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FINE STRUCTURE IN THE COMPTON EFFECT

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ABSTRACT

This is a continuation of two crystal analyses of fine structure in scattered radiation. The displaced scattered radiation from carbon (pure graphite) and beryllium was investigated. A special x-ray tube was constructed with the scattering element near the target. The tube was mounted so that the scattering angle θ was large. The tube operated at 3200 watts.

Fine structure in the displaced scattered radiation from carbon.—The angle of scattering θ was 155°. The displaced radiation has fine structure as follows going toward long wave-lengths: A relatively strong line 0.0421A from Mo $K\alpha_1$ position, and three weaker lines at 0.0012A, 0.002A and 0.0109A from the strong line. These agree closely with fine structure lines previously found by Bergen Davis and D. P. Mitchell. The two pictures are alike, but the displaced one is shifted 0.0421 from the undisplaced. The displacement is less than is to be expected from $d\lambda = 0.0243\ (1-\cos\theta)$. Our results give $d\lambda = 0.022\ (1-\cos\theta)$. This is 9 percent less than is to be expected from theory. Errors could not be so great as this.

Fine structure in the displaced scattered radiation from beryllium.—Displaced scattering investigated at $\theta = 163°$. A strong main line was found at $0.0446\text{A} = 0.0228\ (1-\cos\theta)$ from Mo $K\alpha_1$ position. A line at 0.0051A toward the *long wave-lengths* from this main line. This displacement is near the value to be expected from Be K energy level. A weak line at 0.0009A toward short wave-lengths from main line. These two lines were found by D. P. Mitchell in the undisplaced scattering from beryllium and were ascribed to the K and L_1 energy levels of Be. The L_1 line, however, was shifted 0.00058A, which is much less than the 0.0009A found here in the displaced spectrum.

THIS is a continuation of an investigation of fine structure of scattered radiation by means of the double x-ray spectrometer. Structure in the undisplaced scattered radiation from carbon (graphite) has been previously reported by Bergen Davis and D. P. Mitchell.[1] These latter experiments have been extended by D. P. Mitchell[2] to the undisplaced scattered radition from beryllium and aluminum.

An investigation of the *displaced* scattered radiation (Compton effect) is reported here. The double x-ray spectrometer as an instrument of high

[1] Bergen Davis and D. P. Mitchell, Phys. Rev. **32,** 331 (1928); Phys. Rev. **31,** 1119 (1928).
[2] D. P. Mitchell, Phys. Rev. June 1928.

resolving power has been previously described.[3] The scattering elements used were carbon (graphite) and beryllium. A special x-ray tube was constructed. A standard water-cooled molybdenum target was cut away at one side as shown in Figure 1. The scattering element S was placed with its front face about 1.7 cm from the center of target spot b. A special cathode constructed having a short linear filament. The housing of this filament was of such shape that it directed a uniformly distributed stream of electrons over the area of the target spot. This target spot was square in shape and about 6 mm on each edge. The x-ray tube was so mounted with respect to the slit system, that the angle of scattering θ should be large. The displacement to be expected is $d\lambda=(h/mc)(1-\cos\theta)$. The dimensions of the target spot and the scattering give a considerable divergence in the values of θ. However, since the variation of the cosine at large angles is small, it was found that angle $\theta=155°$ gave sufficient resolving power to separate the spectral lines in the case of carbon. When beryllium was the scattering element, the x-ray tube was set so that $\theta=163°$, but even at this large angle the nearest spectral line was not completely resolved. Care was also taken to mount the tube so that the divergence of the rays in the vertical plane should not be greater than the divergence in the horizontal plane.

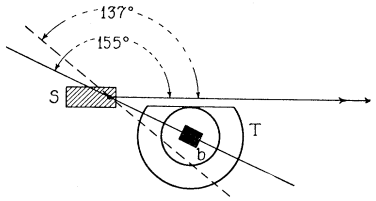

Fig. 1. Arrangement of x-ray tube target and scattering block.

The displaced scattered radiation (Compton effect) is quite weak even when observed from a single crystal. The energy observed in these experiments was very much smaller. The radiation was divided into separate spectral lines and the reflection was from two crystals. The x-ray tube was driven at as great power as safety would permit. The rate of dissipation of energy at the target was 3000 to 3200 watts (75 to 80 milliamperes at 40,000 volts). This great power caused the target spot to become incandescent on the surface even though it was water-cooled. Also one could hear the water boil as it passed through the target.

TABLE I.

Carbon Displacement from Mo $K\alpha_1$		Beryllium Displacement from Mo $K\alpha_1$	
$K\alpha_1'$	0.0421A	$K\alpha_1'$	0.0446A
CL_{111}'	0.0421+0.0012	—	—
CL_1'	0.0421+0.002	Be L_1'	0.0446−0.0009
CK'	0.0421+0.0109	Be K'	0.0446+0.0051
$0.0421=0.0221(1-\cos 155°)$		$0.0446=0.0228(1-\cos 163°)$	

[3] Bergen Davis and Harris Purks, Bulletin Nat. Acad. Sc. Vol. 13. June 1927.

The results obtained are given in Table I and in the figures. The lines of the undisplaced radiation are designated by subscripts (L_1, L_{111} etc.), the corresponding lines of the displaced radiation are designated by primes (L_1', L_{111}' etc.). The displaced scattered radiation from carbon has four lines as shown in Figure 2, a relatively strong line $K\alpha_1'$, and three weaker

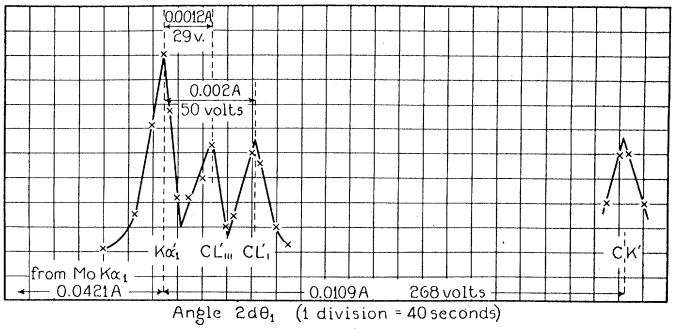

Fig. 2. Fine structure in the Compton effect from carbon.

lines CL_1', CL_{111}' and CK'. The shift of these three lines from the $K\alpha_1'$ is closely the same as the values previously found for the undisplaced scattered radiation. The spectrum of the displaced is a duplicate of that of the undisplaced. The shift, however, of the one spectrum from the other is not quite so great as is to be expected by the relation $d\lambda = h/mc(1-\cos\theta)$(1), in which h/mc has the value 0.0243. The shift of the spectra is better represented by $d\lambda = 0.0221\ (1-\cos\theta)$. The shift is less than the expected value by about 9 percent. This difference is too great to be accounted for by error in measurement of the angle θ. The tube should have been set at 137° instead of 155° to give the observed displacement.

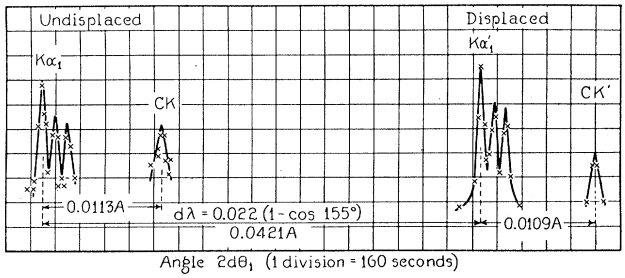

Fig. 3. Complete spectrum, scattered radiation from carbon.

This angle 137° is represented by the dotted line in Fig. 1. It will readily be seen that the difference is too great to arise from error in tube setting. Also the divergence effect due to size of target spot and size of scattering element, (Eq. (1)) would have been so great at 137° that the separate L lines would not have been resolved. The conclusion must be drawn that the constant h/mc does not completely represent the phenomena.

The complete spectrum of the scattered radiation from carbon is shown in Figure 3. The two spectral pictures are quite alike. The shift of the CK' line (0.0109A = 268 volts) from $K\alpha'_1$ is less than the shift of CK line (0.0113A = 279 volts) from the $K\alpha_1$. The shift (0.0109A = 268 volts) is less than the K energy level of carbon (280 volts). This latter shortage in the displacement of the CK' line may have the same physical cause as the shortage in the displacement of the whole spectral group.*

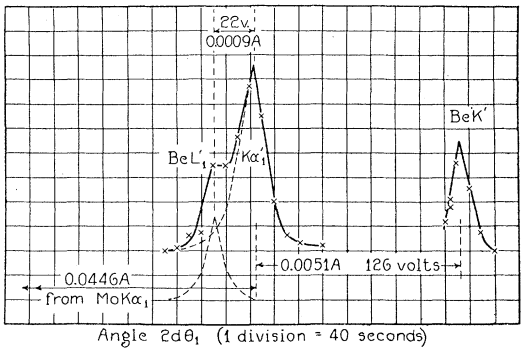

Fig. 4. Fine structure in the Compton effect from beryllium.

The results for beryllium are given in the Table I and in Figures 4 and 5. A relatively strong line $K\alpha_1'$ at 0.0446A from $K\alpha_1$ position, a weak line Be K' 0.0051A toward *long* wave-lengths from $K\alpha_1'$ and a weak line 0.0009A toward *short* wave-lengths from $K\alpha'_1$. This last line corresponds to the B L_1 found by D. P. Mitchell[2] in the undisplaced scattered radiation from beryllium. The Be K' line at 0.0051A corresponds to the Be K line in the undisplaced radiation as found by Mitchell. It is to be ascribed to the K energy level of beryllium. The shift of the displaced spectrum is 0.0446A = 0.0228

* It is perhaps worth while to refer here to some recent experiments of Ehrenberg on scattered radiation from graphite.[4] He used the single crystal photographic method and his results were negative. No lines were observed. His scattering element was Acheson graphite. He suggests that our fine structure might be due to impurities. We would say that the scattering elements used for data in table 1 for Experiment No. 2 was Acheson graphite. That used for Experiment No. 1 was a pure graphite obtained from General Electric Co. The great separation of the α_1 and α_2 lines in the Ehrenberg spectrogram indicates that the slits were very narrow. Our own previous experience with the photographic method and the experiments of P. A. Ross on the Compton effect indicate that it is difficult to observe scattered radiation with such narrow slits. The undisplaced scattering is of about the same intensity as the displaced. It would require many hundreds, perhaps thousands of hours exposure to register fine structure in scattered radiation on a film with such narrow slits. The intensity of the real scattered radiation is of a different order of magnitude than that observed by Ehrenberg. Graphite is a powdered crystal. We would suggest that the lines observed by Ehrenberg are higher order reflections from those minute crystals that are properly oriented for such reflection. A few years ago this experiment was made in our laboratory. Finely powdered calcite was formed into a placque. This was found to give quite strong reflection no matter at what angle the rays impinged on the placque.

[4] W. Ehrenberg, Zeits. f. Physik **53**, 234 (1929).

$(1-\cos 163°)$ from the undisplaced. The constant 0.0228 is less in this case also than h/mc as expected from theory. A most significant point about the two spectra is that the $K\alpha_1$ line is absent or very weak in the undisplaced, but is relatively strong in the displaced radiation. Attention is also directed

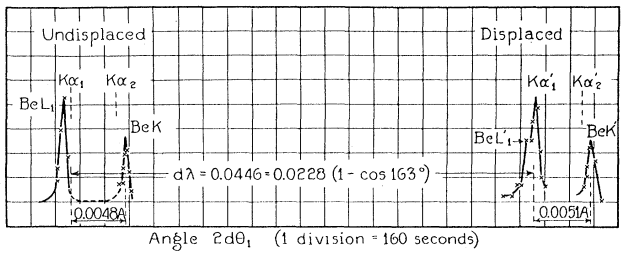

Fig. 5. Complete spectrum, scattered radiation from beryllium.

to the fact that the shift of Be L_1' (−0.0009A) from Be $K\alpha_1'$ is considerably greater than the shift of Be L_1 (−0.00058A) from the $K\alpha_1$ position on the undisplaced spectrum. The possibility of this type of fine structure has been suggested by Compton.[5] The expression for the displaced scattered radiation proposed by him is

$$d\lambda = \frac{\lambda^2}{\lambda_s - \lambda} + \frac{h}{mc}(1-\cos\theta).$$

This is the same as the fine structure found in these experiments, with the exception that the agreement with the constant $h/mc = 0.0243$ is not exact.

Discussion. These experiments together with others give important information as to the possible modes of interaction of photons, electrons, and atoms. (*a*) A photon may lift an electron from an atomic energy level and give it kinetic energy expressed by $h\nu = \frac{1}{2}mv^2 + Ve$, where Ve is the energy level from which the electron originated. The photon as such disappears. This is the photoelectric effect. (*b*) The photon may lift an electron from an energy level to the atomic limit and then escape without imparting either momentum or kinetic energy to the electron. This is represented by the relation $h\nu' = h\nu - Ve$. This is the mode of production of the fine structure in the undisplaced scattered radiation. There is one exception found by D. P. Mitchell[2] in the case of the L_1 level of beryllium. In this instance $h\nu' = h\nu + Ve$. The photon finds the electron already in a higher energy state near the atomic limit. When the two part company the potential energy of the electron is *added* to that of the photon. (*c*) The photon may lift an electron to a higher energy level at or near the atomic limit and then impart to it both energy and momentum in the manner proposed by Compton. This is the origin of the fine structure in the displaced spectrum. The $K\alpha_1'$ line in the case of beryllium is relatively strong. This occupies the position in the displaced spectrum that should arise from scattering from a free or slightly

[5] A. H. Compton, Phys. Rev. **24,** Aug., 1924.

bound electron. Also there is no spectral line on the *long wave-length side* of $K\alpha_1$ or $K\alpha_1'$ in either the displaced or the undisplaced spectrum ascribable to the Be L_1 energy level, but there is a line in both spectra on the *short wave-length side*. This indicates that the normal condition of the beryllium atom is a state of excitation in which those electrons that belong normally in the L_1 energy levels occupy positions at or near the atomic limit. Their energy of position is added to the photon at moment of scattering. (*d*) The photon may scatter from a free or nearly free electron after the manner proposed by Compton. This is indicated by the relatively strong lines at $K\alpha_1'$ position in the displaced spectra of both carbon and beryllium. (*e*) The photon of the wave-length here used probably does not scatter from an atomic nucleus. The $K\alpha_1$ line is absent or very weak in the undisplaced radiation from beryllium. It is present in the case of carbon and also in the case of aluminum (see D. P. Mitchell).[4] The number of nuclei per cc is about the same for beryllium as for carbon and aluminum. The number of bound electrons, however, in beryllium is small, since the two L_1 electrons appear to be in higher energy levels. It is greater in the case of elements of higher atomic number. The undisplaced scattered radiation decreases with atomic number and practically disappears in the case of scattering from lithium, as has previously been found by single crystal experiments. On the other hand it increases in intensity with increase of atomic number and hence with number of bound electrons. The undisplaced $K\alpha_1$ must be scattered from a large mass, since the loss of energy is negligibly small. The scattering in this case is probably from the whole group of electrons bound to the nucleus. The nucleus without electrons does not scatter radiation of the wave-length here used. It is probable, however, that hard radiation such as gamma-rays and cosmic rays may react with the concentrated field or wave pattern of a nucleus.

We wish to acknowledge our obligations to W. C. Beller for assistance in operation and control of x-ray equipment during this investigation.