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X-ray Topographs of Diamond
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RE-PRINTS

X-RAY TOPOGRAPHS OF DIAMOND

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1. Introduction

As is well known, the spots in the Laue pattern of a crystal arise from the reflection of X-rays by particular sets of lattice planes. The size of each spot in the pattern increases with the extension of the area of the crystal traversed by the X-ray beam, and reaches its maximum when the crystal is completely bathed in the latter. In the particular case when the crystal is in the form of a thin plate, its form and size would determine those of the Laue spot, and each spot in the X-ray pattern becomes, in effect, a geometric representation of the crystal plate. The representation would be perfect if there is no blurring and no distortion. The former condition may be secured by arranging that the beam emerging from the target of the X-ray tube is limited by a fine pinhole, and that the crystal plate is placed at a sufficient distance from the latter to ensure that it is completely bathed by the beam diverging from the pinhole. The fact that the spots in Laue patterns as usually recorded with an X-ray beam of circular cross-section are elliptical shows that, in general, distortion will occur in the present arrangement. It is possible, however, to secure that it is practically eliminated in respect of a chosen Laue spot by suitably inclining the photographic film, or the crystal plate, or both, to the beam of X-rays incident on the latter. The particular spot whose definition and freedom from distortion are thus secured, thereby making it an exact representation of the crystal plate, would evidently be formed by the reflection of white X-radiation by the chosen set of lattice planes over a small range of angles of incidence. Each point in the area of the particular Laue reflection would correspond to a particular point in the crystal plate, and if the strength of the incident beam and the reflecting power of the lattice planes are uniform over its area, the reflection would also appear of uniform intensity. The proviso must however be made that the range of angles of incidence employed does *not* include the Bragg angle for any of the monochromatic components present in the incident X-ray beam.

The considerations set out above become of practical interest, if, for any reason, the reflecting power for X-rays is *not constant* over the area of the

crystal plate under study. The geometric representation of the plate obtained by the method explained would then exhibit corresponding variations in intensity over its area, thereby revealing the local variations in the structure of the crystal which are responsible for the variations of reflecting power. The Laue spot becomes, in effect, a topographic map (or for brevity, a *topograph*) of the crystal plate exhibiting these variations of structure.

Topographs of 18 polished cleavage plates of diamond selected from Sir C. V. Raman's personal collection with their catalogue numbers entered against them, obtained in the manner briefly explained above, are reproduced in Figs. 4 to 6 in Plates XXIV and XXV, accompanying the present paper. Their significance will be discussed later in the course of the paper. To appreciate the X-ray topographs fully, they must be compared with the luminescence patterns (Sunanda Bai, 1944), the ultra-violet transparency patterns (Rendall, 1944), and the birefringence patterns (Raman and Rendall, 1944) of the same diamonds reproduced in the plates accompanying other papers published in this symposium.

2. *Practical Details and Theory for Obtaining the Topographs*

The experimental arrangement used is as follows, and is represented diagrammatically in Fig. 1. A fine pinhole P of diameter 0·3 mm. made in a sheet of lead, and placed in front of the window of a tungsten target X-ray tube forms a point-source of diverging white X-radiation. The diverging cone of X-rays is limited by an aperture A_1, placed at a suitable distance (20 cm.) from the pinhole. The crystal plate CD is mounted on a two-circle X-ray goniometer, kept at a distance of 30 cm. from the pinhole, which is adjusted so that one of its axes of rotation is vertical, and the other coincides with the axis of the cone of X-rays. Just in front of the crystal, a second aperture A_2 is placed. This aperture is of such a size that the direct X-ray beam just passes through it, without striking its boundary. In this way, it effectively prevents the X-rays scattered by A_1 from striking the photographic film F. The apertures are of such a size that the crystal is completely bathed in the X-rays. The film holder of the X-ray camera is capable of rotation about a vertical axis. It is also capable of longitudinal motion along the line joining the pinhole and the crystal. The film holder was always set such that the film was tangential to the circular head of the goniometer and the normal distance of the film from the crystal was a constant (2·5 cm. in the present case).

The diamond plates that were employed were usually octahedral cleavage plates with their surface parallel to one set of (111) planes, or slightly

inclined to it at angles of 1° or 2° owing to errors in polishing. A few specimens were however found which were dodecahedral cleavage plates. The setting required for getting the topograph was different in the two cases. Although any one of the Laue spots can be used for the purpose, it is an
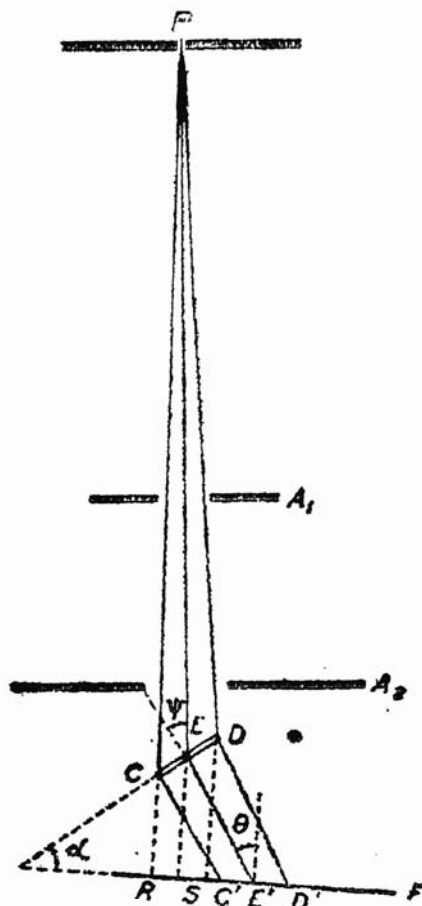

Fig. 1. Arrangement for obtaining topographs

advantage to use a strongly reflecting plane in **order** to minimise the exposure. For the octahedral cleavage plates, any one of the three sets o_f internal octahedral planes, *viz.*, $(11\bar{1})$, $(1\bar{1}1)$ or $(\bar{1}11)$ can be used. For dodecahedral cleavage plates with their surface parallel to the (110) planes, any one of the reflections $(\bar{3}13)$, $(3\bar{1}3)$ $(\bar{1}33)$, $(1\bar{3}3)$ can be employed.

The crystal plate (whether of octahedral or dodecahedral cleavage) is first mounted so that its surface is normal to the incident X-ray beam. A photograph is taken with this arrangement, and with its help, the requisite reflection, the (111) or the (331) as the case may be, is brought so as to be in the same horizontal line as the central spot, by rotating the crystal about the axis of the cone of X-rays. Next, the crystal is rotated about the vertical axis through an angle of $33\frac{1}{2}$° for the octahedral plate and 38° for the dodecahedral plate, so that the same reflection occurs on the opposite side at an

angle of 14° and 19° respectively. The film holder is then rotated in a direction opposite to that of the crystal through an angle of 14° and 3° respectively. An exposure is then taken with this arrangement when an undistorted X-ray topograph is obtained. It may be pointed out that in these settings, the angles of incidence were beyond the Bragg angle for any of the characteristic lines of tungsten, and that the topograph was produced by white radiation alone.

We shall now develop the theory of the method for eliminating distortion, and show how the elimination is secured in the settings described above. Let CD be the crystal, and C'D' the image of it produced on the film F, E and E' being the middle points of these (Fig. 1). Let α be the angle between the plane of the crystal and of the film, θ the angle made by the X-ray reflected by E with the normal to the film, ψ the angle between the axis of the X-ray beam and the normal to the crystal, and ϕ the divergence of the incident X-ray beam, *i.e.*, the angle subtended by CD at the source P. The rest of the symbols are clear from the figure.

$$\text{Now, } C'D' = RD' - RC' = SD' - RC' + RS$$
$$= SD \tan (\theta - \phi) - RC \tan (\theta + \phi) + CD \cos \alpha.$$

This must be equal to CD if there is to be no distortion.

$$\text{Now, } SD = r + \frac{CD}{2} \sin \alpha, \; RC = r - \frac{CD}{2} \sin \alpha.$$

Also, since ϕ is a small quantity, putting $\tan \phi = \phi$, and writing t for $\tan \theta$, $\tan (\theta + \phi) = t + \phi + \phi t^2$, $\tan (\theta - \phi) = t - \phi - \phi t^2$.

Substituting these, the condition for no distortion comes out as

$$2r\phi (1 + t^2) - (CD \sin \alpha) t + CD (1 - \cos \alpha) = 0.$$

Divide this equation by R, the distance PE of the crystal from the pinhole. Then, since $CD \cos \psi / R = \phi$, one obtains

$$\frac{2r}{R} \phi (1 + t^2) - \frac{\phi}{\cos \psi} t \sin \alpha + \frac{\phi (1 - \cos \alpha)}{\cos \psi} = 0.$$

Putting $R/r = K'$, this can be written in the form

$$t^2 - \frac{K'}{2 \cos \psi} t \sin \alpha + \left[1 + \frac{K'}{2 \cos \psi} (1 - \cos \alpha) \right] = 0.$$

or, if $K'/\cos \psi = K$, $t^2 - \frac{K}{2} t \sin \alpha + \left[1 + \frac{K}{2} (1 - \cos \alpha) \right] = 0.$

If this equation is satisfied, then there will be no distortion laterally.

Before proceeding further, it is interesting to notice that when θ and α satisfy the above equation, the image is a normal representation of the crystal. In other words, if F is any point on the crystal, and F' is the corresponding one in the reflected image, then CF = C'F', and this is true for all points F in the cross-section CD. This is easily seen to be so, for the final equation is independent of ϕ, which alone depends on the dimensions of the crystal. Of course, the above theory rests on the assumption that ϕ is a small quantity, but this is true in the present experiment where the dimensions of the crystal never exceeded 10 mm., for which ϕ is less than 1/30. For these, the image will be a true reproduction of the object.

In order to make the theory capable of practical application, curves have been drawn for different values of K, connecting the values of θ and α which satisfy the equation for no distortion. These are reproduced in Fig. 2. It will be noticed that all the curves are closed. Only for conditions corresponding to points on the curves will there be no lateral distortion;
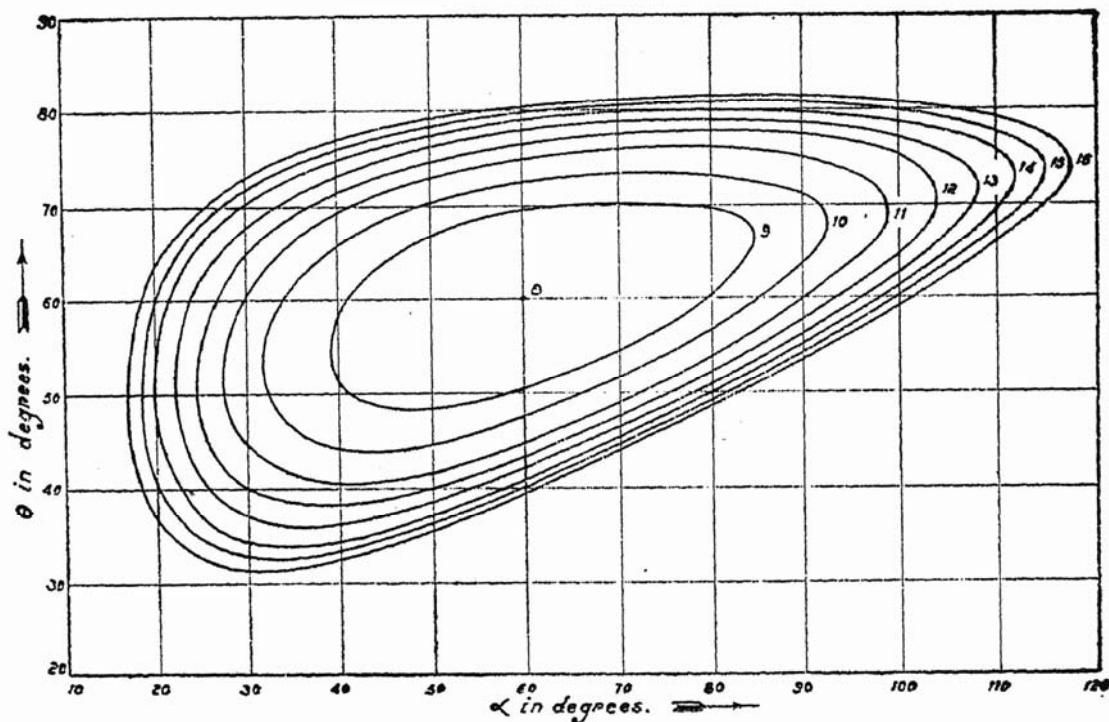

FIG. 2. Curves showing relation between θ and a

if the point is outside, the lateral dimensions of the image will be smaller than that of the object, while if it is inside, the reverse will be the case. It is also found that there is a limiting value of K, (K = 8), below which there can be no undistorted position for any values of θ or α. For this particular value of K, the curve reduces to a point ($\theta = 60°$ $a = 60°$), which is the only position of no distortion.

Taking now the particular case of an octahedral cleavage plate of diamond, it is clear that when it is mounted with the surface normal to the X-rays, the internal (111) planes reflect at an angle of $19\frac{1}{2}°$. As already said, the crystal is rotated through $33\frac{1}{2}°$, so that the same planes reflect at an angle of $14°$ in the opposite direction (which may be denoted by $-14°$). In this case, $\psi = 33\frac{1}{2}°$, and with the present arrangement for which $R/r = 12$, the value of $K = 14\cdot4$. If the film is rotated through $5°$ in a direction opposite to that of the crystal, then it is easily seen that α and θ have the values $38\frac{1}{2}°$ and $33°$, which thus satisfy the condition for no lateral distortion.

It must be mentioned that even with this arrangement, the image will not be a perfect reproduction of the crystal, for there is a small divergence in the vertical direction. The arrangement only secures that the horizontal dimensions are unaltered, but does not compensate for the vertical divergence. However, even this small distortion can be eliminated by further increasing the tilt of the film, so that the working point moves inside the curve of no lateral distortion, and the horizontal dimensions of the image become actually greater than that of the object. The additional tilt can be adjusted so that the lateral dimensions are also increased in the same ratio as the vertical ones. This quantity was not calculated, but was determined by trial to be nearly $9°$. Thus the total tilt necessary is $14°$, which is the one used. With this arrangement, the distortion, if any, would be less than 2%. It might be pointed out that even if the vertical divergence were not corrected for, the consequent increase in the vertical dimensions would only be about 8%.

In the case of the dodecahedral plates, the method employed is to rotate the crystal through $38°$, so that $\psi = 38°$ and $K = 15\cdot2$ for this setting. From the curves in Fig. 2 it is seen that there is no distortion if $\theta = 32°$ and $\alpha = 32°$. Here also, the additional tilt necessary to compensate for the vertical divergence is $9°$, and the final setting is $\theta = 41°$, $\alpha = 41°$, which can be realised by rotating the film in a direction opposite to that of the crystal through $3°$. This justifies the arrangement used.

It will not be out of place here if it is pointed out that this method of obtaining X-ray topographs is quite general, and can be used for any crystal, provided it is available in the form of a plate. Even the indices of the spot need not be known; what is needed is only the angle which the corresponding plane makes with the surface of the plate, which can easily be determined by taking a picture with the plate normal to the X-ray beam. If we call this angle by β, the author found that it is most convenient to make the planes reflect at $-\beta$, rotating the crystal through an angle $\psi = 2\beta$.

Then, the reflected beam is normal to the surface of the plate. In fact, this was the procedure adopted for obtaining the topographs of dodecahedral cleavage plates. For octahedral plates, the method is not feasible on account of the fact that the angle β ($19\frac{1}{2}°$) is in the neighbourhood of the Bragg angle for the characteristic lines of tungsten, so that the angle — 14° had to be employed.

If, however, it is required to obtain the X-ray topograph by surface reflection, an exactly similar method can be used. It may be remarked that, in this case, the condition for no distortion is extremely simple, namely that the film must be parallel to the crystal. This is because the reflected beam is divergent both in the horizontal and the vertical directions, so that if the photographic film is parallel to the crystal plate, the impression on it is merely an enlarged picture of the crystal, and will in fact be a true reproduction of the object.

3. Intensity of X-Ray Reflection in Diamond

As a preliminary to an examination of the individual topographs and of their significance, we may briefly consider here the problem of the structure of diamond in relation to the intensity of X-ray reflections given by it. Many of the physical properties of diamonds are highly variable, *viz.*, the colour and intensity of the visible luminescence exhibited by it under ultra-violet irradiation, as also its transparency to the visible, ultra-violet and infra-red radiations and the corresponding absorption spectra. The question arises as to what the origin of these variations is. An answer to this has been given by Prof. Sir C. V. Raman in two papers appearingearlier in this symposium. According to his theory, diamond can exist in four allotropic modifications. Two of these modifications have tetrahedral symmetry and the other two octahedral. In any actual crystal, these structures may appear either alone, or intermingled with one another and the properties of the specimen are determined by the nature and the extent of interpenetration of the structures that are present in it. Such an interpenetration may be on a macroscopic, microscopic or sub-microscopic scale. Now, any variations from perfect regularity in a crystal will give rise to an enhanced intensity of X-ray reflection as is well-known. But the scale in which these variations occur is an important fact to be considered. If the interpenetration of the different structures is on a macroscopic scale, then what one expects is not an increased reflection, but only what is to be expected for a perfect crystal, except that different parts of the crystal may conceivably behave differently, giving slightly varying intensities of X-ray reflection. On the other hand, if the interpenetration and the consequent

inhomogeneity of the structure is on a microscopic or sub-microscopic scale, the crystal can be considered to possess a mosaic structure, which at once leads to an increased intensity of X-ray reflection.

Striking support is given to these considerations by the fact that the crystallographically most perfect diamonds, which exhibit a blue luminescence, show variations in the X-ray reflection intensity, which is clearly correlated to their luminescence intensity. Diamonds of this class show a strong absorption in the ultra-violet at wave-lengths below 3000 Å.U., and the best specimens appear perfectly isotropic and free from birefringence. According to Sir C. V. Raman, diamonds of this class have an inherently tetrahedral symmetry of structure, but this is, in general, disguised by an intimate inter-penetration of the positive and negative tetrahedral forms with the result that the higher octahedral symmetry of form is simulated. The resulting heterogeneity, however, reveals itself in the capacity of the diamond to luminesce. In agreement with this view, it is found that specimens of this class of diamond which exhibit the feeblest blue luminescence show the lowest X-ray reflection intensities, while those showing an intense blue luminescence give enhanced reflection intensities. This is beautifully shown by the Laue patterns of two diamonds, one feebly and the other strongly blue luminescent, obtained by Dr. R. S. Krishnan, and reproduced in Sir C. V. Raman's article in *Current Science* for January 1943. A similar pair of photographs obtained by the author under strictly comparable conditions for diamonds D31 and D41 are reproduced in Fig. 3, Plate XXIV of the present paper. These two diamonds are of equal thickness, but differ enormously in the intensity of blue luminescence, D31 being very weak and D41 very strong. It will be seen that the Laue pattern of the former is much the weaker. A quantitative study of the patterns, and a theoretical dis-cussion of the same appears as another paper of the symposium.

It has long been known that some diamonds are completely non-luminescent and that these exhibit a higher degree of transparency to the ultra-violet, transmitting freely upto 2300 Å.U., or even shorter wave-lengths. According to Sir C. V. Raman, these belong to the class of diamonds having octahedral symmetry, there being two variants of this class (Oh I and Oh II), which are physically different. In general, both the variants are present in specimens of diamond belonging to this class, exhi-biting a lamellar twinning parallel to one, two, three or even all the four sets of octahedral planes in the crystal. The existence of such lamellar twinning is proved by the external striations visible on the surface of the crystals, and by the finely spaced streaky birefringence patterns, running parallel to the planes of lamination, which are seen when plates of such diamonds are

examined between crossed nicols. The multiple lamellar twinning, in effect, divides the crystal into a great number of very small, and slightly disoriented crystal blocks, with the result that the X-ray reflection intensities of this type of diamond is much greater than even for the most intensely blue-luminescent diamond (Lonsdale, 1942; Hariharan, 1944).

Finally, we have to consider the kind of diamond in which the tetrahedral and the octahedral structures are more or less closely intermingled, and which exhibits a partial transparency in the spectral region between 2300 and 3000 Å.U. These diamonds show a mixed type of luminescence. They also exhibit an X-ray reflecting power intermediate between the two extremes, represented by the feebly luminescent tetrahedral and the non-luminescent octahedral types (Hariharan, *loc. cit.*).

A natural consequence of the possibility of interpenetration or inter-twinning of the four possible structures of diamond is that the structure of any particular specimen may vary from part to part within its volume. Hence, it follows that a cleavage plate of diamond may exhibit variations of its various properties over its area, such as the colour and intensity of its luminescence, its transparency to the ultra-violet, and its absorption spectra in the visible, the ultra-violet and the infra-red. It also follows that diamonds in which the tetrahedral and octahedral forms of diamond intrude into each other should exhibit a birefringence pattern related to the nature and extent of such intrusions. These conclusions are strikingly supported by a comparison between the luminescence, ultra-violet transparency and the birefringence patterns of the same diamond placed side by side. The existence of such variations of structure should also reveal itself as corresponding variations of X-ray reflection intensity, the nature of which would depend upon the precise details of the case.

4. Description of the Topographs

The 18 topographs reproduced as Figs. 4, 5 and 6 in Plates XXIV and XXV show great differences amongst themselves. The cleavage plates of diamond with which they were recorded were, in fact, selected so as to be representative of a wide range of variation of the behaviour of diamond as exhibited in other physical properties, *viz.*, colour and intensity of luminescence, ultra-violet transparency and the absence or presence of birefringence as seen between crossed nicols. The interpretation of the topographs is greatly facilitated by a knowledge of the behaviour of the specimens under study in these respects. While each diamond shows individual peculiarities, the topographs may be broadly classified into three groups:

(A)   Those in which the reflecting power of the crystal plate is more or less uniform over its surface, so that but little detail is visible in the topographs, *e.g.*, D36, D45, D221. It should be mentioned that in these cases the intensity of the X-ray reflection is so weak that exposures of from two to three hours were found necessary to get a satisfactory picture.

(B)   Those in which the topograph exhibits a great general intensity of X-ray reflection, so that from ten to twenty minutes of exposure was found to be sufficient. D206, D207, D208, D209 are examples of this class. It will be noticed that in all of them, sets of parallel streaks running in different directions through the plate are a characteristic feature. This is seen in a particularly striking manner in D208 and D209.

(C)   Those diamonds in which the features described in classes (A) and (B) appear to coexist, so that while the crystal as a whole exhibits comparatively weak X-ray reflection, overlying this some intense regions also appear. These intense regions may be of several kinds. They may consist of:

(i) small areas of comparatively intense, but fairly uniform reflection, or

(ii) a few fine streaks running through the crystal in different directions, or

(iii) a combination of both these features. D180 shows both these features in a very striking way, *viz.*, a central bright patch with fine streaks running out in different directions. D181 is a fine example of a diamond showing a fairly uniform weak X-ray reflection, which is overlaid by a set of intensely reflecting parallel streaks. All the diamonds not mentioned under class (A) or (B) may be included in this class.

5.   *Interpretation of the Topographs*

The interpretation is somewhat simplified on account of the fact that the classification in the preceding section also follows the classification that one would make considering the other properties of diamond. Thus, the diamonds in class (A) are weakly blue-luminescent, are opaque to the ultra-violet, and show no noticeable birefringence. They must therefore belong to the tetrahedral variety, and the extent of interpenetration of the two types Td I and Td II must be uniform throughout these specimens, as is shown by the uniform intensity of their luminescence. The mosaic structure in these diamonds must be on an extremely fine scale, showing no gross variations in the structure.

Diamonds belonging to the class (B) are transparent to the ultra-violet upto 2250 Å.U., are non-luminescent and show an intense birefringence, the

restoration under crossed nicols consisting of a large number of parallel streaks, related to, but not necessarily identical with, those in the topograph. It is clear, therefore, that they are purely of the octahedral type, in which the intense reflection arises from the fact that the two modifications Oh I and Oh II interpenetrate. The fact that the intensity is not uniform, but that the topograph exhibits parallel bands of intense reflection shows that the extent of interpenetration of the two structures is variable.

Diamonds belong to class (C) exhibit the properties of both the above classes. In fact, they are mixtures of the two structures, part of them being of the octahedral type, and the remainder of the tetrahedral. The mixing of the two types may occur in different ways. The whole diamond may consist of the tetrahedral type, and a few streaks of the other type may intrude into it. In this case, the intrusions alone will give a strong X-ray reflection, while the rest of it will be very weak. On the other hand, there may be an intimate mixture of the two types on a rather fine scale. It is not then possible to detect it by X-ray methods alone. Here, it may be pointed out that an intense X-ray reflection given by a portion of a diamond may mean one of two things—either it may be due to an increased interpenetration of the Td I and Td II structures, or it may be due to the presence of the octahedral structure.

The results obtained from the X-ray topographs confirm, and are confirmed by, those from the other patterns. First, we shall take up the evidence of the luminescence patterns. As already said, D36, D45 and D221 exhibit practically uniform fluorescence over their body, as is to be expected from their X-ray behaviour. D180 shows an intense central triangular region in the X-ray topograph, and this beautifully corresponds with a similar bright region in the luminescence photograph. A few bright streaks running in various directions are also seen in the topograph in addition. These are presumably due to the intrusion of the octahedral diamond, and are not shown by the luminescence pattern, although they are revealed by a spectroscopic study of the light transmitted by the various parts of the diamond. The topograph of D38 shows a few streaks brighter than the surrounding, but these correspond to dark regions in luminescence, showing that they are streaks of the octahedral diamond. A similar relation exists between the two patterns of D188. This diamond exhibits an intensely blue-fluorescing region at its centre, which is surrounded by a feebly blue-fluorescing background traversed by yellow bands running in various directions, and forming a figure similar to that of a spider web. In the X-ray topograph, the central portion shows itself as an intensely reflecting region.

The portions corresponding to the yellow bands also come out as bright streaks, showing that they arise from the intrusion of the octahedral strcture.

In the ultra-violet transparency patterns, the transparent and consequently bright portions in the pattern are of the octahedral type, while the opaque portions must contain the tetrahedral structure. D235 is a fine example of a mixed type, in which the top semi-circular portion, and one of the bottom corners show transparent patches, while the rest is mostly opaque to the ultra-violet. The X-ray picture confirms this, since the same two portions give more intense reflections than the rest of the diamond. The other parts of the picture are however crossed by a few bright bands, showing that these portions are not purely of the tetrahedral structure. Another interesting example of the correlation between the ultra-violet and the X-ray patterns is that of D188, already described, whose ultra-violet pattern also shows transparent bands surrounding the centre of the diamond.

Intrusions of the octahedral variety in the other type will clearly set up strains, and give rise to birefringence. Hence, the X-ray topographs of the mixed type of diamonds must show some similarities to the birefringence pattern. One of the finest examples is that of D181, which shows practically uniform blue fluorescence, but in which a few faint yellow bands could be seen only with difficulty. The presence of these streaks of octahedral diamond is, however, clearly demonstrated by the X-ray topograph in which they reveal themselves as a set of bright parallel streaks. The birefringence pattern of this diamond shows features remarkably corresponding to those in the X-ray patterns, and thus confirms the finding of the latter. So also, the two patterns of D179 show a very close similarity. In the topograph of D174, there is a bright central region, surrounded by a bright boundary in the form of an irregular pentagon. In the birefringence pattern of the diamond, the same figure is visible, and outside it, there are a number of bands parallel to the sides of the figure.

The X-ray patterns of other mixed diamonds are too complicated to be resolved and interpreted. But the case of D195 is interesting. Here, there is a central triangular portion which luminesces strong blue, and corresponding to this, there is also a bright triangular patch in the X-ray pattern. Round this triangle, and parallel to its sides, there are a few bands in the topograph, showing that the octahedral structure is present in these portions. These regions either luminesce green or are non-luminescent.

6. Summary

The paper reports a method by which it is possible to obtain topographic maps representing the variations in the reflecting power for X-rays over the area of a plate of any crystal. The method consists in using white X-radiation diverging from a pinhole, and photographing the Laue reflection from any set of crystallographic planes within the crystal. The distortion, which is inevitable in such an arrangement, can be eliminated by suitably tilting the crystal and the photographic plate. Eighteen such "topographs" of cleavage plates of diamond in the collection of Sir C. V. Raman are reproduced in the plates accompanying the paper. A discussion is given of the relation of these to other patterns, such as the luminescence, ultra-violet transparency and birefringence patterns of the same diamonds. It is shown that the evidence of these corroborates and supports that of the X-ray topographs, and that the increased intensity of X-ray reflection arises out of the mosaic structure produced by the interpenetration of the various possible structures of diamond.

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