The Scattering of X-rays.

IN an exceptionally successful session of Section A of the British Association at Toronto this year, perhaps no discussion created such widespread interest as that which centred round the papers of Prof. A. H. Compton of Chicago, and Prof. Duane of Harvard, on the scattering of X-rays. The subject is one which has had considerable influence on the development of modern physical theory. It was as a result of the theory of scattering advanced by Sir J. J. Thomson that Barkla was able to deduce from his experiments that the number of electrons in the atom was approximately equal to one-half of its atomic weight, a result confirmed by other methods some years afterwards by Moseley. Later developments indicated that the phenomenon of scattering was more complex than Thomson's theory assumed. The work of various observers on γ-rays showed that the absorption of these rays was greater after scattering than before, a fact which suggested that during the scattering there was a shift in the wave-length towards the long wave-length end of the spectrum. Similar results had been obtained with X-rays. Recent developments of X-ray technique have made it possible to carry out experiments of a much higher order of accuracy and have placed at the disposal of the physicist powerful sources of monochromatic radiation. It was natural, therefore, to expect that the problem would be attacked anew, and this has been done by several observers, notably Compton and Duane.

Compton's work was undertaken primarily to test the truth of a theory advanced independently by himself and by Prof. Debye of Zurich. The theory is of great interest, and a brief sketch may be given. Whereas the original theory proposed by Thomson was based on classical electromagnetic conceptions, that of Compton and Debye is founded on the quantum theory. In the simplest case a quantum of radiation of frequency ν falls on the scattering substance, and may be considered as colliding with an electron which is either free or very loosely bound to an atom. This electron takes up some of the energy of the quantum, and the radiation passes on as a quantum of somewhat lower frequency. The remainder of the energy appears as kinetic energy of the electron. It is assumed that, during the encounter between the radiation and the electron, the laws of conservation of energy and momentum are obeyed. The energy of the quantum is $h\nu$ and its momentum is taken as $h\nu/c$, where c is the velocity of light. If the equations representing the conservation of energy and momentum are solved, it is found that the change in wave-length of the radiation scattered in a direction making an angle θ with the original beam is given by $h/mc(1-\cos\theta)$ or $0{\cdot}024(1-\cos\theta)$ Å.U.

If this theory is correct, and we allow a beam of monochromatic X-rays to fall on a scattering substance and analyse the radiation scattered at an angle θ, we should expect an increase in wave-length of $0{\cdot}024(1-\cos\theta)$. Such a change is well within the range of measurement of modern X-ray spectroscopy. Compton conducted a series of experiments on these lines, and found that in the scattered radiation two wave-lengths predominated, one being identical with, the other longer than, that of the unscattered beam. The difference in wave-length was found to agree within experimental error with that predicted by the theory. Again, the separation of the two depended on the angle of scattering in just such a manner as anticipated by the theory. Further, a series of absorption experiments yielded results consistent with his hypothesis, and, finally, a study of C. T. R. Wilson's track photographs revealed the existence of electrons with the energy and direction of motion to be expected.

Further confirmation of the Debye-Compton theory came from independent observers, notably Profs. Ross and Bergen Davis. Ross used a photographic method instead of the ionisation apparatus employed by Compton. He found two lines on his plates, one corresponding to the wave-length of the original beam, the other to a radiation of longer wave-length. The separation increased with the angle of scattering as in Compton's experiments.

Had it not been for the experimental work of Duane, there is little doubt that these results would have been generally accepted as affording strong evidence in favour of the theory, if not as entirely establishing it. For the past year or two, however, Duane and his research school have been engaged on a series of experiments on the radiation emitted from various substances when bombarded by X-rays. They find, in addition to radiations identical with the primary beam, other radiations of longer wave-length. Their measurements indicate that these can be explained as due to the photoelectrons ejected from the matter by the primary radiation. It requires a certain amount of energy to eject an electron from its parent atom, the amount depending on the energy level from which it has to be removed. The kinetic energy of the electron will be less by this amount than the energy corresponding to a quantum of the X-radiation. If, in their turn, these electrons strike other atoms of the scattering substance, they will give rise to X-rays the maximum frequency of which will correspond to their kinetic energy in accordance with the Einstein equation $\frac{1}{2}mv^2=h\nu$.

Duane finds that his experiments are consistent with such an explanation. It is clear that, on this theory, different substances will give rise to different radiations according to the energy required to remove an electron from the matter. On the Compton-Debye theory the wave-length of the softer radiation is independent of the nature of the scattering substance. In the case of carbon bombarded by the K radiation of molybdenum—the rays used by Compton—the chief effect observed by Duane nearly coincides with the Compton effect, but for heavier atoms the two theories give rise to radiations of different wave-lengths. Duane found that, with his apparatus, he was unable to find evidence for the existence of the effects observed by Compton, Compton, on the other hand, could not repeat satisfactorily Duane's experiments. A matter of such importance could not be left in such a position. Each observer investigated the apparatus used by the other and convinced himself of its trustworthiness. Duane observed that the only obvious difference in the experimental arrangements was that Compton's X-ray tube was enclosed in a wooden box covered with lead, while his own tube was not so enclosed, the tube being in one room and the rest of the apparatus in the adjoining room. Improbable as it appeared that such a difference could account for the difference in the experimental results, Duane tried the effect of such a box and found to his surprise that, in addition to the effects he had previously observed, a new peak appeared in approximately the position observed by Compton. The exact position of this effect depended on the orientation of the box. At the time of the Toronto meeting this represented the state of affairs.

In the general discussion various other members took part. Prof. Webster gave a detailed description of the experimental arrangements used by Ross, and contended that the box in which Ross's tube was enclosed could not possibly account for the results he obtained. Prof. Gray described experiments on γ-rays and showed that they were consistent with the Compton theory. Prof. Raman made an eloquent appeal against a too hasty abandonment of the classical theory of scattering. Compton sketched an extension of his theory in which he considered not only free electrons but also those which were more tightly bound. He showed that the extended theory gave rise in the limiting case to the formula used by Duane and therefore embraced Duane's results. The fundamental difference between the two theories remains; Duane uses only the well-established quantum energy equation, while Compton in addition introduces the idea of conservation of momentum in the interaction between the radiation and matter. There are difficulties in the way of both theories, but at the present stage of the experimental work it is needless to dwell upon them. Before the theoretical side of the question can be satisfactorily discussed, further experimental work must be done. At the time of the meeting each observer appeared to have almost overwhelming evidence in favour of his point of view, and had the audience only had to listen to one side—either side would have done equally well—it would probably have been convinced as to the accuracy and soundness of the views advanced. As it was, however, the average member left the meeting inclined to echo the sentiments of the lover in the "Beggar's Opera" who sings,

> "How happy could I be with either,
> Were t'other dear charmer away!"

The Spectrohelioscope.[1]

By Prof. GEORGE E. HALE, For. Mem. R.S.

MONOCHROMATIC images of the sun, photographically recorded with the spectroheliograph, reveal the phenomena of the solar atmosphere in projection against the disk. The light from a spectral line of calcium, hydrogen, or other substance is singled out by a narrow second slit, which moves across the plate while the first slit moves across the solar image. A monochromatic picture is thus built up of countless narrow slit images, recorded side by side in slow succession.

The vortices and other significant structures thus disclosed, with the exception of an occasional brilliant eruption or unusually dark hydrogen flocculus, are beyond the reach of visual observation with the spectroscope. The simple method of opening the slit, which affords an excellent view of prominences at the sun's limb, because the light of the sky is sufficiently weakened by dispersion, is seriously limited when applied to the intensely brilliant disk. Even with the highest dispersion the slit cannot be opened sufficiently to reveal the characteristic structure of the dark hydrogen flocculi. Moreover, with a widened slit the image is not strictly monochromatic.

This simple expedient of rapidly oscillating the narrow spectroscope slit, and synchronously with it a second slit transmitting the Hα line to the eye, was tried by the earliest observers of the prominences. With suitable precautions this device gives excellent images of prominences through persistence of vision, but it did not survive the introduction by Zoellner and Huggins of the wide slit method, and apparently was not tried for observing the sun's disk.

Many years ago I made some preliminary trials of the oscillating slit method with the 30-foot spectroscope and 60-foot tower telescope on Mount Wilson. I have only recently found opportunity to develop a satisfactory instrument based on this principle with which I have now secured good visual observations of both bright and dark flocculi.

An image of the sun two inches in diameter, given by a cœlostat and a 12-inch objective formerly belonging to the Kenwood Observatory,[2] was observed with a grating spectroscope mounted horizontally. In this instrument the light passing through the slit falls on a 6-inch concave mirror of 13-feet focal length, which returns a parallel beam to a point just below the slit, where a 6-inch plane grating is mounted. This sends the diffracted beam to a second 6-inch concave mirror, supported below the collimating mirror, which forms an image of the spectrum in the same plane as the first slit, and immediately below it. A fixed second slit at this point permits any part of the spectrum to be isolated. The grating was ruled by Jacomini with about 15,000 lines to the inch on the ruling machine of the Mount Wilson Observatory, with a diamond ground after Anderson's formula so as to give great brightness at the red end of the first order spectrum. The definition is perfect, and the brightness near Hα remarkable, as the attempt to concentrate most of the light in one spectrum and to favour the red end proved successful.

Suppose the first and second slits to be carried at opposite ends of a brass bar, mounted on a bearing half-way between them and thus free to revolve about this centre. Place the bar vertical, and turn the grating until the Hα line in the bright first order is bisected by the second slit. With the optical arrangement employed, a small displacement of the first slit to the right causes an exactly equal displacement of the Hα line to the left. Thus if the bar is oscillated back and forth by means of a small electric motor, a monochromatic image of the sun will be seen through a low power positive eyepiece focussed on the second slit.

This arrangement serves very well for the observation of prominences at the limb, where they can be seen at their full height with slits of moderate width. It also shows exceptionally bright or dark flocculi on the disk, though the slits must be narrower in order to give sufficient purity and reduce the brightness of the continuous spectrum. For flocculi of ordinary intensity the best results have been obtained with the aid of multiple slits, five at each end of the bar, 0·003 inch wide and 0·08 inch apart. A fixed slit, slightly less than 0·08 inch wide, must be used behind the upper slits, to prevent the formation of overlapping spectra. Two complete oscillations of the bar per second, corresponding to twenty illuminations of the retina, give a sufficiently steady image. A rotating disk, carrying a large number of radial slits, is in some respects a more satisfactory device for the same purpose.

This instrument, which may appropriately be called a spectrohelioscope, should prove a valuable auxiliary of the spectroheliograph in several kinds of work. It will permit the rapidly changing forms of eruptions on the disk to be followed visually, and be of special service in deciphering the curious differences of structure sometimes found on photographs of flocculi taken simultaneously with the opposite edges of Hα. As the oscillating bar can be moved toward red or violet by a micrometer screw while observations are being made, the possibility of passing instantly from one edge of the line to the other should assist in the interpretation of the spectroheliograph results.

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[1] Communicated to the National Academy of Sciences, Washington, on July 7, and published in the Proceedings of the Academy for August, vol. 10, No. 8, 1924.

[2] Kindly loaned me by Prof. Frost. The apparatus was set up temporarily in my garden at South Pasadena.