[3] Negative terms occur also in another series of the calcium spectrum $1d-md'$. The first group was given by Götze (*loc. cit.*). Russell and Saunders succeeded in finding the second group in which the terms $2d'$ are negative. It is most probable that the $1p-1p'$ series of strontium is produced in quite the same way as the analogous series of calcium, but only the first two groups of the strontium series are known.

[4] As $\omega_1/2\pi = v_1$, the expression may be written $n_1 h v_1$. Compare: M. Planck, *Wärmestrahlung*, section 137. Leipzig, 1921.

THE COMPTON AND DUANE EFFECTS

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Late in 1922, Professor A. H. Compton[2] developed a quantum theory for the scattering of X-rays by collisions with electrons. According to this theory when radiation of wave-length λ falls on a scattering substance the scattered wave-length increases by an amount given by the formula

$$\Delta\lambda = \frac{2h}{mc}\sin^2\frac{\theta}{2} = 0.0484\sin^2\frac{\theta}{2} \qquad (1)$$

where θ is the angle between the direction of the incident and emergent beams. We shall call this the Compton shift.

Compton, using an ionization spectrometer with low dispersion, actually found the wave-length shifted by the predicted amount. P. A. Ross[3] at Stanford University repeated the experiment using a photographic plate to detect the radiation and fairly high resolving power. He not only found the correct Compton shift but also an unshifted line, which is most likely due to collisions of the radiation with massive nuclear systems. On repeating his experiment, Compton also found this unshifted line which in some cases is more intense than the shifted one.

Bergen Davis at Columbia University also reported finding these two lines but according to him the Compton shift depends slightly on the atomic number of the scattering substance.

Since then the Compton shift has been verified also in England in the Davy-Faraday Laboratory by Muller. He used the K α-rays of silver, molybdenum, and copper scattered by paraffin, glass, and aluminum. All together these workers have verified the Compton shift as given by formula (1) for incident wave-lengths ranging from 0.2 to 1.5 Å. with scattering substances well spread over the periodic table and for various angles.

On the other hand Professor William Duane[4] and his collaborators working with the ionization method have been unable to find any evidence for the Compton shift. They do, however, find a new line or band whose short wave-length limit is shifted toward longer wave-lengths by an amount given by

$$\Delta\lambda = \frac{\lambda_1^2}{\lambda_2 - \lambda_1} \quad (2)$$

where λ_1 = incident λ and λ_2 = critical absorption λ of the scattering element. Their theory of tertiary radiation accounts for this Duane shift. They have used tungsten K radiation with carbon, aluminum, sulphur, copper, molybdenum, and silver scatterers as well as molybdenum K radiation falling on lithium, carbon, aluminum, sulphur, sodium chloride, and ice.

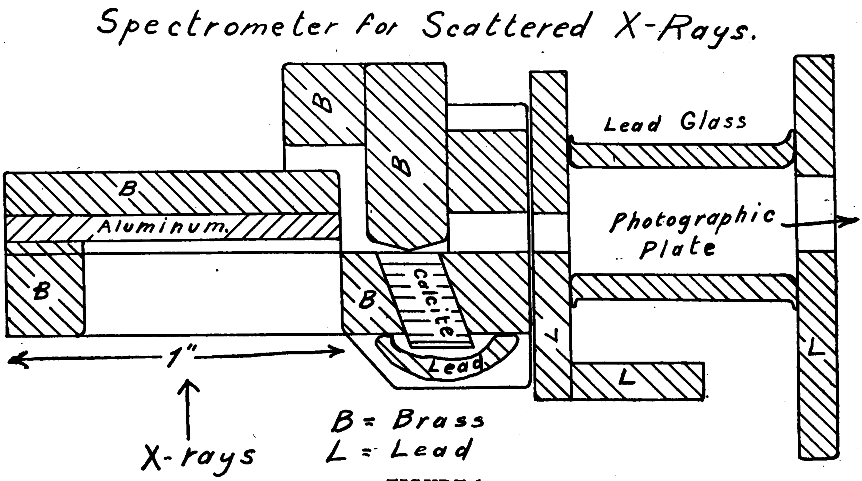


FIGURE 1

In all these cases they find evidence for their tertiary radiation which varies with the scattering substance but in no case do they see any evidence for the Compton shift.

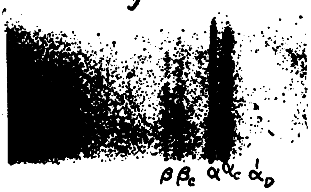
There can be little doubt that these two effects are distinct and that both exist. What remains to be explained is why Duane does not find the Compton effect and vice-versa. Of course there are differences in the experimental arrangements but at first sight none of these seem essential.

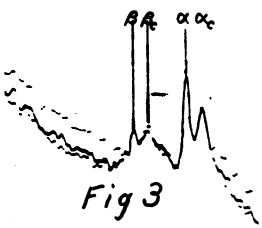
To test out the suggestion first proposed by Mr. Smythe of this laboratory that the essential difference between the methods was one of intensity, the following experiments were performed. A standard water cooled molybdenum target Coolidge tube was used throughout. It was operated at about 40 kilovolts peak without a rectifier. In all the experiments aluminum was used as scatterer and the angle between the incident and scattered beam was about 100°. Under these conditions the

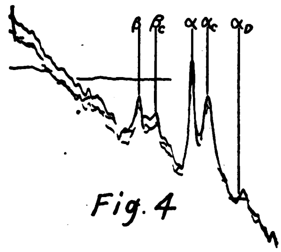
Compton shift should amount to 0.027Å. while the Duane tertiary radiation shift should be 0.069Å. for α_1. The separation α_1 to β for molybdenum amounts to 0.077Å. and for α_1 to α_2 it is 0.004Å. In other words the Compton shift amounts to about six times the α doublet separation or to about one-third of the $\alpha_1\beta$ separation, while the Duane shift for α_1 should be about nine-tenths of the $\alpha_1\beta$ separation. With aluminum it should therefore be readily possible to get both Compton and Duane shifts on the same plate for both α and β lines.

Figure 1 shows in cross-section the relative positions and dimensions of the X-ray tube, the scatterer, and the calcite crystal used as a Seemann spectrograph. It will be noticed that the aluminum subtends a large enough angle at the slit such that all of the wave-lengths which are of interest can be reflected at all times without moving the crystal. This method also allows the source of the scattered radiation to be moved very close to the crystal. In both of these respects it is distinctly better than the Bragg rotating crystal method. The spectrometer was supported

Fig. 2







on an insulated stand. Between it and the lead box which enclosed the apparatus a series of insulated lead screens were placed. Lead glass tubing connected the openings in these screens and prevented any stray direct or scattered radiation from getting into the passage from the crystal to the photographic plate. It was found essential to screen the aluminum, crystal, and photographic plate from all possible stray radiations. The spectrograph gave clear sharp lines whose widths were only slightly greater than twice the slit opening and did not increase when the distance from the crystal was increased four-fold.

Film 2 was placed 42 cm. from the crystal and exposed for 61 hours with 25 ma. through the tube. While the impressions are too faint for reproduction they show a distinct Compton shift for both α and β lines. The α doublet is clearly resolved into its two components and the lines are quite sharp. The magnitude of the shift is 0.0275Å. for each of the three lines. There is no indication of a Duane shift.

Since we were primarily interested in studying how these shifts changed as the intensity falling on the aluminum was decreased rather than in the dispersion, the photographic film for the following exposures was placed

21 cm. from the crystal. The dispersion was now such that the $\alpha_1\alpha_2$ lines just overlapped while the $\alpha_1\beta$ separation was 2.56 mm. The width of the lines was about 0.2 mm.

Film 3 was exposed for 61 hours. It shows the unshifted α doublet and β line together with the Compton shifted lines. The latter were slightly less intense and only a trifle wider than the unshifted lines. The size of the shift is about 0.026Å. for α and 0.025Å. for β. There is no indication of a Duane shift for either α or β.

Film 4 was a repetition of 3 in all details except that the current through the tube was 8.5 ma. for 180 hours. In other words, the intensity is one-third while the time is multiplied by three. This film shows not only the shifted and unshifted α and β lines with about the same relative intensity as in 3, but also a faint new line, α_D, whose short wave-length edge is displaced from the α peak by just the amount predicted by Duane's tertiary radiation. This film is reproduced in Figure 2. α_D is too weak to show up. Through the courtesy of Mr. Pettit films 3 and 4 were photometered at the Mt. Wilson observatory. Three independent runs over three different regions of each film were made. These were then juxtaposed and photographed. They are shown in Figure 3 and 4, respectively. The fact that the lower intensity film does show a slight Duane shift is some confirmation of the hypothesis that the essential difference between Compton's and Duane's experimental procedure is one of intensity. If in our experiment the intensity could be reduced further by a factor of three it might very well be that the Duane shift would become much more pronounced compared to the Compton shift. To follow up this clue would require a whole months exposure. The author is unable to continue this work. The suggestion together with its partial experimental support is published in the hope that it will help clear the situation in the controversy.

The author is indebted to Professor Ross of Stanford University for his keen interest and valuable suggestions in regard to experimental technique. He is also indebted to Professor Watson and Messrs. Brode, Mott-Smith, and Du-Mond of the local institute for their suggestions and help in setting up the apparatus.

NOTE (July 25). At Stanford University Professors Webster, Ross and I measured with an ionization chamber the total intensities of Radiation from blocks of graphite aluminum and lead illuminated by rays from a molybdenum target seven centimeters away. The tube was run at 40 kilovolts with currents of 1.25, 2.5, 6.25, 12.5, and 25 milliamperes. This total radiation should include both Compton's and Duane's rays and could not be expected to be proportional to the primary, if the above theory of intensity effects is correct, except by an extraordinary coincidence. The fact is however that it is proportional to better than 1%. D. L. WEBSTER, J. A. BECKER.

[1] NATIONAL RESEARCH FELLOW.

[2] Compton, *Bull. Nat. Res. Coun., Washington*, Oct., 1922. See also *Physic. Rev.*,

Ithaca, Feb. 1923, p. 207; May 1923, p. 483; June 1923, p. 715; *Phil. Mag. London*, Nov. 1923, p. 897.

[3] Ross, these PROCEEDINGS, July 1923, and June 1924.

[4] Duane and others, these PROCEEDINGS, Dec. 1923, p. 419; Jan. 1924, p. 41; March 1924, p. 92; April 1924, p. 148.

COULOMB'S LAW AND THE HYDROGEN SPECTRUM

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In the Bohr theory of the hydrogen atom restricted, let us say, to circular orbits so as to deal only with the simplest case, Coulomb's law has been assumed to hold. This is carrying over to the microcosm our molar laws of electricity and might seem a doubtful procedure in the face of our giving up so much of our mechanics just as it seems to some questionable, after taking the electron as the indivisible electric unit, to talk of the distribution of electricity over or through the electron.[1] In favor of Coulomb's law for the microcosm we have our general tendency to carry over and apply old laws whenever they work and insofar as they work. Further in favor are the scattering experiments of Rutherford dealing with the positive nuclei.[2] And it may be that best of all our evidence is the success with which theories of spectra have been worked out by combining Coulomb's law with elementary mechanics plus the quantum hypothesis.

Is then the law of Coulomb really implied by the quantum theory? The equations of motion for the electron in its circle are

$$mrw^2 = -F = dV/dr \qquad \text{force equation} \qquad (1)$$

$$mr^2w = nh/2\pi \qquad \text{quantum condition} \qquad (2)$$

$$E_2 - E_1 = h\nu \qquad \text{frequency condition} \qquad (3)$$

$$\nu = N(1/n_1^2 - 1/n_2^2) \qquad \text{spectral law} \qquad (4)$$

Here F is the central force, V is the potential energy, r is the orbital radius, m is the mass, w is the angular velocity, E is the total energy, etc.

$$E = V + \frac{1}{2}mr^2w^2 \qquad \text{energy equation} \qquad (5)$$

From (4) and (3) we have

$$E_1 + Nh/n_1^2 = E_2 + Nh/n_2^2 \qquad (6)$$