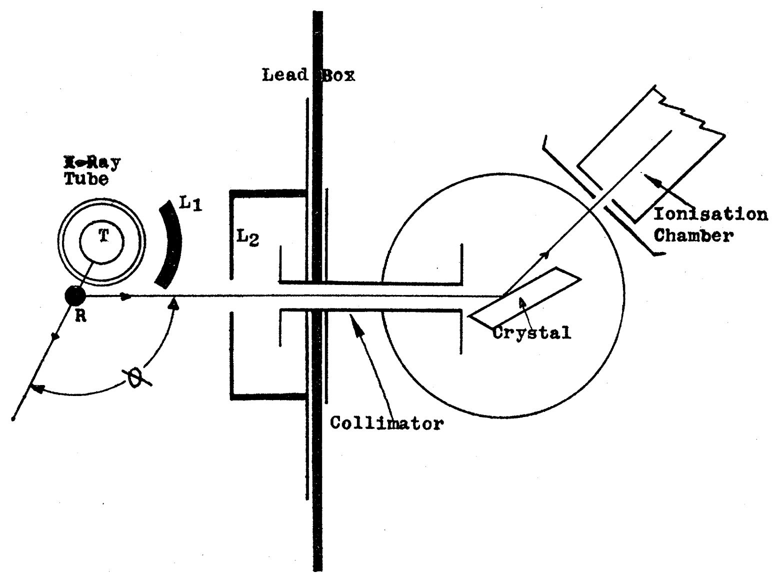

Fig. 1. Diagram of apparatus.

The primary x-rays from the target T of an x-ray tube fell upon the secondary radiator R, which was placed in line with the collimator. Lead screens, L_1 and L_2, disposed between the tube and the collimator, prevented stray radiation from leaving the lead box which contained the x-ray tube. The rays from the secondary radiator R, after passing through the collimator, struck the calcite crystal of the Bragg spectrometer, which reflected some of them into the ionization chamber. A sensitive Compton electrometer measured the ionization in the usual way.

[1] A. H. Compton, Phys. Rev. **22**, 409 (1923).

The collimator, due to Soller,[2] was composed of a pile of sheets of lead foil separated by strips of lead foil. Two collimators, each with a length of about 17 cm, were employed in the present work. The x-ray tube, of small diameter, was of the type described by Compton.[1] For this work a current of 35 to 45 mil-amp. passed through the tube, coming from a generating plant consisting of transformers and kenotrons producing an intermittent direct current at about 65 peak kv. The primary voltage of the high tension transformer was supplied from the mains and was carefully controlled by an induction regulator so that the variation was kept within half a volt.

With these devices, and by using a large calcite crystal to reflect the broad beam from the collimator to the ionization chamber, it was possible to secure sufficient intensity without loss in resolving power. This seems to make a satisfactory apparatus for studying the intensity of the secondary radiation by the ionization method.

Experimental Results

For the study of the energy distribution between the modified and the unmodified rays it was necessary to employ radiators of light elements in order to secure intensity sufficient for precise measurements. In the present experiments paraffin, wood, carbon (graphite), aluminium and sulfur were used as the scatterers. While the samples of paraffin, wood and carbon were in the form of a cylinder 1 cm in diameter, the aluminium and the sulfur were in the form of flat plates. In every case of the first four radiators the spectrum of molybdenum $K\alpha$ rays was scattered at 60°, 75°, 90°, 105°, 120°, 135°, 150°, and 165° (in the case of aluminum no reliable result was obtained at 165°). Because of an accident to the x-ray tube, the experiments with sulfur were performed only at 75°, 90° and 105°.

One set of the experiments with paraffin as the secondary radiator is represented by Fig. 2, in which the curves represent the inoization current in arbitrary units as a function of the glancing angle of incidence of the rays on the calcite crystal. Curves similar to those in Fig. 2 were obtained for the experiments with wood, carbon, aluminium and sulfur as the radiators. Detailed tabulation of these results would be tedious and unnecessary. For measuring the spctra at 60°, 75° and 90° the width of the slits in the collimator was 0.2 mm, while for 150° and 165° the width of the slits was increased from 0.2 to 0.4 mm in order to secure greater intensity. For 105°, 120° and 135° both collimators were employed at convenience.

[2] W. Soller, Phys. Rev. **23**, 272 (1924).

Two sets of experiments were performed with each of the five samples as the secondary radiator. From these measurements the distribution of energy between the modified and the unmodified lines was estimated. In view of the fact that the wave-length range investigated in the present work is small, we can assume to a close approximation that the energy in the different lines is proportional to the area under the ionization curves. This approximation is the more exact since the

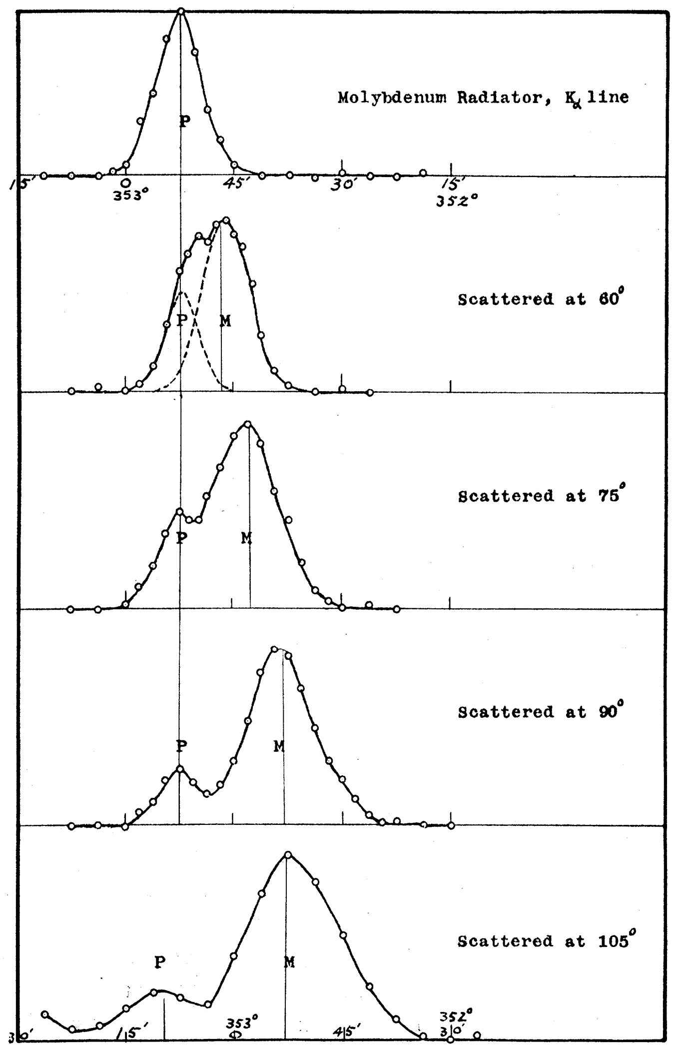

Fig. 2 (A). Intensity distribution of x-rays scattered from paraffin at various angles. P marks the position of the primary Mo $K\alpha$ line, M the position of the modified peak calculated from Compton's theory.

reflection coefficient of a calcite crystal is nearly independent of the wave-length, and since the ionization chamber was filled with ethyl bromide vapor and thus absorbed nearly all the x-rays of the wave-length studied. The relative energy of each spectrum was therefore obtained by integrating with a planimeter the area under the curve which represented the line.

Since the modified and unmodified lines were not distinctly separated from each other at 60°, the relative intensity was estimated by resolving the overlapping lines into two parts as shown in the second curve of Fig. 2(A). For measuring the spectra at 165°, the scatterer had to be placed so far away from the target of the tube (about 10 cm) that the measurement was made difficult by the reduction of the intensity of the incident radiation. Thus in the experiment on aluminium the 165° reading was repeated several times without success.

On integrating the area under the peak, attention should be called to the question of drawing the baseline of the ionization curve. It was found that when the collimator with narrow slits (0.2 mm) was employed, the general radiation under both the short wave-length side of the unmodified ray and the long wave-length side of the modified line was usually equally strong and so the line joining the readings of the general radiation is taken as the required baseline. However, when the collimator with wide slits (0.4 mm) was used, the general radiation under the former was always stronger than that under the latter. This was especially so if the scattering angle was large. Since the sensitivity of the electrometer was maintained constant by the use of a sputtered fiber, this effect is considered due to the presence of the modified beta peak. Thus the readings of the general radiation under the modified ray are taken to represent the height of the baseline of the modified and unmodified peaks. The curve representing the unmodified line is then completed to this adopted baseline in such a way that it has the same form as that of the fluorescent molybdenum Kα spectrum as shown in the second curve of Fig. 2(B).

In this connection we may mention the fact, pointed out by Allison and Duane,[3] that the intensity of the unmodified line relative to the general radiation is less in the scattered spectrum than when obtained direct from the target of the tube. This may perhaps be ascribed to (1) the presence of the modified beta peak in the secondary radiation as mentioned above and (2), as suggested by A. H. Compton, the presence of the second order of white radiation, which is excessively

[3] Allison and Duane, Phys. Rev. **26**, 300 (1925).

strong in the scattered rays due to the larger effective scattering volume in the radiator of the shorter wave-lengths. While the first effects depends on both the angle of scattering and the width of the slit, the second varies with the voltage put on the tube.

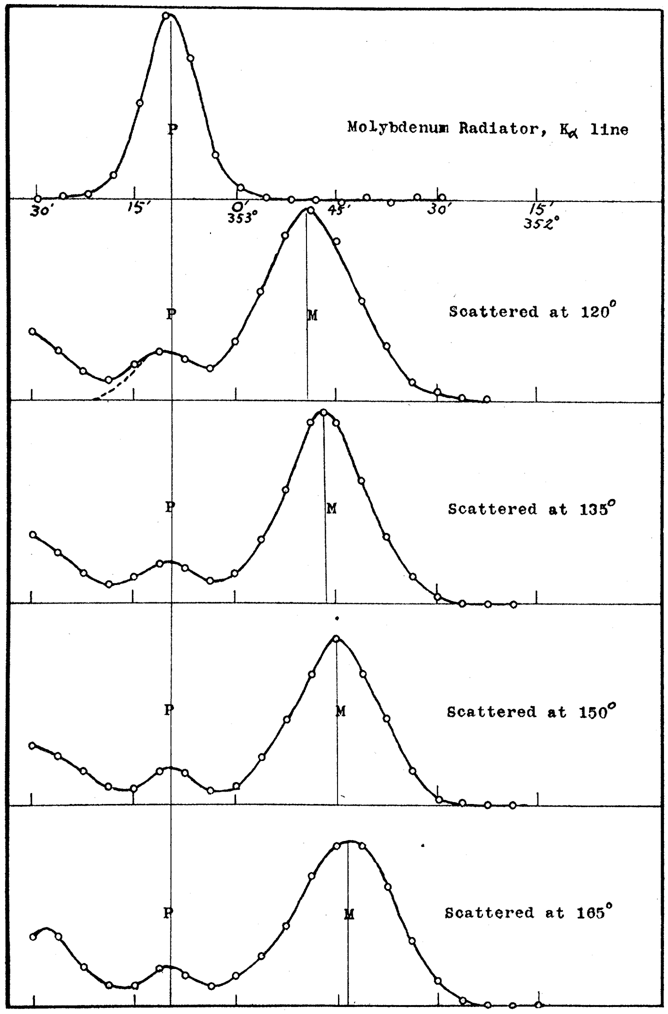

Fig. 2 (B). Intensity distribution of x-rays scattered from paraffin at various angles.

A special series of experiments was also performed by allowing primary rays of different intensities, produced by varying the current passing through the x-ray tube, to fall on a radiator at a definite distance from the target of the tube. It was found that the relative energy in the modified and the unmodified line is within the limit of experimental error independent of the intensity of the incident radiation.

The results of this measurement of the relative intensities are tabulated in Table 1, where ϕ represents the scattering angle, R the ratio

TABLE I

Ratio of the energy in the modified line to that in the unmodified line for different radiators and various angles

	Wood		Paraffin		Carbon		Aluminium		Sulfur	
	s	R	s	R	s	R	s	R	s	R
60°	0.2	1.19	0.2	2.29	0.2	1.08	0.2	0.46	...	....
75°	0.2	1.85	0.2	3.10	0.2	1.31	0.2	0.74	0.2	0.25
90°	0.2	2.73	0.2	4.69	0.2	1.45	0.2	0.91	0.2	0.41
105°	0.2	3.21	0.4	5.16	0.2	1.82	0.4	1.23	0.2	0.67
120°	0.2	4.57	0.4	5.49	0.2	2.26	0.4	1.45	...	....
135°	0.4	5.38	0.4	6.52	0.2	3.42	0.4	2.11	...	....
150°	0.4	6.21	0.4	6.98	0.4	4.05	0.4	2.52	...	....
165°	0.4	7.00	0.4	7.47	0.4	4.86	...	....	...	....

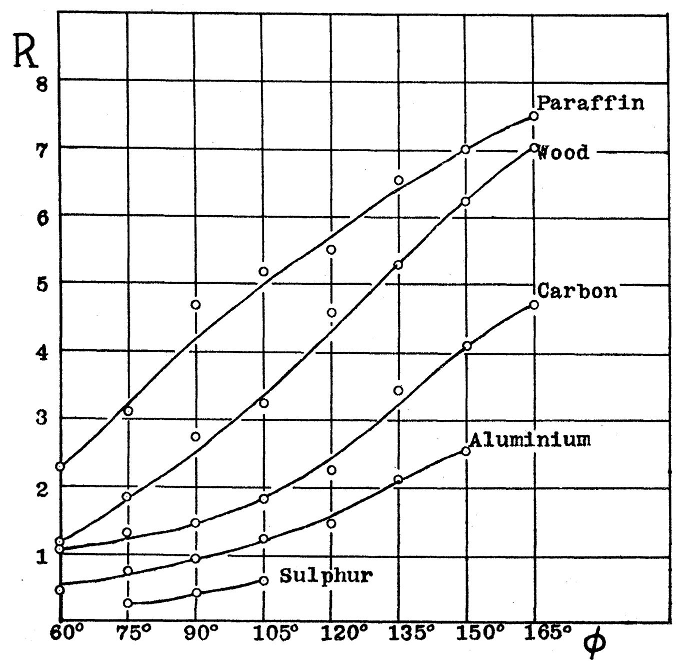

Fig. 3. $R-\phi$ curves for various radiators.

of the energy expressed in arbitrary units in the modified ray to that in the unmodified, and s the width in mm of a single slit in the multiple-slit system.

In Fig. 3 the intensity ratio R is plotted against the scattering angle ϕ. It appears that each set of data approximately fits a smooth curve, showing the variation of the intensity ratio as a function of the scattering angle. In all cases except for paraffin the experimental curve seems to be concave upward at small angles and convex upward at large ones. As the curve for paraffin is a little irregular, it may be noted that in this case the intensity of the unmodified ray is so small that the electrometer readings are relatively uncertain.

It is worthy of note that the unmodified line in the spectra scattered from graphite is more prominent than that in the spectra scattered from wood, and that in the spectra from paraffin the unmodified ray is particularly faint. Wood is composed of cargon, hydrogen and oxygen, whereas paraffin is a compound of carbon and hydrogen. This clearly indicates that the element hydrogen is most effective in scattering the modified line. In view of the faintness of the unmodified line in the spectra from paraffin it seems probable that the unmodified part of the scattered spectrum is entirely due to the carbon in it. Thus a spectrum scattered from hydrogen would have only the modified radiation. This consideration is supported by the study of the intensity of the secondary rays scattered from lithium, which will be described in the following section.

Intensity of Secondary MoKα Rays Scattered from Lithium

Unpublished results of experiments with lithium as the secondary radiator performed early in May, 1924, by A. H. Compton and the writer showed that, when the lithium sample was freshly prepared, the unmodified line was very faint, though it was undoubtedly present. The same effect has also been noted by B. Davis.[4] Recently Allison and Duane[3] have measured the scattered molybdenum Kα rays from lithium by keeping it from oxidizing with a coating of paraffin oil during the experiments. Their results still indicate the presence of a faint peak at the position of the unmodified line. As pointed out by these authors, their results may have been affected by the scattering from the carbon in the oil.

The writer recently performed a series of experiments by keeping the lithium radiator in a lead cell filled with hydrogen. Two mica windows, 0.005 mm thick, were provided on the lead cell, so that one of them allowed the primary x-rays to fall on the scatterer and the other permitted the secondary radiation from the radiator to pass into the collimator. Since the scattering from lead is negligible and since hydrogen is lighter than lithium, the present experiments were not affected

[4] B. Davis, Phys. Rev. **25**, 737 (1925).

by either of them. Special care was also taken to shield the wax cementing the mica windows.

The results of this measurement are shown in Fig. 4. Curve 1 represents one of the results of the experiments with the lithium sample cleaned in air, while curves 2 and 3 are two of the measurements obtained with the radiator carefully cleaned in an inverted glass jar

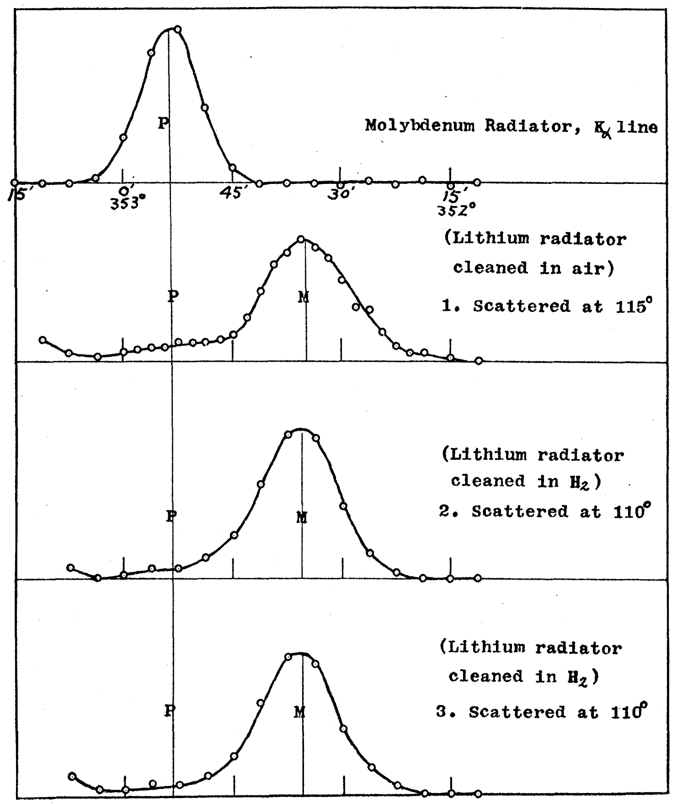

Fig. 4. Scattering from lithium. *P* marks the position of the primary Mo Kα line, *M* the position of the modified line calculated from Compton's theory.

filled with hydrogen. As far as they go, the results indicate that in the secondary x-rays scattered from metallic lithium the unmodified ray in the Compton effect disappears.

Discussion of the Results

The discussion is conveniently divided into two parts: (1) The scattering from all the radiators except lithium and (2) the scattering from lithium.

(1) From results tabulated above it is seen that the energy ratio increases with the scattering angle in the way shown by the curves in Fig. 3. Since the conditions which determine whether an x-ray quantum shall be scattered according to the simple quantum law or in some other manner must also govern the distribution of the energy in the modified and unmodified rays, the present results thus point to the conclusion that the scattering angle should play in some way or other an important role in the determining factors.

A theoretical investigation of the question of the variation in the intensity ratio of the modified to the unmodified ray with angle of scattering for a given element and given incident wave-length has been recently published by Jauncey.[5] The theory requires an increase of the intensity of the modified relative to that of the unmodified line as the angle of scattering is increased. Unfortunately while the agreement between this theory and the present results is qualitative, it is not quantitative. Assuming a resolving power represented by 0.002A, Jauncey[5] gives for the ratio of intensity of modified ray relative to unmodified, 1.74 for carbon at 90° and 0.62 for sulfur at 90°, whilst the present experiments give for this ratio 1.45 for carbon at 90° and 0.42 for sulfur at 90° though the spectrometer arrangement in this work had a resolving power not greater than that corresponding to a wave-length width of 0.004A. This seems to indicate that Jauncey's theory overestimates the relative intensity of the modified and unmodified lines. However, it is of particular interest to note that the curve calculated according to Jauncey's theory to show the variation of the intensity ratio with the scattering angle is of the same general form as that of the curves in Fig. 3 obtained from experiments. This appears to point to the possibility of a further development of Jauncey's treatment.

Finally, it may be remarked that the present experiments also show that for a given angle of scattering the intensity of the modified ray relative to that of the unmodified line decreases as the atomic number of the scatterer increases, and that the width of the modified ray is greater than that permitted by Compton's simple equation. These are in accordance with the results of earlier work done in this field.

(2) From the result of the measurement of the intensity of the scattered radiation from lithium the following conclusions can be readily drawn.

First, it presents conclusive evidence that the Compton effect can not be attributed to anything other than true scattering, and there-

[5] G. E. M. Jauncey, Phys. Rev. **25**, 314 (1925) and Phys. Rev. **25**, 723 (1925).

fore Barkla's idea[6] of differentiating these phenomena is difficult to defend.

Second, it favors Compton's first hypothesis[7] for accounting for the existence of the unmodified rays, that the binding energy of the electron is such that the energy imparted to the electron during the process of scattering is insufficient to eject it from the atom; but it is not quite consistent with his alternative hypothesis that the primary quantum is scattered by a group of electrons instead of a single one. It is also inconsistent with the possible explanation of the origin of the unmodified line that the primary quantum is scattered by the nucleus.

Third, it supports the consideration leading to the conclusion that the spectrum scattered from hydrogen would have no unmodified line.

In conclusion, the writer wishes to express his sincere thanks to Prof. A. H. Compton for his valuable suggestions and ever ready assistance during the course of this work.

Ryerson Physical Laboratory,
University of Chicago,
October 23, 1925.

[6] C. G. Barkla, Nature, **114,** 753 (1924).
[7] A. H. Compton, Phil. Mag. **46,** 897 (1923).