ON THE PLEOCHROISM OF AMETHYST QUARTZ AND ITS ABSORPTION SPECTRA

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1. INTRODUCTION

IT is well known that the purple variety of quartz, amethyst, is pleochroic: in other words, one of the factors on which its spectral absorption depends is the direction that the vibration in the crystal makes with reference to the crystallographic axes of quartz, *viz.*, the *c*-axis, and the three electrical *a*-axes. On the precise nature of this dependence however, existing data[1-4] appeared to us inadequate—and hence this investigation. The usefulness of such a factual study will be apparent; for any detailed theory of the mechanism of the absorption which gives to amethyst its purple colour, must, of necessity, also explain the observed features of the pleochroism.

2. GENERAL FEATURES

A complete analysis of the pleochroism of amethyst, it might be thought, requires merely a study of the absorption for the vibration-direction along the optic axis, and for one normal to it (regarding the material as non-rotating along directions oblique to the *c*-axis). That the matter is not so simple however, would appear at once on examining an arbitrarily cut section of amethyst.

A characteristic feature of the typical amethyst section-plate, and one that has evoked attention, is the manner of distribution of the colour. The colour is not spread uniformly over the area of the plate but segregated into a number of discrete geometric *sectors*. Examination of an arbitrarily cut section through a polaroid reveals a pleochroism that is truly remarkable; remarkable firstly for the very pronounced contrast not only in the intensity but also in the hue of the colours shown by any one sector, for the two vibration-directions; and secondly in that the pleochroism of the different sectors are entirely dissimilar, though, in general, uniform over any one sector.

With each well-defined segment of colour it is usually possible to associate a rhombohedral face of the main crystal, since such sectors generally show certain well-known characteristics of which excellent illustrations may be found elsewhere.[5-7] Among such characteristics are: proximity of a coloured segment to a natural rhombohedral face, or to a similar 'artificial face' formed by an impurity-plane running within the crystal; the occurrence of triangular or horn-shaped sectors with apices pointing inwards, and bases spanning or turned towards the corresponding rhombohedral faces; the presence, within a sector, of laminations, or of lighter and darker layers of colour, with the plane of the banding appearing parallel to a pair of parallel rhombohedral faces—the face in question being located uniquely by the criterion of proximity, or from an inspection of the grouping of sectors. It would appear then, natural to ask whether any relation connects the pleochroism of a uniformly behaving sector with its associated rhombohedral face.

In describing certain of the pleochroic features shown by an arbitrary section of amethyst, we have refrained from mentioning certain further complications that occur not infrequently; namely the presence even within a sector, of discrete patches of colour showing entirely different pleochroic behaviour, as also of areas of colour with a non-descript, non-uniform pleochroism. The fact is that the pleochroism is dependent not only on the segmental colouration but also on yet another characteristic feature of most amethyst plates, namely, twinning—to a discussion of which we now turn.

The theory that the amethystine colour is in some manner due to the close twinning of the enantiomorphous forms of quartz,[8] had at one time obviously such currency, that 'amethyst' came as much to signify optically twinned quartz, as to denote that purple variety that goes by that name today. Nevertheless Brewster,[9] and later Brauns,[10] reported that the colour was not due to optical twinning—though the latter had at one time held views to the contrary[6,11]; and our observations, to be described later, completely substantiate their conclusions—it being possible to obtain areas of colour with no detectable traces of twinning.

To say that twinning is not the cause of the colour is not to say that it does not affect the colour in any manner whatsoever. For, where twinning—of either the optical or electrical variety—intrudes into, or subdivides a coloured region, the colour and pleochroism at the region of intrusion are observed to be clearly modified. (A case of this sort has, for example, been mentioned by Groth[5].) And this factor must obviously be taken into account in studying the pleochroism.

Broad recognition had been taken, not only of all the general features till now outlined, but of some more. Of these a particularly important property, and one that becomes quite pronounced for the more densely coloured regions, is the invariably present biaxiality of uniformly behaving sectors—a feature which, it has been reported,[12] can be driven away together with the colour by heat. It is in the pleochroism, however, more than in the refractive properties, that the fall from uniaxial symmetry is most complete: for there is in it no general tendency towards diminution, much less towards complete disappearance, as the *c*-axis is approached.[1-3]

3. PRELIMINARY STUDY OF THE MATERIAL

For reasons already indicated, it was necessary, prior to the study of the pleochroism, first to select untwinned areas of colour in which the material of different sectorial species did not overlap, and which could be associated with corresponding rhombohedral faces; secondly to determine the handedness and where possible, the orientation of the positive directions of the *a*-axes in such areas: that the pleochroism depends on these factors being inferred from the complications caused by the incidence of twinning. This section contains merely the particulars of such a preliminary study; and we have thought it fit to describe this study in some detail because of its relevance not only to the topic of the pleochroism, but also to the twinning theory of the origin of the colour mentioned previously.

Those specimens which were in the form of plates were given a weak etch with dilute hydrofluoric acid, preceded by fine grinding of the two surfaces and followed by examination of the gross reflection sheen under a spot-light; the areas of the surface occupied by separate twin members could, in this way, be thrown into relief, and the actual twin-boundaries—both optical and electrical—easily located. While both sectorial as well as extremely patchy twinning patterns are common, the etch technique, in conjunction with optical tests to be described, showed that coloured areas with no detectable traces of twinning occur quite frequently. Most strikingly and impressively indicating that twinning was not a necessary accompaniment of colour—or even of the banding of colour—were two flawless specimens, both nearly a square inch in area, cut from the same crystal, having several discrete coloured segments and with the major area of the plate made up of one untwinned entity.

For roughly basal sections, the positive directions of the *a*-axis in any required sector, was determined by the etch technique—the entire procedure followed being that found described in detail elsewhere.[13] This together with a knowledge of the handedness of the sector yielded by optical study (though indeed, the etch method is capable of giving even *that* information for basal sections) enabled us to find whether the rhombohedral face associated with any particular sector belonged to the primary or the secondary rhombohedron. The result emerged that sectors of both 'primary' and 'secondary' types do occur. We shall find it convenient to refer only to the handedness and 'type' (*i.e.*, primary or secondary) of any sector, omitting mention of the polarity of the *a*-axes, since this, in any case, is got from a knowledge of the first two features. In amethyst material from Hyderabad, from which many of the specimens were taken, it is possible that primary sectors are a rarity, except as lightly coloured zones separating more dense secondary sectors.

Arising from the contrary rotation of the enantiomorphous forms, optical twinning and its disposition in the depth of the material could be studied by the usual optical procedure of examination in white and monochromatic light; for this, the specimen, immersed when not a basal plate, was viewed between polaroids, precisely along the central direction of the optic figure as seen in the *uncoloured* areas. Attention has previously been called to the presence of pleochroism along the *c*-axis, and to the biaxiality of every amethystine sector: in the optical examination, these two conspire to give a somewhat misleading appearance, which can in practice, when the colouration is not intense, be distinguished from the effect due to a colour-boundary being a true twin-boundary. (We may mention, in passing, that the manner in which the twinning boundary, in certain cases, closely follows the colour-boundary is something remarkable.) Mapping of the twinning in contiguous uncoloured areas was in many cases generally useful, *e.g.*, for showing where any twinning shoots from the uncoloured regions might possibly pierce the segment; and where twinning at the colour boundary was absent, such examination was most convenient for determining the handedness of the segment—since the determination of the sign of rotation for uncoloured areas poses no problem.

In the convergent-light figure through an optically untwinned sector, Airy's spirals—formed when right and left material overlap—should be conspicuously absent. The isolation of the convergent light through even a small sector, which is of the essence in such tests, could be done with the aid of a single pocket lens—the eye being kept in a position conjugate to the sector. In an untwinned sector the black isogyres seen with crossed polaroids should not penetrate, as such, into the slightly distorted uniaxial figure shown in light or moderately coloured areas; while when the more biaxial regions were under test, it was similarly verified that by setting one polaroid parallel and the other perpendicular to the axial plane, the isogyre lying in this plane did not pass unmodified through the eyes. The handedness of the sector (adopting the observer's standpoint) is the same as the sense in which the analyser should be rotated for the rings to expand in the former case, and for the eyes to be extinguished in the latter. For thin sections the direct method of determining the handedness of coloured regions will be stated later—the above methods not being feasible.

Certain rare cases occurred where sectors satisfied the tests for twinning described above, and yet did not show absolutely uniform characteristics; these we interpret as due to the difficulty of detecting small traces of twinning—especially of the electrical variety—in the depth of the material, and to the possibility of the overlap of the material of different sectorial types. In any case, uniformity of pleochroism was itself included among the criteria of selection; and we now proceed to give the substance of our observations on coloured areas satisfying these criteria.

4. EXAMINATION OF THE PLEOCHROISM IN PARALLEL POLARISED LIGHT

(*a*) *Absence of uniaxial symmetry*

To avoid any effects connected with the presence of optical activity[1-3] and heterogeneity of the coloured material in the depth of the specimen (Johannsen[14]), it was thought advisable, in the first instance, to investigate the pleochroism at oblique directions to the *c*-axis. Viewed thus, moderately coloured and uncoloured areas showed the same extinction positions between crossed polaroids—the entire material being regarded for our qualitative purposes, as non-rotating along such directions. In consequence the absorption for the various directions of vibration in the optical indicatrix, could be conveniently scanned in the following fashion. (And it is to be implicitly understood that throughout this section all description of pleochroic behaviour refer to observations made with the arrangement to be now described—with the specimen to be examined kept all the while in an immersion fluid.)

Against the background of an extended source of white light a polaroid was set, with its vibration-direction vertical. The direction of sight was kept horizontal. By mounting the crystal—on a suitable contraption—with its *c*-axis always in the plane defined by these two directions, the vibration of the incident light lay automatically always on a principal plane. The optic axis could first be set at any desired inclination to the vertical by tilting the specimen about a horizontal axis perpendicular to the line of sight; the specimen could then be taken through a complete revolution about its own *c*-axis—a suitable arrangement being made for performing these two operations.

Any provision for the last operation—which shows the absorption as the vibration is taken over a cone of directions described about the *c*-axis—would be superfluous for an absorbing system having uniaxial symmetry. This however is what amethystine sectors do not possess. Not only does the colour of any one sector not remain constant as the specimen is so rotated; a rotation of 180° may in general leave the colour profoundly altered, showing that the *c*-axis cannot even be a diad axis of symmetry as far as the pleochroism is concerned. To stress these points we refer briefly even at this stage to Figs. 1 and 2 in Plate XI, which show the respective wedge-type spectrograms for two vibrations both inclined at 45° to the optic axis of the quartz and both lying in a plane containing this axis. The large difference in the colour of the sector for these two polarizations (Fig. 1—deep red; Fig. 2—clear blue) is reflected in their dissimilar absorption spectra.

(*b*) *A relationship between sectors*

It would next be necessary to see whether any relation holds between the pleochroism of different sectors, before observations on a single sector can have much significance. The loss of trigonal symmetry suggests that the different observed species of pleochroism perhaps correspond to different possible orientations (with respect to the crystallographic features of quartz) of the same non-uniaxial absorbing system.

Those plates having two or three sectors of the same handedness, but associated with adjacent faces of either the primary or the secondary rhombohedron, were examined in polarized light in the arrangement described above. Independent of the tilt of the *c*-axis, it was found that on rotating the specimen about this axis, such adjacent sectors went through the same cycle of colours, but with a 'lag' of 120°—which caused them to appear differently coloured at any one setting. The angle was arrived at in the case of specimens with two such sectors by noting the position at which each sector went through a particularly notable colour change in the cycle; and more accurately for the triple-sector plates by noting the successive azimuths at which the different pairs of adjacent sectors (selected in cyclic permutation) showed a matching of the hues within the pair. The point to note is that the pleochroism of sectors of similar handedness and type (*i.e.*, primary or secondary) bear the same relation to their reference rhombohedral faces. For the vibration along the optic axis the sectors, as may be expected, are identically coloured. This is also the case when the specimen is viewed along the optic axis in unpolarized light.

(*c*) *Existence of a symmetry axis*

The existence of any element of symmetry for the absorption characteristics of a single sector cannot *a priori* be assumed; but if a symmetry axis does exist then any two vibration-directions in the (roughly uniaxial) optical indicatrix which are related by a rotation of 180° about this axis are equivalent as far as the absorption in that sector is concerned. Detection of such equivalence, involving as it does the comparison of the colour of a sector for two entirely different orientations of the specimen, would be difficult if attempted directly. But the absorbing system is effectively present in several different orientations on the same plate—in the form of several sectors; so that we may be led to significant conclusions if we attempt to find the loci of vibrations for which two sectors are identically coloured.

When comparing the pleochroism of adjacent sectors of similar handedness and type, by the method described, we referred to the equality in the colour-tone attained by any two such adjacent sectors at certain azimuths during the rotation: these occurred at positions 180° apart. Set at one such azimuth, a tilting of the specimen about the horizontal axis normal to the line of sight, or the turning of the polarizer to a perpendicular position, altered the hue of the two sectors together without destroying their match. In other words: for the vibration normal to a particular plane A containing the optic axis, as also for any vibration lying in this plane, the two sectors are identically coloured. (To fix our ideas, we may remark that the plane A turns out to be normal to one particular *a*-axis of quartz.) Remembering that the second sector is simply in that position which the first would occupy when rotated by 120° in, say, a clockwise sense, it should be possible to transform the above statement to one involving the first sector alone. So let us draw a plane B, got by rotating A in the opposite sense (anti-clockwise) by 120°, about the *c*-axis. Then we can say: the two vibrations normal to A and B, as also any two vibrations which lie respectively on A and B and are related by a 120° rotation about the *c*-axis, are equivalent as far as the absorption in the first sector is concerned. If—though the above statement is only qualitative—we regard this equivalence as the expression of a symmetry element possessed by that sector, we may derive a further conclusion; for, any two vibrations of the type described are related to one another only by the following possible operations: (*a*) reflection across a plane C bisecting the obtuse angle between A and B; (*b*) a rotation by 180° about the normal to such a plane; (*c*) a rotation of 120° about the optic axis. And since the pleochroism is not in conformity with trigonal symmetry, the absorbing system in the sector has, qualitatively speaking, a plane of symmetry C, or a digonal axis of symmetry normal to such a plane, or both. (It is not possible to distinguish between these cases, insofar as we consider, for our qualitative purposes, that the two waves propagated without change of form in any direction oblique to the *c*-axis, are plane-polarized and thus have no handedness or sense.)

The symmetry axis of the sector (as we shall henceforth call the normal to the plane C) was found qualitatively to coincide with one of the crystallographic *a*-axes of quartz: and this *a*-axis passed through one corner of the rhombohedral face associated with the sector. (These conclusions followed from the fact that the plane A—whose azimuth could be placed to within 15°—was normal to a rhombohedral face associated with one of the two adjacent sectors concerned.)

The existence of the symmetry axis for the pleochroism of any sector received confirmation in the following manner. Two basal plates each with one large sector were mounted side by side, in the first instance with their triangular sectors in parallel orientation and with their *c*-axes in line, in such a fashion that the two sectors were checked to show the same pleochroism at all tilts (confined to oblique directions to the *c*-axis). One of them was then turned over by rotating it through 180° about the axis expected to be the symmetry axis of the sector concerned. The two sectors still showed identical pleochroism at all orientations.

5. THE 'TRICHROIC COLOURS' AND THEIR ABSORPTION SPECTRA

We have seen that one axis of the absorption-ellipsoid for any wavelength in the visible coincides with, or at least does not disperse far from, an *a*-axis of quartz passing through a corner of the rhombohedral face associated with the sector. The absorption for vibrations on a plane perpendicular to this—on which the other two axes of the ellipsoid are constrained to disperse—could be examined in the following way: keeping the plane of the incident vibration horizontal, the sector could be tilted about its symmetry axis, after setting this vertical and normal to the line of sight. It was then found that two vibrations on this plane both inclined at 45° to the *c*-axis (β and γ in Fig. 1) represented the rough regions of two extremal positions of the colour intensity. For one of these vibrations the absorption was most intense, and the colour in artificial illumination, a very deep red (with perhaps a tinge of purple)—the corresponding wedge-type spectrogram, illustrated in Fig. 1 in Plate XI, showing an absorption maximum in the neighbourhood of 5250 Å. For the other vibration the colour was blue and the absorption maximum, as may be seen from Fig. 2 in Plate XI, was near 5750 Å. Fig. 3 in the same Plate (obtained at the

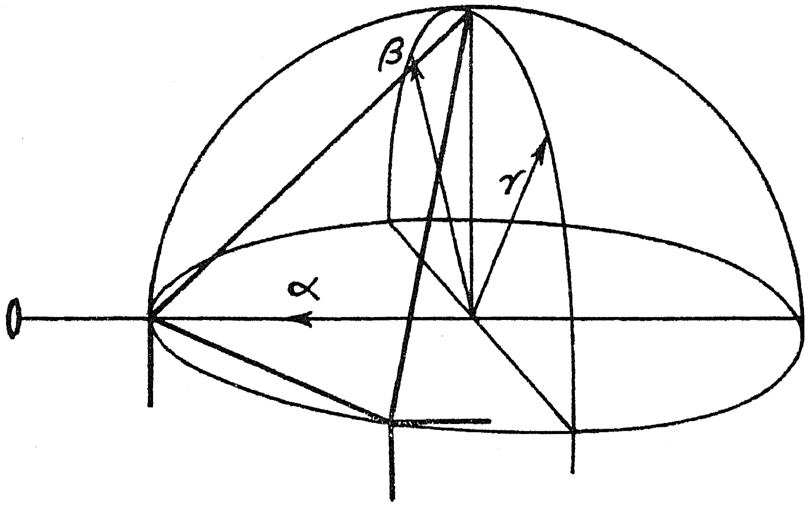

FIG. 1

latter tilt by turning the polarizer to a perpendicular position) gives the absorption spectrogram for the vibration along the symmetry axis α, for which the colour was a light orange. This represents the least absorbed vibration-direction (especially to the eye, transmitting, as it does, the yellow-green wave-lengths of high visual luminosity), the absorption maximum occurring in the region of 5000 Å. For this last case, the apparent position and intensity of the absorption are perhaps slightly modified by the dip in that region of the spectral sensitivity of the photographic plates used (Ilford HP. 3). This may be seen from Fig. 4 in Plate XI which gives the direct spectrogram taken with the tungsten lamp illuminant and the glass optics used.

We should not be taken as implying that two directions both inclined exactly at 45° to the *c*-axis and in a plane normal to the symmetry axis α, are true axes of the absorption ellipsoid for all wave-lengths in the visible. If they were so, there would be (for practical purposes) no pleochroism in evidence when viewed along the diad axis of symmetry; the pleochroism, however, did not appear to be absent in this direction when a rough test was made.

Regarding the absorption spectrograms—which were taken by giving successive strips along the length of the slit, exposures increasing by a constant multiplying factor of 2·25—we may mention a few relevant experimental points. A Foucault's prism was used for polarizing the light. The specimen was immersed in water, and a rough allowance for refraction was made when tilting the plate. The section used being, roughly speaking, basal, the depth of the material traversed for the tilt corresponding to

Fig. 1 was only slightly larger than that for the tilt corresponding to Figs. 2 and 3 in Plate XI; the region of the very intensely coloured secondary sector that was used, was of larger area than the incident pencil of light; also the processing conditions in all three cases were roughly the same. These conditions being so, the fact that the exposures for the strips in Fig. 1 were 30 times (roughly), those for the corresponding strips in Figs. 2 and 3, serves to further emphasize the relatively great intensity of the band for the deep red 'axis of absorption'.

6. Observations in Convergent Light

Very intensely coloured untwinned sectors when viewed in unpolarized light roughly along the *c*-axis and tilted about in various directions, display such violent and rapid changes in the depth and hue of the colour, that the use of convergent light for studying the associated phenomena is immediately suggested. When this is done, an idiocyclophanous figure stands revealed.

In an optically inactive biaxial medium the reason why an idiophanous figure can be seen in the neighbourhood of an optic axis, if the pleochroism there is very pronounced, is well known. Roughly we may say, that for any direction the incident unpolarized light is split into two linear vibrations (as determined by the refractive index ellipsoid) the respective absorptions of which are determined by their intercepts on an absorption ellipsoid; in the neighbourhood of an optic axis, a small change in the direction of propagation, by causing an appreciable change in the inclinations of the two principal planes to the axial plane, will in general lead to a large variation in the total absorption—thus enabling an idiophanous figure to be seen. This generally takes the form of a dark brush interrupted by a bright spot in its passage through the optic axis. Further if the section of the absorption ellipsoid normal to that optic axis, has its principal diameters lying in and perpendicular to the axial plane, the dark brush occurs in the same position as would the isogyre of the biaxial interference figure when seen in 'the 45° position'.

The idiophanous figure in amethyst is illustrated in Fig. 5 in Plate XII. Diverging from the neighbourhood of the *c*-axis are four dark purplish brushes set against the lighter background of an orange coloured cross. By viewing in parallel light along the directions corresponding to these brushes, it is seen that in reality two of the brushes on one side of the thinner arm of the orange cross are of a somewhat reddish-purple colour, the other two being more bluish-purple. The entire figure is therefore in conformity with the existence of an axis of symmetry lying parallel to the thinner arm of the cross, which is also found to be roughly coincident with an *a*-axis passing through a corner of the associated rhombohedral face—thus illustrating our previous findings in a simple manner. Similarly on moving over to an adjacent sector, the figure is rotated round by 120° (it being understood that the sectors are of the same handedness and type and are associated with alternating faces of the hexagonal pyramid).

Viewed between polaroids, such dense sectors are seen to be pronouncedly biaxial (Fig. 6 in Plate XII). The *c*-axis is, qualitatively speaking, the acute bisectrix, and the axial plane is found to contain the symmetry axis of the sector. The isogyres in the 45° position correspond roughly to the brushes seen in unpolarized light. The idiophanous figure, therefore, consists in reality of two hyperbolic brushes each interrupted in its passage through a corresponding optic axis—thus giving the intervening space the appearance of a cross in which one arm is thinner than the other.

The broad features of the phenomena observed in the vicinity of an optic axis of an optically inactive pleochroic medium can be fairly well explained even on neglecting the ellipticity of the two waves propagated without change of form in such directions (*vide* Pockels,[15] Drude[16]). We find empirically that the main features of the idiophanous figure in amethyst can be accounted for, on neglecting, also, the presence of optical rotation. Thus for any direction along the lightly coloured cross, though the vibration normal to the diad axis of symmetry is very strongly absorbed, the other half of the incident light emerges without much attenuation, and is coloured orange and polarized with its vibration roughly parallel to the diad axis. While, the large total absorption for directions along the brushes is because here *both* vibrations (being inclined at roughly 45° to the symmetry axis) have moderately strong and roughly equal absorption coefficients—intermediate between that for the symmetry axis, and for a vibration normal to it and the *c*-axis.

On inserting a polaroid with its vibration-direction perpendicular to the axial plane, the orange interspaces are practically suppressed, and replaced by a very deep purple cross set against a somewhat lighter purple background—which is exactly what should be expected. (It is in fact this purple cross which gives the appearance of being black isogyres in Fig. 6 in Plate XII, though this was taken with parallel polaroids.) Following one arm of the purple cross either way in the plane normal to the diad axis of symmetry, one is led to the blue and deep red ‘ axes of absorption ’ mentioned in the previous section. On the other hand, when the polarizer is in the perpendicular position, the idiophanous figure is broadly unaltered, but with the contrast very considerably increased, since no longer is half the incident light almost completely suppressed for the directions along the arms of the lightly coloured cross.

Such observations with a single polaroid afforded a ready and convenient means of locating the axis of symmetry for sectors with moderate and uniform colouration—for which insufficient depth of absorption prevented the idiophanous figure from being directly seen. The features observed were essentially the same, though present in a less contrasted scale, as those described in the previous paragraph. The two orientations of the polaroid for which the resultant figure produced was *symmetrical* with respect to its vibration-axis gave the symmetry axis of the sector, and the direction normal to it and the *c*-axis. In such tests, uniformity of the colouration along the depth of the material was apparently of the essence. For in many lightly coloured areas it was common to find optic interference figures showing up with a single polaroid, apparently because the medium there could not be regarded as constituting a single optical phase. But even in such regions the pleochroism at directions oblique to the axis became a constant and characteristic property.

Viewed between crossed polaroids set along and perpendicular to the diad axis, the slightly distorted uniaxial figure in light and moderately coloured areas, appeared symmetric with respect to these directions. (When the section was thin the cross at the centre was not absent—only nebulous; the sense of rotation when required was opposite to that in which the analyser should be turned from this crossed position, for the cross to open out into four spots.)

The fact that both the pleochroism and the biaxiality had, qualitatively speaking, a common axis of symmetry suggested that the presence of birefringence along the *c*-axis could be traced to the presence of pleochroism along the same direction. The contribution of the pleochroism in the visible to birefringence could be detected in certain oblique sections. A plate which roughly contained the symmetry axis of a particular sector as well as its deep red 'axis of absorption', illustrated this fairly well. The section was kept in front of the slit of a spectrograph between two polaroids both inclined at 45° to the principal planes, such that the upper half of the spectrum in Fig. 7 in Plate XII was illuminated through the moderately coloured sector, and the lower half through the contiguous uncoloured quartz. The interference bands channelling the spectrum, indicate as may be expected, a slight increase of the positive birefringence on the longer wave-length side of the absorbing regions, and a decrease at shorter wave-lengths. For this particular orientation at any rate, no change from the birefringence of quartz, other than that due to the band in the visible can be seen. Nevertheless the biaxial interference figure did not give any definite indication of crossed axial plane dispersion; for when the figure in one particular sector was examined successively through an orange and a blue filter, the biaxiality was seen to be pronounced in the former case, but relatively feeble in the latter—which is more indicative of a progressive diminution of the axial angle towards shorter wave-lengths. *Apropos* of this, we may remark that, on comparing the spectrograms reproduced as Figs. 2 and 3 in Plate XI, a distinct indication of pleochroism in the ultra-violet band is in evidence.

7. FACTORS FIXING THE PLEOCHROIC ORIENTATION

We may recall that the dependence of the pleochroism on two features—namely the handedness and ‘type’—of any sector, has as yet not been clarified. When this is done, it is found that our qualitative picture of the pleochroism of any sector is completely fixed in terms of the associated rhombohedral face.

Looking from above the apex of the quartz pyramid, the symmetry axis of any sector was found to pass through the left or anti-clockwise corner of the associated rhombohedral face, when the sector was left-rotating; and *vice versa*. So that Fig. 1 is drawn correctly only if the sector happens to be right-rotating. This relation was found to hold for both primary and secondary sectors.

Again, the deep red position of the vibration was more oblique to the normal of the associated face than the blue, in the case of the primary sector; and *vice versa*, for a secondary sector. So that in Fig. 1 in the text, it is the vibrations in the vicinity of γ (and not of β) that are deep red if the associated face belongs to the secondary rhombohedron. If, therefore, the rhombohedral faces associated respectively with a primary and a secondary sector, both of the same handedness, are kept in parallel orientation, the two absorbing systems would be related to one another by a rotation of 180° about the *c*-axis.

8. THE RELATIONSHIP BETWEEN THE PLEOCHROISM OF DIFFERENT SECTORS

Arising from the dependence of the pleochroism on twinning and the sectorial property, various possible relationships between the pleochroism of different sectors on the same plate may be envisaged, and were in fact met with. Three of these, the explanations of which may be got from a little consideration of our findings in the previous section, may be mentioned.

A right- and a left-rotating sector associated respectively with two adjacent faces of either the primary or the secondary rhombohedron, will have their symmetry axes either in line or inclined at 60°, depending on their mutual orientation. In a case of the former type, the pleochroism of both sectors were found to be identical at all tilts (confined to oblique inclinations to the *c*-axis). This was also true for a case where two sectors of complementary type had occurred on the same plate—by itself, a rare feature—the two being of the same handedness but associated with diametrically opposite faces of the hexagonal pyramid. In the third instance to be mentioned, a Dauphiné twin-boundary had cleft a coloured area in two; the two halves, though of the same handedness, were naturally of complementary types, so that their pleochroism were different; but, for all tilts it was only the colour for the 'extraordinary vibration' that differed, that for the vibration normal to the *c*-axis being identical in both the regions. These three cases involving as they do, a judging of the identity of two colour tones, lend support to our general interpretation of the remarkable pleochroism of amethyst quartz.

In concluding, the author wishes to record his deep sense of indebtedness to Prof. Sir C. V. Raman, for constant guidance and encouragement throughout the course of this investigation.

9. SUMMARY

Amethyst is optically biaxial, and does not conform to the trigonal symmetry of colourless quartz, though the *c*-axis appears as the acute bisectrix in its biaxial figure. The pleochroic and biaxial properties taken together conform only to a symmetry of the monoclinic class, the axis of symmetry being coincident with one of the electrical axes of the colourless quartz in which it appears. For vibrations along this axis, the colour of the transmitted light is light orange (absorption maximum near 5000 Å); while for the two vibrations in the perpendicular plane which make approximately 45° on either side with the *c*-axis, the colours are respectively, blue (absorption maximum near 5750 Å), and a deep reddish-purple (absorption maximum near 5250 Å).

Which of the *a*-axes of quartz is the symmetry axis of amethyst is determined—in relation to the particular rhombohedral face with which the colour-sector is associated—by the right- or left-handedness of the segment; while the disposition of the other two colour axes with reference to the

associated face depends on whether this belongs to the primary or the secondary rhombohedron. Hence, the presence of any twinning naturally complicates the pleochroism.

Photographs are reproduced illustrating (*a*) the absorption spectra for the trichroic colours; (*b*) the idiophanous and biaxial figures seen through dense sectors in convergent light (the optic axial plane containing the symmetry axis); and (*c*) the anomalous dispersion of the birefringence.

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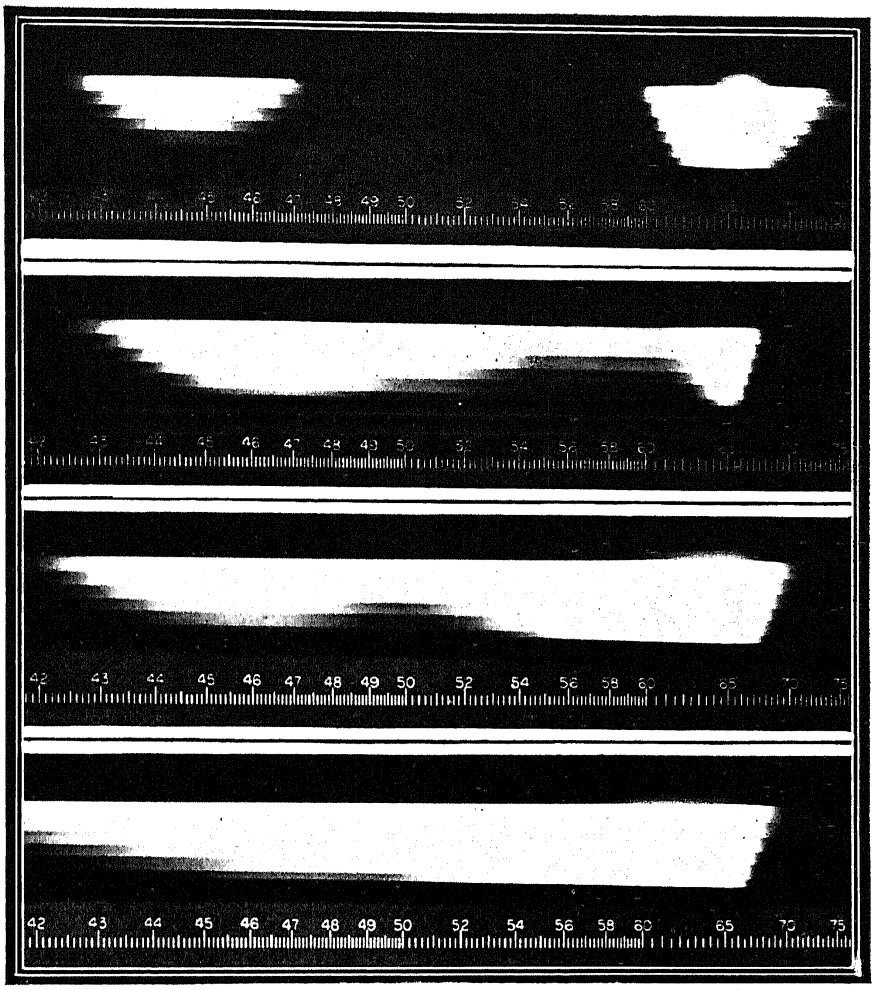

FIG. 1 Deep Red

FIG. 2 Blue

FIG. 3 Orange

FIG. 4 Incident Light

Absorption Spectra of Amethyst