A SEARCH FOR PREFERENTIALLY DIRECTED ELECTRON VELOCITIES IN CRYSTALLINE GRAPHITE WITH THE MULTICRYSTAL SPECTROGRAPH

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Abstract

The author's theory of the broadening of the Compton line as a Doppler effect of electron velocities is briefly reviewed and it is pointed out that only the *component velocity* along a direction which nearly bisects the angle between primary and scattered x-ray beams should be effective in broadening the line. Crystalline Ceylon graphite possesses properties which lend hope to the belief that a class of weakly bound or structure electrons in this crystal might have momenta restricted uniquely to parallelism with one plane in the crystal: the (0001) plane. A composite scatterer was built up out of blocks consisting of the crystal flakes all orientated with their (0001) planes in mutual parallelism and the blocks in turn were so orientated that the normals to these planes bisected the angle formed by the primary and scattered x-ray beams. If the electron momenta are orientated parallel to the plane of the graphite flakes one should expect the contribution of such electrons to the shifted scattering to give a sharp line or peak superposed on the broader structure caused by the remaining isotropically distributed momenta. Details of the experimental set-up are described and the spectrum obtained from scattering by the Ceylon graphite scatterer is compared with the spectrum from an isotropic Acheson graphite scatterer. The breadth and structure of the shifted line proves to be quite identical in the two cases and the conclusion is drawn that if a class of electrons having selectively orientated momenta exists in the crystalline graphite it constitutes less than 5 percent of the total number. The bearing of this result on related questions is discussed.

Introduction

Interpretation of the breadth of the Compton modified line as a Doppler effect of electron motion

In a paper[1] published in this journal in 1929, the senior author proposed and analyzed the theory that the large observed spectral breadth of the Compton line can be regarded as a Doppler effect of the motions of electrons in the atoms and between the atoms of the solid scattering body. He has since then collected a large body of evidence[2,3,4] for the reality of this breadth, its structure and for the correctness of the Doppler interpretation.

The Doppler effect of the motion of a scattering particle changes the wave-length of the radiation scattered under a definite angle with the incident beam in a way that can be understood very simply by analogy with the classi-

[1] Jesse W. M. DuMond, Phys. Rev. **33**, 643 (1929).
[2] DuMond and Kirkpatrick, Phys. Rev. **37**, 136 (1931).
[3] Hoyt and DuMond, Phys. Rev. **37**, 1443 (1931).
[4] DuMond and Kirkpatrick, Phys. Rev. **38**, 1094 (1931).

cal Doppler effect of a moving mirror. Referring to Fig. 1, it is almost self evident that a motion of the mirror in the direction, y (or z) normal to x will leave the wave-length of the reflected beam unchanged, while a motion of the mirror along the direction, x, will impose a maximum Doppler effect on the wave-length of the reflected light. For a mirror moving with velocity, v, in any direction whatever only the component of v along x will be effective in modifying the wave-length of the reflected light.

The direction, x, will be for brevity called the longitudinal direction and the directions y, or z, normal to the axis, x, will be called transverse directions. If the change in wave-length relative to the wave-length itself is sufficiently small the direction, x, corresponding to maximum Doppler effect, very closely coincides with the bisector of the angle formed by the incident and reflected (or scattered) beams.

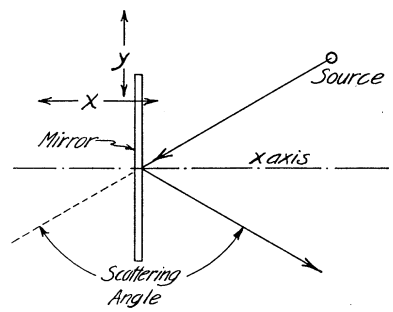


Fig. 1. Illustrating Doppler effect of a moving mirror.

It is evident that a given velocity of the mirror in Fig. 1 will modify the wave-length of the reflected beam more or less according as θ (the angle through which the reflection deviates the beam) is large or small. The effect will in fact be proportional to sin $(\theta/2)$ (to a non-relativistic approximation) being greatest if the beam is reflected directly back on itself as one would quite naturally expect.

All of the above statements can be taken over to the case of the scattering of x-rays by an electron if we replace the word mirror by the word electron. It must of course be remembered that while the mirror reflects the light almost uniquely in the specular direction the electron may scatter the quantum in any direction whatever. The statements we have made nevertheless apply to all those cases in which the electron does scatter the quantum in the particular direction, θ, chosen for observation.

Out of the multitude of electrons of a body scattering x-rays a certain fraction at any instant are scattering x-rays under a definite scattering angle, θ, (defined within certain narrow limits). What velocities should we expect these electrons to possess? We should expect them to have ordinarily a quite random distribution of velocities due to their quantized motions within the atoms and between the atoms *plus* a systematic velocity of recoil *away* from the x-rays. In accord with the law of conservation of momentum, this imparted recoil velocity will occur precisely in the direction x and will be pro-

portional to sin $(\theta/2)$ being greatest when the beam of radiation is scattered back along its original path.

We should expect, therefore, an initially sharp monochromatic wave to suffer a Doppler *shift* due to this imparted recoil velocity and a Doppler *broadening* due to the initial random velocities of the electrons. We should expect the shift to vary as $\sin^2 (\theta/2)$ because the Doppler effect itself, as we have just pointed out, is proportional to sin $(\theta/2)$ and because the recoil velocity accountable for the shift is itself proportional to sin $(\theta/2)$. We should expect the broadening to be proportional only to the first power of sin $(\theta/2)$ because the initial random electron velocities do not depend on the scattering angle, θ. An accurate theoretical analysis of the problem verifies these qualitative statements and the results of experiment support the theory. In fact the shift above referred to is the well known Compton shift while the broadening is now well established by experiments of the senior author in conjunction with H. A. Kirkpatrick.[2,4]

That the Doppler explanation of the broadening is the true one can scarcely be doubted in view of the results of the senior author and H. A. Kirkpatrick which show that the broadening really does vary as sin $(\theta/2)$ *just as it should and further that the broadening varies with the primary wave-length used in the correct way.*

Effect of departure from isotropic momentum distribution

Up to the time of the present experiment the senior author has always assumed the directions of the initial electron velocities in and between the atoms of the scattering body to be quite random in orientation. This assumption is well justified for polycrystalline scatterers consisting of an immense number of individual crystals with completely random orientation. There remains, however, the possibility that in some monocrystals some of the electrons (especially the outer ones) may have directions of motion quite definitely related to the crystal structure. If a crystal exists in which a reasonably populous and isolated class of electrons have no component of motion whatever along some one axis in the crystal these electrons moving exclusively in directions parallel to a single plane then it should be possible to detect this fact by making this axis coincide with the x-axis of Fig. 1. We should then obtain not a broad Compton line but a narrow one as far as the scattering due to the anisotropically directed electrons is concerned. Even though this constituted but a small fraction of the entire shifted scattered radiation it should deform the now familiar shape of the Compton line by giving a more or less sharp peak at the center.

On the suggestion of Dr. A. Goetz of this Institute we decided to try Ceylon graphite crystals as the scattering body which might contain anisotropically directed electrons. Ceylon graphite cleaves much more readily along the (0001) plane than in any other direction. Also it is strongly diamagnetically anisotropic along an axis normal to the plane of easy cleavage. Both these facts encourage the hope that a class of electrons may perhaps possess velocities exclusively parallel to the plane of cleavage though they do not render it certain by any means.

The experiment seemed highly promising due to its bearing on several questions of interest in physics. As pointed out in a recent letter to the Editor of the Physical Review,[5] if the experiment should give a positive result, i.e., a narrow or peaked shifted line structure, this would be exceedingly, convincing corroboration of the correctness of the Doppler explanation of Compton line breadth.

A positive result might also explain the narrow line breadths reported by two other investigators[6,7] in sharp discord with our own observations and to some extent discordant with each other since these investigators might have used crystalline scatterers more or less fortuitiously orientated so as to reduce the longitudinal component of electron momentum. (Any departure from an isotropic momentum distribution might have a narrowing effect on the shifted line.)

Either a positive or negative result might throw considerable light on the behavior of the outer electrons in crystalline graphite. So little is known about the solid state that any information in this field is extremely valuable.

Finally, it should be emphasized that a negative result—i.e., a broad Compton line structure identical to that which is obtained from isotropic amorphous or highly polycrystalline scatterers is decidely *not* negative evidence for the author's Doppler interpretation of Compton line breadth as an effect of atomic electron momenta. *That theory is the only one yet proposed which satisfactorily explains the observed behavior of the breadth as a function of scattering angle and primary wave-length* and this is the strongest argument for its correctness. A negative result can only be reasonably interpreted as evidence that the outer electron momenta in the graphite crystals are not preferentially orientated as postulated above.

Theory of the Experiment

Simplified theory

Referring to Fig. 2 a simple form of the theory of scattering of x-rays by free or weakly bound electrons can be set up if, as a first approximation, we assume the change in wave-length due to scattering to be a small fraction of the wave-length itself and neglect the effect of relativity which is small. With this assumption the momentum imparted to the electron by the radiation is directed along x and of magnitude

$$2\frac{hv}{c}\sin(\theta/2). \tag{1}$$

The initial momentum of the electron is, mv, directed at angle ψ with x and the square of its final recoil momentum given by the parallelogram law is

$$p_2^2 = (mv)^2 + 4\left(\frac{hv}{c}\right)^2 \sin^2(\theta/2) + 4mv\frac{hv}{c}\sin(\theta/2)\cos\psi. \tag{2}$$

[5] Jesse W. M. DuMond, Phys. Rev. **39**, 166 (1932).
[6] J. A. Bearden, Phys. Rev. **36**, 791 (1930).
[7] Newell S. Gingrich, Phys. Rev. **36**, 1050 (1930).

If we divide this by $2m$ we have the energy imparted to the electron and hence lost by the radiation which can therefore be equated to $h(\nu_1-\nu_2)$. Transforming this in turn to a change in wave-length by multiplying through by $\lambda/h\nu$ (since $\nu_1-\nu_2 \ll \nu_1$) we obtain the shift

$$\lambda_2 - \lambda_1 = 2(h/mc)\sin^2(\theta/2) + 2\lambda\left(\frac{v}{c}\cos\psi\right)\sin(\theta/2). \tag{3}$$

The first term in the right member is the familiar "Compton shift" and the second term which may be either positive or negative accounts for the broadening of the line when we integrate over all possible values that v/c and $\cos\psi$ can assume in the multitude of scattering processes that occur. For a class of electrons of definite speed, v, and isotropically distributed as to spatial direction of motion the spectral breadth of the Compton line is evidently

$$\Delta\lambda = 4\beta\lambda\sin(\theta/2) \quad (\beta = v/c) \tag{4}$$

and the line, or rather band, should take the form of a rectangular spectral distribution bounded by sharp discontinuities as the senior author has shown

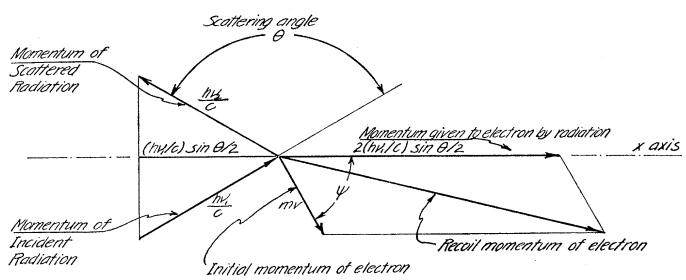


Fig. 2. Diagram of momentum vectors involved in scattering of radiation by a particle possessing initial momentum mv at angle, ψ_1 with an axis of reference bisecting the angle between the directions of incident and scattered rays. This is the simple approximation in which the change in wave-length is considered negligible in comparison to the wave-length itself. The angle, ψ, need not lie in the plane of the incident and scattered beams.

in previous papers.[1,2,4] (The observed shaded or continuous structure of the line can then be accounted for as an effect of the distributed values of v/c for all the electrons in the scatterer.)

Results of more elaborate theory

In a more elaborate treatment[2] the senior author has taken account of the fact that the change in wave-length is finite in comparison to the wave-length. The result obtained above is then only slightly modified and the breadth turns out to be for a random distribution of directions

$$\Delta\lambda = 4\beta\lambda^* \tag{5}$$

where $\lambda^* = \frac{1}{2}(\lambda_1^2+\lambda_c^2-2\lambda_1\lambda_c\cos\theta)^{1/2}$ (which becomes $\lambda\sin(\theta/2)$ when $\lambda_c=\lambda_1$); θ = scattering angle, λ_1 = primary wave-length, $\lambda_c = \lambda_1 + 2(h/mc)\sin^2(\theta/2)$ (shifted wave-length for initially stationary, electrons), $\beta = v/c$.

These results hold rigorously for free electrons and suffer from but slight error if the electron is weakly bound, the error being a fraction of the wavelength of the order of the binding energy divided by the quantum energy of the incident radiation.

The dependence of breadth, $\Delta\lambda$, on scattering angle and on primary wavelength, given in Eq. (5), has been tested by the senior author and H. A. Kirkpatrick using the multicrystal spectrograph and proves to be clearly verified experimentally.

The longitudinal axis in the more rigorous treatment just referred to does not quite bisect the angle between the incident and scattered radiation. It assumes in fact the direction of the vector difference between incident and scattered light quanta. This amounts, however, to a very slight difference indeed for molybdenum K radiation and hence has been neglected in the present experiment.

Effect of restriction of electron momenta to one plane

Reference to formula (3) shows that the broadening of the Compton line is to be ascribed to the *components* $(v/c)\cos\psi$ of all electron velocities resolved along the longitudinal axis, x, which very nearly bisects the angle between incident and scattered x-ray beams. If a scattering body could be found in which a reasonably large isolated class of electrons possessed no component velocity along some axis then the breadth and structure of the Compton line scattered by such a body would depend on the orientation of the body with respect to the longitudinal axis, x, bisecting the angle formed by the incident and scattered x-ray beams. With the axis of null velocity of the scattering body placed parallel to the axis, x, between the x-ray beams the contribution of the systematically directed electrons to the total scattering should be a narrow shifted line. One should expect to find this narrow line superposed on a broader diffuse line contributed by the scattering from the more tightly bound electrons whose directions of momentum would be less dependent on the lattice structure and hence practically isotropically distributed in space. With the axis of null velocity *normal* to the longitudinal axis between the x-ray beams one should expect a broader structure, as a contribution from the systematically directed electrons. In particular if these electrons had momenta isotropically distributed as to direction in the plane in which their vectors are restricted one should expect *two peaks* or maxima as the resulting spectral distribution when this plane is placed *parallel* to the longitudinal axis, x, between the x-ray beams. The perspective drawings in Fig. 3 illustrate the two cases just described together with the line structures one might expect to obtain from them.

Apparatus and Methods

Preparation of graphite blocks

The Ceylon graphite used in this experiment occurs in very small hexagonal flakes a few microns thick and from 0.01 to 0.03 mm across. The multicrystal spectrograph used for analyzing the scattered radiation requires a

large scattering body lying on a circular arc. For this experiment the circular scattering body was built up of fifty small blocks, one for each crystal of the multicrystal spectrograph, each block being composed of a multitude of the tiny flakes of Ceylon graphite stuck together with a slight quantity of gum Damar as a binder. A minimum amount of the gum was used so that the blocks were very fragile and had to be handled with the greatest care.

The technique of purifying the Ceylon graphite, preparing the blocks, and measuring their diamagnetic anisotropy was entirely worked out by Dr. A. Goetz and his collaborators, Dr. Faessler and Mr. Focke, and the authors wish here to express their deep appreciation for this very helpful cooperation. We wish also to thank Mr. L. Alden who purified a sufficiently large quantity of graphite for the fifty blocks and performed the tedious work of preparing the blocks and mounting them as a composite scattering body. In a recent letter[8] to the Editor of the Physical Review this technique has been described

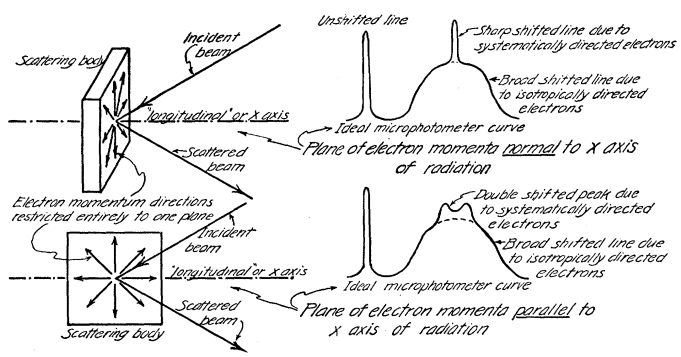


Fig. 3. Illustrating ideal Compton line shapes to be expected from a crystalline scatterer containing an isolated class of electrons with momentum vectors all parallel to one crystal plane and isotropically distributed therein.

at some length by Dr. Goetz, including the detection of the impurities (iron and quartz) in the graphite and the methods for removing them. The reader is referred to Dr. Goetz' article for this information.

The blocks were prepared by placing a suspension of the Ceylon graphite in a solution of 3 to 5 percent of the gum Damar in benzene. This suspension was held in small rectangular cellophane boxes open at the top. The cellophane box was placed in a horizontal magnetic field of a strong electromagnet. The suspension was allowed to settle until a sufficient quantity of graphite had accumulated at the bottom to form a block of the requisite thickness. By the combined action of the magnetic field and of the Bernoulli effect on the thin falling flakes these latter settled into horizontal positions with surprisingly good regularity. The alignment of the flakes was tested by examination of the block with a microscope both on its exterior surface and in some cases on the interior by cleavage of the block. An even better method of testing this alignment consisted in measuring the ratio of diamagnetism of the block

[8] Alexander Goetz, Alfred B. Focke and Alfred Faessler, Phys. Rev. **39**, 168 (1932).

normal and parallel to the general direction of the planes of the individual flakes. The ratio of diamagnetic anisotropy for the block as a whole can be taken as a measure of the perfection of crystal flake alignment. Even assuming the diamagnetic anisotropy ratio for individual flakes (comparing the directions normal and parallel to the flake) to be infinite, measurements of anisotropy ratios for the whole block indicate a departure of the flakes from parallelism of only a very few degrees. Blocks were obtained with anistropy ratios as high as 15.4. No blocks were used in the scatterer with anisotropy ratios lower than 9.2. It is probably safe to say that the mean deviation of the flakes from parallelism was of the order of three to five degrees of arc.

After the graphite had settled out of suspension in the cellophane holders these were placed in a rectangular hole in a block of brass into which they fitted. A rectangular brass block was then forced down through the open top

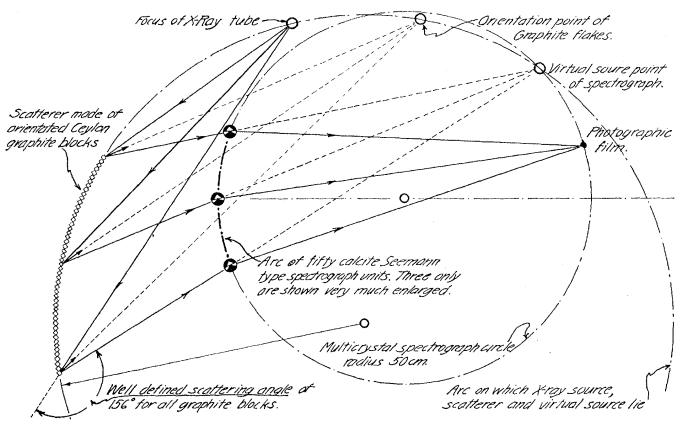


Fig. 4. Geometry of orientated Ceylon graphite block scatterer and multicrystal spectrograph fulfilling the conditions for (1) focusing the spectra from fifty crystals, (2) giving sharply defined scattering angle and (3) orientating the normals to the (0001) plane of the graphite flakes along the bisector of the angle between incident and scattered beams.

of the cellophane box and thus the deposited graphite was compressed and the excess fluid pressed out. After the block had dried the cellophane could be removed in most cases without damaging the block by exercising a little care.

Geometry and arrangement of scatterer and multicrystal spectrograph

The graphite blocks were of dimensions 50 mm×10 mm×8 to 10 mm, the planes of the flakes lying parallel to the 50 mm×10 mm face. The circular scattering body was built up of these blocks standing close together with their long dimensions vertical and each one so orientated that the normal to the plane of its flakes bisected the angle between its incident and scattered x-ray beam. Fig. 4 shows a plan view of the geometrical arrangement of the x-ray tube, the composite scatterer and the multicrystal spectrograph. The end of each block is shown and the small arrows indicate the normal to the planes of the graphite flakes in each block. These normals meet in a point on the large circular arc midway between the focal spot of the x-ray tube and

the virtual source point of the multicrystal spectrograph. The "focussing" principle of this spectrograph has been sufficiently explained in previous articles.[2,4,9] The present experiment differs from previous ones only in the nature of the scatterer consisting of individually orientated crystalline graphite blocks instead of a continuous curved strip of practically isotropic polycrystalline graphite. Fig. 5 is a photograph showing the x-ray tube, the scatterer of monocrystalline graphite blocks and the multicrystal spectrograph with its system of baffles in front of the crystals to reduce fogging of the film. It was of course necessary to be certain that each of the fifty small blocks was exactly in the proper position to furnish scattered radiation to its crystal in

Fig. 5. Photograph showing x-ray tube in cylindrical lead-rubber sheathed housing, scatterer consisting of fifty orientated Ceylon graphite blocks and multicrystal spectrograph with baffles to reduce fogging projecting in front.

the multicrystal spectrograph in the proper region of the spectrum, i.e., from about 800 X.U. to about 615 X.U. This was done by placing a strong light behind the photographic film-holder of the multicrystal spectrograph and stopping off everything except the region of the holder where the above mentioned spectral range was already known to appear. The light shining through this carefully defined opening is reflected from the fifty individual crystals of the multicrystal spectrograph along precisely the reverse path to be later followed by the scattered x-rays. The erect graphite blocks correctly spaced and orientated on a wooden board are then adjusted as a whole so that each reflected light beam from the fifty calcite crystals of the multicrystal spectrograph just covers the face of its respective graphite block. The entire geome-

[9] Jesse W. M. DuMond and Harry A. Kirkpatrick, Rev. Sci. Inst. **1**, 88 (1930).

try of the system is so simple that it is not at all difficult to position the blocks on their supporting board with the required accuracy by graphical methods. The geometrical elements were laid out to full scale on a large table and a thin board was cut with the proper saw tooth profile required to establish the proper positions and orientations of the bases of the graphite blocks. Two such saw tooth profiled boards attached to a base board formed a series of fifty depressions into which the bottoms of the graphite blocks fitted. A little cotton gently wedged into place behind each graphite block held it erect. These wooden base boards were covered with lead to prevent them from scattering x-rays. They were not in alignment to scatter radiation into the spectrograph.

The tube, scatterer and virtual source point in the spectrograph were es-

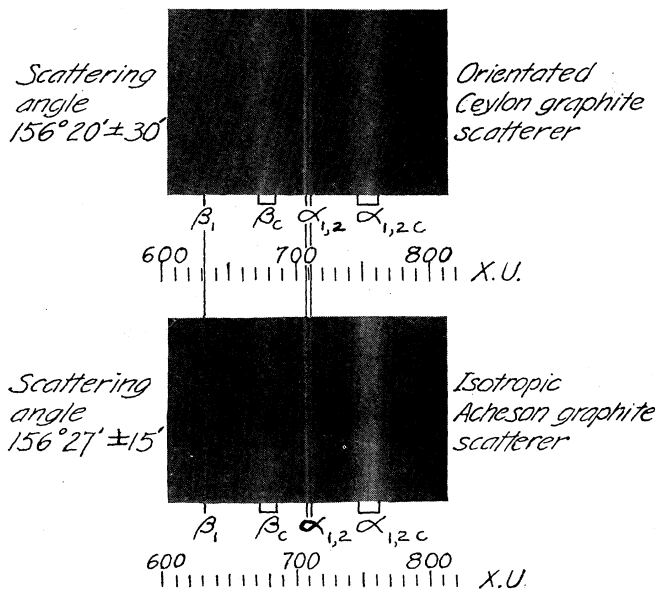


Fig. 6. Reproduction of spectrograms of molybdenum K radiation scattered at 156° 20′±30′ from isotropic Acheson graphite and from orientated Ceylon graphite scatterers.

tablished on the same circular arc by means of the swinging radius arm with attached plumb line and the scattering angle was measured by observing the angle through which this arm must swing. In this respect the methods are entirely similar to those described in previous papers.[2,4,9]

Exposure conditions

An exposure of 990 hours was made with a molybdenum target x-ray tube running steadily night and day at 21 milliamperes current input and 50 kilovolts effective. The scattering angle was 156° 20′± 30′. At this large angle the tube must be placed so that the distance from the focal spot to the nearest point on the scatterer is about 70 cm and the distance to the farthest point is about 120 cms hence the necessity for such a prolonged exposure.

Eastman high speed duplitized "Diaphax" film was used without any in-

tensifying screen to avoid any possible falsification of the line-structure. The film was placed in a thin black paper envelope to avoid fogging by stray light in the spectrograph in the same manner as in previously described experiments.

Results

A very fine clear exposure of the scattered spectrum was obtained—indeed one of the best to date. This exposure along with a similar exposure taken under identical conditions with a long continuous arc of isotropic Acheson graphite as a scatterer is reproduced in Fig. 6. *No essential difference in the structures of the shifted line for the two cases can be detected.* Neither do the microphotometer curves taken on the two spectrograms reveal any essential difference in the structures of the lines. Typical microphotometer curves are

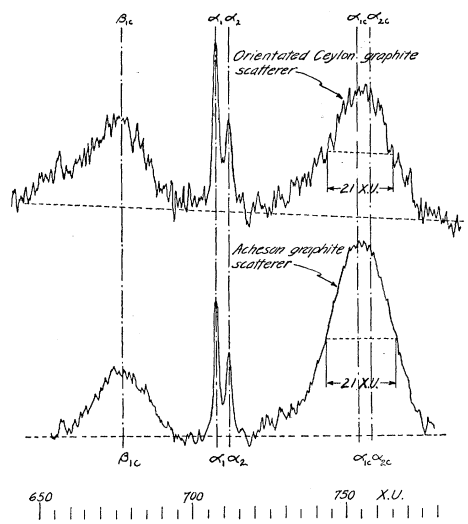


Fig. 7. Microphotometer curves taken from spectra of Fig. 6.

shown in Fig. 7. If anything the shifted line from the orientated graphite seems a little the broader and more diffuse of the two.

From a comparison of the areas under the shifted alpha line and under the unshifted beta line (which is clearly distinguishable on the original film) it is possible to form an estimate of what fraction of the total intensity of shifted alpha could have been detected if it had been present in the form of a narrow sharp line. The authors believe it is safe to say that a sharp line only 5 percent as intense as the total intensity of shifted alpha could easily have been detected if it were present. Since the scattering is proportional to the number of electrons it seems safe to conclude that if an isolated class of electrons exists in the crystalline graphite possessing negligible momentum components normal to the (0001) planes of the flakes this class must be less than 5 percent of all electrons or less than one to every three atoms. This estimate is highly conservative. The unshifted alpha doublet and the shifted beta line are more in-

tense relative to the shifted alpha line on the exposure with the orientated Ceylon graphite than they are on the exposures made with a continuous strip of Acheson graphite as a scatterer. This is probably caused by the nonuniform distribution of the scatterer over the range of wave-lengths of the spectrum on account of the blocks of which the scatterer consists, the different parts of the spectrum being scattered from different parts of the block.

There seems to be no reason to expect that any narrowing or peaking effect on the line would be found for other orientations of the graphite in view of the present result and as these experiments are expensive and very time consuming a further search for orientated velocities does not seem justified.

The film taken with isotropic Acheson graphite shows a region of slightly different density at one edge. This it will be noted, does not appear in the later film made with the orientated Ceylon graphite. This region of slightly greater blackening was accounted for by Dr. Kirkpatrick some months past as being due to a tiny leak in the construction of the lead spectrograph box which permitted the entry of a very small quantity of radiation scattered directly from the primary beam by the air outside the box, without suffering reflexion by the crystals. This was sufficient in the long period of exposure to cause this local fogging. This leak has since been completely eliminated. The possibility of falsification of the line structure by air scattering and subsequent selective reflection from the crystals is completely negligible since any such effect must be compared with scattering by the scatterer itself and it is an easy matter to compute the relative number of electrons in the region of air capable of scattering radiation to the crystals in comparison to the number of scattering electrons in the scatterer. This ratio is extremely small.

Conclusion

In the author's opinion the obvious conclusion to be drawn from this experiment is that the momenta of the electrons in the graphite crystals are isotropically directed in space, or if a class of electrons exists for which this is not true such a class constitutes a very small proportion of the total number (less than 5 percent).

It might have been supposed that the electrons responsible for the diamagnetic anisotropy of the graphite flakes executed flat orbits parallel to the (0001) plane of the flake. This also is the plane of easy cleavage and one might suppose that this easy cleavage could be explained by the flatness of such orbits and the consequent absence of any strong electron bonds due to electrons crossing these planes transversely. It must be noted, however, that even if this were the case it does not necessarily follow that these electrons will not possess *momenta* normal to the planes of easy cleavage. A rough picture of such a state of affairs can be visualized—the electron executing an orbit in a plane and at the same time performing small but rapid oscillations normal to the plane. Indeed the uncertainty principle leads us to expect that if an electron were sufficiently constrained in its *position* measured normal to some plane in which it might be supposed to execute an orbit, its spread in momentum along this same direction could become indefinitely large. The *shapes*

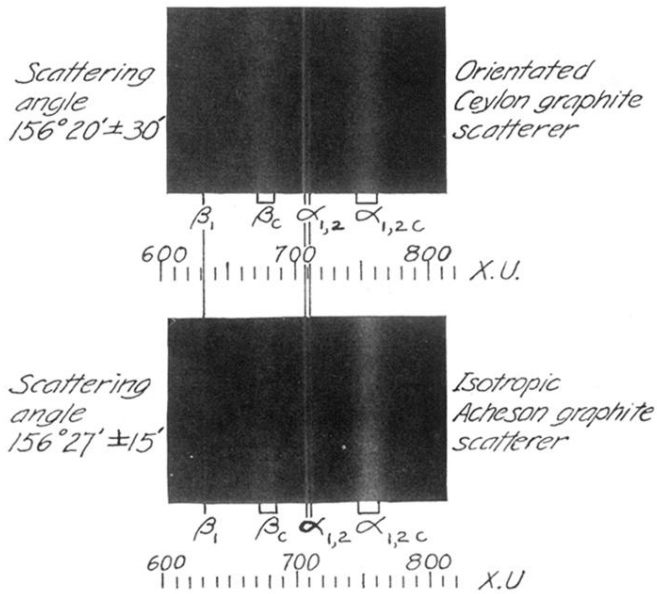
of the orbits and the distribution of electron momenta are thus not simply connected as one might naively expect from analogy with macroscopic particle dynamics.

The results of this experiment leave no opening for an explanation of the narrow shifted line structures reported by Gingrich and by Bearden.[6,7] Each of these men used the double crystal spectrometer. Dr. Hoyt and the senior author have, with the double crystal spectrometer, obtained good verification of their broad line structures in accord with the results obtained with the multicrystal spectrograph. Furthermore, P. A. Ross, by the use of very large polished calcites in a double spectrometer, has recently obtained very excellent spectral curves showing the broad Compton line also in complete agreement with our observations. In a letter to the author Ross states that he has also observed the variation in breadth with scattering angle first discovered by DuMond and Kirkpatrick. The breadth of Ross' shifted line is not an effect of polishing the crystals as he obtains narrow unshifted lines with them. The evidence for the broad Compton line and for DuMond's predicted dependence of that breadth on primary wave-length and scattering angle seems now very clear cut.

As stated above, the interpretation of the broadening of the Compton line as a Doppler effect of electron momenta in the scattering body is based on the observed behavior of the breadth with change of scattering angle and primary wave-length. The negative result of the experiment here reported leaves this interpretation still unchanged. Indeed it is the only interpretation so far offered which satisfactorily explains the observed experimental facts.

This investigation which has involved a great deal of expense has been carried out with the aid of funds from the Seeley W. Mudd X-Ray Research Fund and we take this opportunity to express our sincere appreciation for this financial aid.

Fig. 5. Photograph showing x-ray tube in cylindrical lead-rubber sheathed housing, scatterer consisting of fifty orientated Ceylon graphite blocks and multicrystal spectrograph with baffles to reduce fogging projecting in front.



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