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Some observations on pleochroism and idiophany in mineral plates.

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Contents.

1. General remarks.

In this paper an attempt is made to state and explain, in a simple manner, the essential features of the phenomena which are seen when plates of pleochroic minerals are examined in ordinary light.

The pleochroic effects exhibited by minerals are usually studied in light of practically normal incidence. For the observation of facial colours, transparent crystals, or, better still, specially orientated cube-shaped pieces of minerals, are examined in ordinary light. In general, by this mode of observation, only facial colours are seen when ordinary light is used, and for the observation of axial colours[1] the incident light must be polarized.

It is otherwise if the plate be examined in light of oblique incidence; since in this case the transmitted portion of the light may be effectively polarized by the plate itself as a result of reflection and refraction. In consequence of this, under certain conditions, axial colours may predominate when the plate is examined in ordinary light; and interference effects may in some cases also be seen.

A thorough treatment of this subject of the pleochroism of plates in ordinary light, on a practical basis, would necessitate the examination of a large number of choice specimens of coloured minerals, carefully cut in various ways. On account of the scarcity and expensive nature of such specimens, the writer has not been able to get much variety of material for study; and in presenting the few observations on the subject which are contained in this paper, he does so without any pretence at exhaustive treatment. His chief aim is to show that, by considering the behaviour of plates in ordinary parallel rays of oblique incidence, and by correlating this with the behaviour of plates in a convergent beam, the latter is more easily understood. Moreover, by treating the subject as a whole in this way, the phenomena of pleochroism in ordinary light assume a form far more varied and interesting than that in which they are usually presented; and their observation in some cases is a matter of extreme simplicity.

In what follows it is assumed that the observer will take care to see that the light used is not appreciably polarized or analysed by any agency other than that of the surface of the plate itself and cleavage surfaces parallel to it.

2. Factors to be considered.

The explanation of the phenomena displayed by pleochroic plates in ordinary light involves the consideration of several factors, which may with advantage be stated at the outset. Of these factors, the following may be regarded as of chief importance, and perhaps sufficient to explain the effects observed.

[1] In this paper, the phrase 'axial colour' is used in the wide sense as meaning a single-ray colour in a doubly-refracting crystal.

(1) *Variation of absorption with change of direction.* In anisotropic minerals the absorption is generally different for different vibration-directions. Hence the colour of these minerals, when examined in ordinary white light, generally varies with the direction of transmission of the rays. For some directions this variation is so slight that no appreciable pleochroism results from a change of direction of the ray over a considerable angular distance. For other directions it is so pronounced that a slight variation in the direction of transmission may cause a striking change of colour.

A good example of a direction of transmission in the near vicinity of which the change is very sudden and striking, is an optic axis of a pleochroic biaxial crystal, the least deviation from which, except in the optic axial plane, is accompanied by an effective change in colour.

It is otherwise with the optic axis of a uniaxial crystal, which, unlike that of a biaxial crystal, is usually an axis of optical symmetry.[1] The vibration-changes accompanying deviations in the near vicinity of such an axis are of the same order as those which accompany change of direction in the axial planes of a biaxial crystal, and are characterized as a rule by a slow and gradual rather than a sudden change of colour.

(2) *Absorption-polarization,* usually produced when light traverses a pleochroic crystal along a direction of double refraction. The colour seen along such a direction in ordinary light is called a facial colour; and a plate yielding such a colour generally acts to some extent like a polarizer, its efficiency in this respect depending upon the difference between the amounts of absorption represented by the two axial colours of which the facial colour is composed. The emergent light corresponding to a facial colour may thus be regarded as partially plane-polarized, the plane of polarization coinciding with that of the least-absorbed ray. This phenomenon of partial polarization is exhibited in some degree by all pleochroic minerals, and is so frequently met with in pleochroic plates that it may be conveniently referred to in a general way as polarization by absorption.

Tourmaline is a familiar and extreme example of this; but tourmaline itself is very variable, and several other strongly pleochroic minerals are for some purposes quite as effective: e.g., penninite, biotite, and andalusite.

The longer the path of the ray in a pleochroic plate, the more pronounced is the absorption-polarization. In the extreme case illustrated

[1] The behaviour of amethystine quartz (p. 12) appears to indicate that, as regards absorption, this is not necessarily the case for all uniaxial crystals.

by dark tourmaline, the limiting thickness beyond which the facial colour becomes identical with the least-absorption axial colour, in consequence of the complete absorption of the ordinary ray, is quite small. But in many other minerals this limit is approximated to in fairly thin plates.

These considerations bring out a fact connected with absorption-polarization which is especially worthy of note; viz., that facial colours which are compounded of the extreme axial values in a strongly pleochroic plate approximate closely to the least-absorption axial value. This fact is of considerable importance in the explanation of absorption-figures, as we shall see later.

(3) *Reflection-polarization* which takes place in consequence of the fact that, for obliquely incident rays, the vibration-components parallel to the plate are partly lost by reflection, and the vibrations of the transmitted rays contain an excess of the components lying in the plane of incidence. We may therefore regard the transmitted refracted ray as partially plane-polarized, with its plane of polarization at right angles to the plane of incidence. This effect is inoperative for rays of normal incidence, and reaches its maximum for rays incident at the polarizing angle.

Experiment to illustrate the operation of absorption- and reflection-polarization in the same plate.

The operation of factors (2) and (3) can be shown conveniently by brown phlogopite, cleavage plates of which usually show a well-marked biaxial character, and exhibit the characteristic reddish-brown and greenish-grey axial colours. If a basal section of calcite two or three millimetres thick be placed between two such plates of phlogopite, and held close to the eye, a good uniaxial figure is observed, the crossed nicols effect being observed when the like axes are at right angles, and the parallel nicols effect when they are parallel. Now let the arrangement be such that, when the crossed nicols effect is obtained, the vibration-direction of least absorption lying in the plate adjacent to the observer is placed vertically, whilst that in the plate remote from the observer is placed horizontally; and let the latter plate be turned about this horizontal directioninto an oblique position. It will be found that, when a certain angle has been passed, the crossed nicols effect gives place to that for parallel nicols.[1]

[1] The best way to do this experiment is to cement the calcite section to one of the plates of phlogopite, as this facilitates manipulation.

The first part of the experiment is equivalent to the use of a tourmaline pincette arrangement for observing a figure in convergent polarized light, and illustrates absorption-polarization, which, as already mentioned, generally accompanies a facial colour. The second part of the experiment, which cannot be performed with similar results in the case of tourmaline, for reasons which will appear later, is clearly understood as a consequence of polarization by reflection and refraction. We may explain the whole experiment briefly as follows: When the plate of phlogopite is held with its face at right angles to the line of sight, the transmitted light is partially polarized, the plane of polarization coinciding with that of the less-absorbed ray. If, therefore, we place the vibration-direction of maximum absorption (𝔟 axis) at right angles to the plane of incidence, the plane of polarization of the transmitted light remains unchanged when the plate is tilted into an oblique position, since the vibration-directions of the refraction-polarized rays lie in the plane of incidence and all the directions lying in this plane are directions of weak absorption. If, on the other hand, the axis of maximum absorption be placed vertically, i. e. in the plane of incidence, the reflection-polarization effect militates against the absorption-polarization effect when the plate is tilted, the former predominating when a certain angle has been passed, and the plane of polarization consequently moves through 90°.

Either of the plates can be tilted, and if the experiment be repeated with the axes of the mica plates in different relative positions, it will be observed that the figure only changes when the axis of maximum absorption in the tilted plate is lying in the plane of incidence.

3. Classification of pleochroic plates.

The behaviour of pleochroic plates in ordinary light depends essentially upon the nature and disposition of the absorption axes in relation to the face of the plate. Thus, all the vibration-directions lying in the plate may have the same absorption value; or this value may vary with the vibration-direction between two extreme values. In either case the absorption for vibration-directions at right angles to the plate may be stronger or weaker than for those lying in the plate. For our present purpose, we may conveniently restrict our attention chiefly to plates containing the chief absorption axes, and classify them simply as follows:—

Case I.—Plates in which there is no variation of absorption for rays whose vibration-directions are parallel to the face of the plate; e.g. basal sections of uniaxial minerals.[1]

(*a*) Ordinary ray more absorbed than extraordinary.

(*b*) Extraordinary ray more absorbed than ordinary.

Case II.—Plates in which, for rays whose vibration-directions are parallel to the face of the plate, the absorption varies with the direction of vibration; e.g. principal sections of uniaxial minerals, and axial sections of biaxial minerals.

(*a*) Absorption comparatively weak for vibration-directions at right angles to the plate.

(*b*) Absorption comparatively strong for vibration-directions at right angles to the plate.

The adoption of these sub-divisions will facilitate the treatment of a few examples illustrating the operation of the above-mentioned factors. Special attention will be given to biotite and phlogopite, cleavage plates of which are readily obtained and afford good material for study. In what follows we shall, for the sake of brevity, refer to the sub-divisions as Cases I (*a*), I (*b*), II (*a*), and II (*b*).

4. Behaviour of pleochroic plates in parallel rays.

Case I (*a*).—The readiest examples of this case are black 'uniaxial' biotite and green penninite, which are easily obtained in good cleavage plates. In these there is practically only one absorption value for rays whose vibration-directions are parallel to the cleavage. When such a plate is held at right angles to the line of sight, we see the axial colour due to the absorption of the ordinary ray. When the biotite is tilted into an oblique position, one usually sees little or no change, unless the plate contains numerous cleavage rifts. Basal plates of tourmaline act much in the same way. This is contrary to expectation. The absorption of the extraordinary ray in sections normal to the base is so comparatively small in biotite and tourmaline that one might expect a considerable diminution of absorption on tilting a basal plate. In penninite, the expected change takes place, the green axial colour for the ordinary ray giving place to a yellowish-green facial colour.

The optic axis in black biotite and tourmaline is a line of transmission in the vicinity of which there is no perceptible change of absorption with

[1] Many biaxial minerals, e.g. amazon-stone and black biotite, are practically 'dichroic' and are capable of yielding plates which act pleochroically much like basal plates of uniaxial minerals.

change of direction. In the above observation it should be noted that the length of path increases with the angle of incidence, and that the ordinary ray is to some extent impoverished by reflection-polarization; though these factors in this case appear to be relatively unimportant.

The pseudo-pleochroism of certain micas.—An interesting case of pseudo-pleochroism may be considered here, viz., that provided by a variety of so-called silver-mica which owes its silvery sheen to the presence of numerous cleavage rifts which overlap each other and reflect the light copiously.[1] If such a plate of mica of suitable thickness, say 0·5 mm. or so, be held with its face at right angles to the line of sight, it will be found to be opaque or only feebly translucent. On tilting the plate into an oblique position it becomes more transparent, the degree of transparency gradually reaching a maximum and then diminishing as the plate approaches the horizontal position. The fact that these plates show a greater degree of transparency when held obliquely, in spite of the apparently greater thickness which the light has to traverse, is not due to pleochroism. It is, indeed, best seen in the colourless silvery phlogopites which show practically no pleochroism; and moreover, we have just seen that in the case of black biotite, which is intensely pleochroic, the expected increase of transparency on tilting does not occur.

The phenomenon[2] is due to the action of the cleavage rifts, which overlap extensively and act as do the air-films in a 'pile of plates'. Ordinary light rays of normal incidence are more copiously reflected by a pile of clear transparent plates than are obliquely incident rays. This seems paradoxical when we consider the fact that for a single plate the oblique rays suffer more reflection than do those of normal incidence. The explanation of this property of a pile of plates becomes clear when we examine the pile in polarized light. We then find that when the plane

[1] 'Silver-mica' appears to be generally phlogopite. There are two sorts; one of which owes its sheen to the presence of rod-like inclusions lying along the lines of the pressure- and percussion-figures, the other to the presence of cleavage rifts. The former possesses in a pronounced degree the property of asterism; the latter, with which we are here dealing, shows pseudo-pleochroism. Cleavage rifts and rod-like inclusions may both be present in considerable quantities, but pseudo-pleochroism is not seen when the latter are abundant.

[2] It can be readily reproduced by taking a plate of transparent muscovite and splitting it into a number of plates. When these are superposed, the pile will be found to be practically opaque to normally incident rays if the plates are numerous enough, though it is comparatively transparent to obliquely incident rays.

of polarization coincides with the plane of incidence, the amount of light reflected gradually increases with the angle of incidence, at least up to a certain point. On the other hand, when the plane of polarization is at right angles to the plane of incidence, the amount of light reflected gradually diminishes as the angle increases.[1] Hence ordinary light of normal incidence is more copiously reflected than obliquely incident light, on account of the fact that the latter yields refraction-polarized rays which suffer comparatively little reflection.

The same holds good of the pseudo-pleochroic variety of silvery mica to which we have referred above; it provides a natural and very efficient pile of plates, and transmits with comparative readiness the refraction-polarized ingredient of an obliquely incident ray, whereas it is relatively opaque to rays of normal incidence. Doubtless, however, absorption plays some part in making the silvery mica so effectively opaque to normally incident rays; though the evidence available shows clearly that the phenomenon is essentially one of pseudo-pleochroism, arising from the presence of cleavage rifts.

Case I (b).—In this case, when the plate is tilted into an oblique position, the increased length of path and the loss of light by reflection-polarization both tend to emphasize the effect arising from increased absorption due to change in direction of the rays. Hence we should expect the change in this case to be more perceptible as a rule than in Case I (*a*).

It so happens, however, that examples of this case are rare among minerals. Magnesium platinocyanide, an artificial substance, the crystals of which are tetragonal, is a frequently quoted example, and should apparently be included here. It provides a good example of rapid change of absorption with change of direction in the near vicinity of the optic axis.

Green microcline (amazon-stone) furnishes an approximation to this case, and since it yields fairly good cleavage plates which can be readily obtained, it is worthy of note as a specially interesting instance some-

[1] This experiment can be performed with a few cover-slips mounted on a stage-goniometer; but it is shown to best advantage with a piece of silvery mica sufficiently thick to be perceptibly translucent to rays of normal incidence. It is necessary that the surfaces and substance of the plates should be free from dust particles, &c. This can be seen by making a pile of cover-slips the surfaces of which have been slightly smoked. Such a pile scatters the refraction-polarized rays, and is less transparent to rays of oblique than it is to rays of normal incidence. A pile of celluloid plates acts in the same way, owing to the fact that celluloid is crammed with dusty inclusions.

what complicated by twinning. Though triclinic in symmetry, amazon-stone is practically 'dichroic' in its pleochroism. In a basal cleavage plate the axis of maximum absorption is obliquely inclined, but the variation of absorption for vibration-directions parallel to the plate is very slight and almost inappreciable; and a basal plate appears practically colourless when examined in transmitted light of normal incidence. Now it may be assumed that the axis of maximum absorption, if not coincident with the $\mathfrak{b}$ axis, is somewhere in its vicinity, and, like it, is inclined to both the faces (010) and (100). The intimate nature of the twinning, however, modifies matters. Thus in the albite-lamellae the axis of maximum absorption is for all practical purposes inclined at equal angles on opposite sides of the plane of composition in adjacent lamellae; hence with regard to this plane (010), the absorption is fairly symmetrical. Consequently, when the basal cleavage plate is tilted in such a way that the edge (001):(010) is at right angles to the plane of incidence, the change from colourless to green is well seen whether the plate be tilted towards or away from the observer, which typifies the action to be expected in Case I (*b*). If the edge (001):(010) be placed in the plane of incidence, a deep green is seen when the plate is tilted in one direction, but the plate remains colourless when tilted in the other direction, due presumably to the one-sided effect of the pericline-twinning.

Case II (*a*).—This case naturally yields a richer variety of effects than is to be observed in the two preceding cases. It includes such examples as basal cleavage plates of brown and markedly biaxial phlogopite, (010) cleavage plates of amazon-stone, and in some instances pink andalusite.[1]

A cleavage plate of brown phlogopite provides an extremely interesting example, in which the factor of paramount importance is the reflection-polarization of obliquely incident rays. As we have already seen in the experiment described on p. 4, if such a plate be held normal to the line of sight and examined in parallel rays, it shows the true facial colour of the plate. When tilted into an oblique position through a sufficiently large angle, and rotated in its own plane, it shows axial colours, chiefly due to the fact that the transmitted light is refraction-polarized. Hence we get the strong absorption effect when the axis of maximum absorption is lying in the plane of incidence, and the weak absorption effect when it is at right angles to that plane. This clearly cannot be a case of varying facial pleochroism, such as one might at first expect it to be;

[1] I am indebted to Professor G. A. J. Cole for calling my attention to a plate of pink andalusite in his collection which appears to come under this case.

for if it were, then the strong absorption effect would occur with the axis of maximum absorption at right angles to, instead of in, the plane of incidence.

Brown phlogopite exhibits this phenomenon in an exceptionally striking manner. Indeed, when a plate of it is examined in ordinary light after the manner described above, it shows an axial pleochroism quite as pronounced as that seen when the plate is examined by means of a nicol prism or a dichroscope in light of normal incidence. In explaining this one needs to remember the cleavage rifts, which are invariably present in the micas though not always conspicuous, and which intensify the reflection-polarization effect.

Case II (*b*).—As examples of this case we may take principal sections of deep-coloured tourmaline, and plates of green penninite and 'uniaxial' black biotite cut at right angles to the cleavage. In these, when a plate is held at right angles to the line of sight, we see a facial colour.

If in any of these instances the axis of least absorption be held horizontally, and the plate turned round this axis into an oblique position so that the ordinary ray is vibrating in the plane of incidence, the facial effect remains practically unchanged. At most, a slight diminution of intensity is observed, owing to impoverishment of the extraordinary ray by reflection-polarization.

If the axis of maximum absorption in the above instances be placed horizontally, and the plate turned round this axis into an oblique position so that the extraordinary ray vibrates in the plane of incidence, the facial colour darkens, and the effect approximates to that of the maximum-absorption axial value as the horizontal position is approached. With tourmaline in the latter position the effect is very pronounced, the light being almost completely, if not completely, absorbed, as would be expected.

In these instances, therefore, reflection-polarization exerts little or no perceptible effect, being overwhelmed by the influence of the relatively strong absorption of the ordinary ray. Pleochroic biaxial plates which come under this case act somewhat differently in so far as they are perceptibly 'trichroic' rather than 'dichroic'; but, like the instances above quoted, they would not be expected to show axial colours as the result of refraction-polarization.

5. Behaviour of pleochroic plates in a convergent beam.

Instead of examining pleochroic plates in parallel rays, we may use a convergent beam of ordinary light, such as may be obtained by placing one's eye close to the plate and looking at a broad expanse of sky, or by using a microscope and examining with a system of converging lenses similar to that used for the observation of interference-figures.

By making the observation in this way, the effects of normal and oblique incidence are seen simultaneously. The phenomena thus obtained were originally studied in biaxial plates showing the emergence of the optic axes, and were later described as 'absorption-brushes' (Fr., houppes; Ger., Absorptionsbüschel). The term 'Absorptionsbüschel' is now used by the Germans to include also the effects seen in the uniaxial plates which we have referred to under Cases I (*a*) and I (*b*). Since, however, the term 'absorption-brushes' is inadequate for use in this wide sense, we shall use the name *absorption-figures* for the phenomena as a whole; but as the term *brushes* has become quite established in crystal optics as a translation of *houppes* and *Büschel*, we may perhaps use it freely as a convenient name for the colour-patches of an absorption-figure. The brushes of an absorption-figure should not be confused with Haidinger's 'polarization-brushes' (Ger., Polarisationsbüschel), as they are by some writers.[1] The two phenomena are quite independent of one another.

The consideration of absorption-figures follows naturally on that of the behaviour of pleochroic plates in parallel rays, and becomes more intelligible thereby. We shall see from a study of the behaviour of brown phlogopite, that reflection-polarization can play a conspicuous part in these figures, a fact which appears not to have been hitherto recognized.

We may, as in the case of parallel-ray effects, conveniently distinguish two kinds of plates, viz., those of Cases I and II. As a rule, plates cut at right angles, or approximately at right angles, to an optic axis of a pleochroic uniaxial crystal, fall under Cases I (*a*) and I (*b*); and in these there is no similarity between the absorption- and interference-figures in a convergent beam. On the other hand, plates cut at right angles to the acute bisectrix or an optic axis of a pleochroic biaxial crystal, fall under Cases II (*a*) and II (*b*); and for this reason they are as a rule capable of showing absorption-figures somewhat resembling those due to interference.

One remarkable exception to the rule stated above for uniaxial crystal plates normal to the optic axis is provided by amethystine quartz, which

[1] 'Textbook of Mineralogy,' by E. S. Dana, 1908, p. 219; also 'Mikroskopische Physiographie der petrographisch wichtigen Mineralien', H. Rosenbusch and E. A. Wülfing, 1904, vol. i, part 1, p. 341. On this point see further remarks in historical résumé, p. 25.

shows a considerable variation of absorption for vibration-directions at right angles to the optic axis. Plates cut at right angles to this axis, or approximately so, may show strong pleochroism in normally incident polarized rays, although in a principal section from the same crystal the pleochroism may be so slight as to be almost imperceptible. If a simply rotating portion of such a basal plate of amethyst be examined in convergent ordinary light, it will, if the pleochroism be sufficiently pronounced, show a fine absorption-figure somewhat resembling that of fig. 5, but uniaxial in form. If examined by means of a nicol, it will change as the nicol is rotated. In one instance observed by the writer the axial colours on the base were blue and colourless. When the short diagonal of the nicol lay along the axis of maximum absorption, a blue cross occupied the field, the intervening quadrants being comparatively colourless. When the nicol was turned through 90°, the cross was colourless, the intervening quadrants being coloured. In this latter position the absorption-figure seen was essentially an intensification of that seen in ordinary light; though with the nicol the interference-rings on the brushes were quite perceptible. This uniaxial absorption-figure for amethyst, which is unlike any that the writer has seen described for uniaxial crystals, can be fully explained after the fashion of the explanation given on p. 15 for the absorption-figure of brown phlogopite. Moreover, this observation furnishes a clear reason why in the interference-figure of a simply rotating amethyst between crossed nicols in white light, the central disc for one position of the nicols should give place to a bluish cross when the nicols are rotated.

Cases I (a) and I (b).—These do not call for much consideration, as the effects are usually inappreciable among minerals. Indeed, from what we have seen of the behaviour of these cases in parallel rays, we should not expect to get pronounced effects in a convergent beam. As already seen, even for large angles of incidence the variation is inappreciable in tourmaline and many biotites, and not very pronounced in penninite. Penninite, however, shows the effect fairly well in plates of suitable thickness, and may be taken as a good and ready illustration of Case I (*a*). The central and larger portion of the field is occupied by the green axial colour of the ordinary ray; whilst around the margin there is a halo of yellowish facial colour due to the fact that the marginal rays are sufficiently oblique to show a diminished absorption for the extraordinary ray.

In Case I (*b*), on the other hand, the central area shows less absorption than the margin. As previously remarked, this case is rarely met with among minerals, and is usually illustrated by magnesium platinocyanide. Basal cleavage plates of amazon-stone show the marginal colour, but not as a continuous halo, for the reason already explained.

Pseudo-absorption-figures in mica.—The plates of biotite referred to above as showing no marginal halo are those comparatively free from cleavage rifts. If the observation be made on mica containing many rifts, preferably a colourless phlogopite (approximately uniaxial), it will be found to yield a well-marked halo in plates of suitable thickness (fig. 1). This marginal halo in silvery phlogopite is far more pronounced than that shown by penninite; but, as already explained in dealing with

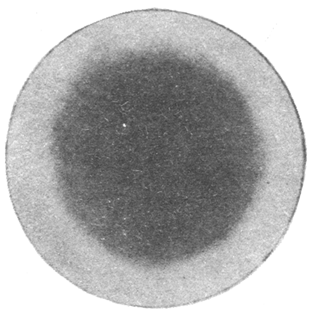
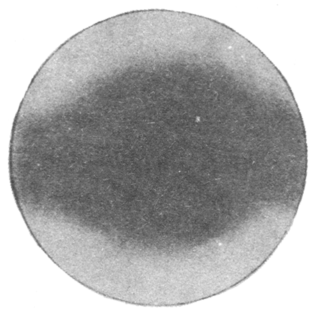


Fig. 1.—Pseudo-absorption-figure seen in 'uniaxial' mica containing numerous cleavage rifts, when examined in convergent ordinary light.

A



A′

Fig. 2.—Pseudo-absorption-figure seen in the same plate, when examined in a convergent beam with one nicol. The short diagonal of the nicol lies along *A A′*.

the behaviour of such micas in parallel rays, this is not an instance of genuine pleochroism. It is essentially due to the action of the cleavage rifts, rather than to the absorptive effect of the mineral itself. The rays transmitted around the margin are refraction-polarized, as can be seen by examination with the analyser, when two areas of pronounced extinction appear at the margin where the plane of incidence is at right angles to the short diagonal of the analyser (fig. 2). This particular observation shows very effectively the refraction-polarization suffered by the obliquely incident rays in such a plate.

Cases II (a) and II (b).—These cases of absorption-figures include the familiar examples of 'Absorptionsbüschel' seen in plates of pleochroic biaxial minerals which show the emergence of one optic axis; and also the still more interesting instances of plates showing the emergence of both optic axes. These latter were the instances originally observed by Sir David Brewster.[1] The examples described by him included blue topaz and mica in basal cleavage plates. Such plates, as we shall see below, are decidedly more complicated in their effects than those showing the emergence of only one optic axis, to which workers since Brewster have chiefly restricted their attention. The writer has been unable to find a detailed description or explanatory account of the absorption-figures originally noticed by Brewster in cleavage plates of mica, notwithstanding the fact that brown phlogopite provides perhaps the best absorption-figure to be seen among minerals, and is obtainable in cleavage plates of considerable size with a minimum of trouble.

The most important difference between Case II (*a*) and Case II (*b*) is that in the latter the rays emergent around the margin are likely to be absorption-polarized, as are those emerging from the centre of the plate; whereas in the former case the axial effect due to refraction-polarization gets a better chance of predominating over the facial effect, as we saw happened in the oblique position for parallel rays.

With regard to plates included in Cases II (*a*) and II (*b*), other than those showing the emergence of the optic axes, we need only remark that the effects to be observed are chiefly marginal and often inappreciable. In some instances, however, they are well marked. A principal section of dark tourmaline, for example, shows in ordinary light a bright band lying along the axis of maximum absorption, the margin of the field on either side being dark. This effect is clearly explained by what we saw of the behaviour of such plates in parallel rays.

With these remarks on the less interesting instances of Cases II (*a*) and II (*b*), we may now proceed to consider at greater length the more special and interesting examples of plates showing the emergence of the optic axes.

One of the best examples we can take of this case is a suitably thick basal cleavage plate of brown biaxial phlogopite, since it can be prepared with a minimum of trouble, and shows the emergence of both optic axes, the acute bisectrix being nearly normal to the plate. If we examine such a plate by placing it close to the eye and viewing it against a considerable expanse of sky or suitable source of artificial light, or better still by means of a microscope in a convergent beam of ordinary light, we see effects which are represented in fig. 3. In the central

[1] D. Brewster, Phil. Trans., 1819, vol. cix, p. 17.

area, the absorption-figure has a form which to some extent resembles that seen when the plate is examined between two parallel nicols so arranged that the short diagonals lie along the optic axial plane. The diameters lying in and at right angles to this plane are occupied by a pale yellow cross, the limbs of which are separated by four brushes of brownish colour which occupy the intervening quadrants. These brushes radiate outwards around two hyperbolic curves which have their apices in the traces of the optic axes. The two limbs of the cross which lie along the axis of least absorption of the plates, i. e. along the optic axial plane, expand towards the margin, where the colour becomes paler. The other two limbs, which lie at right angles to the optic axial plane, are more uniform in width, and do not reach the margin, having their ends surrounded by marginal areas of brownish colour which unite the

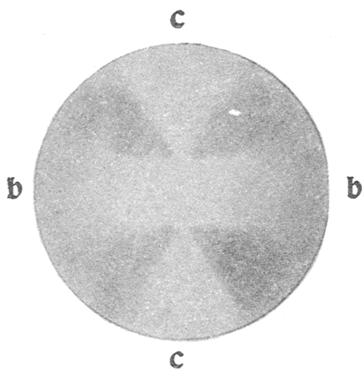


Fig. 3.—Absorption-figure of brown biaxial phlogopite, seen in convergent ordinary light.

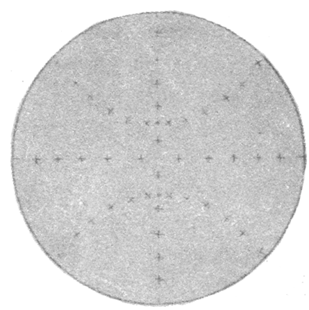


Fig. 4.—Plan of vibrations to explain the effects represented in fig. 3. The black dots mark the points of emergence of the optic axes.

adjacent brushes. These effects can be clearly explained, keeping in mind what we have already seen of the behaviour of brown phlogopite in parallel rays, by reference to fig. 4, in which the vibration-directions of rays traversing various parts of the plate are represented.

Consider first the rays emerging along the axes b and c. At and near the centre, it is clear that these will show a facial colour. We have already remarked that a facial colour, in a strongly pleochroic plate, approximates closely to the colour of the least-absorbed ray. Hence we should expect that the rays emergent along the two axes referred to would show comparatively weak absorption, in so far as they yield a facial colour, as they do in the central area. In the marginal portion of the field, however, the rays emergent along these axes are refraction-polarized, i. e. vibrating in the plane of incidence. Hence the rays emergent in the optic axial plane show a colour approximating to the 𝔠 axial colour, whereas those emergent along the 𝔟 axis show approximately the 𝔟 axial colour in the marginal portion of the field.

Now consider the rays emergent along and in the vicinity of the hyperbolic curves diverging from the optic axes, as shown in fig. 3. These rays are also of two sorts, polarized at right angles to each other, but their absorption values are practically the same, being in each case something between the greater and lesser axial values of the plate. The light emergent at these points, therefore, instead of being made up of two very unequally absorbed rays, one of which suffers comparatively little absorption, is made up of two almost equally absorbed rays, both of which suffer substantial absorption. Consequently, these rays show a more marked absorption than do the rays emergent from the 𝔟 and 𝔠 axes. Rays emergent in the spaces between the hyperbolic curves and these axes suffer more or less absorption according as they are nearer the curves or the axes. In the marginal portion of the field the hyperbolic brushes are not appreciably affected by reflection-polarization, since practically only one absorption value is represented by them.

We find, therefore, a considerable variation in the rays of a convergent beam emergent from such a plate of phlogopite. Along the 𝔟 and 𝔠 axes in the central portion of the field the emergent rays are partially polarized by absorption, whereas in the marginal portion of the field they are refraction-polarized. Along and in the vicinity of the hyperbolic curves above referred to, the two sets of rays arising from double refraction have much the same intensity, and are therefore not to any appreciable extent either absorption- or refraction-polarized. In the intervening areas there is a gradual transition from one condition to another.

This condition of things explains, and is verified by, the effects observed when we examine the ordinary-light absorption-figure by means of a nicol prism—the analyser or polarizer. When the short diagonal of the analyser lies along the optic axial plane (𝔠 axis), there is a perceptible, though perhaps not very striking, difference in the effect. The facial colour along the 𝔟 and 𝔠 axes in the central area gives place to the 𝔠 axial colour. At the same time the marginal axial colours due to reflection-polarization disappear, since the incident rays are now all vibrating in the axial plane. There is, however, less intensity at the margin on the b axis than on the c axis, owing to reflection-polarization. These changes result in a sharpening of the contrast, and produce a more pronounced figure (fig. 5).[1] Moreover, we now get slight interference-effects on the hyperbolic brushes.[2]

If the short diagonal of the analyser be placed at right angles to the optic axial plane we get an effect which is represented in fig. 6. Along the b axis we get the b axial colour, which is fairly uniform throughout, as there is little or no reflection for these rays at the margin, since they are vibrating in the plane of incidence. Along the c axis (in the optic axial plane) the colour is darker, approaching extinction at and near the margin, owing to the fact that the incident rays are largely lost by

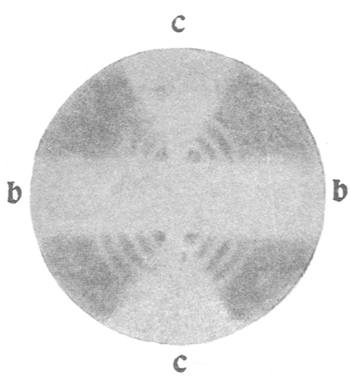


FIG. 5.—Absorption-figure of brown biaxial phlogopite in polarized light. The short diagonal of the nicol lies along the c axis.

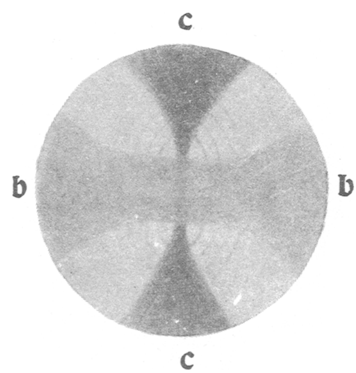


FIG. 6.—Absorption-figure of brown biaxial phlogopite in polarized light. The short diagonal of the nicol lies along the b axis.

reflection, since they are vibrating at right angles to the plane of incidence. In the intervening quadrants, the spaces previously occupied by the coloured brushes are now the brightest portion of the field, and as before they are marked by interference-effects.

It would be difficult to find another mineral, plates of which would yield an absorption-figure showing such strong marginal reflection-polarization effects as do cleavage plates of brown phlogopite.[3]

[1] It is for this reason that absorption-brushes can often be seen by means of a nicol when they are imperceptible in ordinary light. In very thin or weakly pleochroic plates the colour of the brushes becomes indistinguishable from the facial colour in ordinary light, though it may be quite perceptibly different from the extreme axial colours.

[2] For further remarks on these, see p. 19.

[3] This is the slightly ferriferous variety of phlogopite, showing a fairly pro-

Muscovite shows an absorption-figure, but the plates require to be fairly thick. The best way to see them in an ordinary muscovite is to make a pile of plates in which the optic axes of the various plates are coincident. By placing such a pile close to the eye and examining against the sky or a suitable source of artificial light, the figure seen is essentially similar to that of the phlogopite just described. In this instance, however, the convex sides of the brushes are remote from the acute bisectrix in consequence of the wider axial angle. On examining in polarized light a pile of muscovite plates tilted so as to show the emergence of one axis only, the extinction of the rays lying in the optic axial plane is very pronounced when the short diagonal of the nicol is at right angles to that plane. The absorption-figure of muscovite shows interesting variations on that of phlogopite, but these are easily explained as consequences of the weaker pleochroism and wider axial angle of the former.

The writer has not examined plates normal to an acute bisectrix, and showing the emergence of both optic axes, which would come under Case II (*b*). Indeed, it seems to be very rarely that an acute bisectrix, in a crystal with a small axial angle, is met with in conjunction with the other condition necessary for the exhibition of good absorption-figures.[1] It is presumably for this reason that absorption-figures are usually described only for plates showing the emergence of one optic axis, as in the familiar examples of andalusite and basal cleavage plates of green epidote. Both these minerals show good absorption-figures in ordinary light, the more easily studied case being that of epidote, because of its ready cleavage on the base, on which a more or less eccentric optic axis emerges. The figure for one optic axis can be well seen in brown phlogopite in ordinary light by holding a plate close to the eye and tilting it until one of the optic axes lies along the line of sight. It will be noticed that, under these conditions, reflection-polarization exerts

nounced axial angle, which occurs as a product of metamorphism in dolomitic limestones, &c. Even when the plates are not more than a millimetre in diameter, as often happens in these rocks, they are frequently pleochroic enough to show good absorption-figures under the microscope.

[1] Brewster described them in blue topaz and cordierite, in both of which the acute bisectrix is normal to the basal plane. The figure can be seen in ordinary brown Brazilian topaz, but only imperfectly, since owing to the wide axial angle the optic axes emerge near the margin of the field; and moreover, owing to the weakness of the pleochroism, it is necessary to use a nicol to see the figures clearly.

little visible effect upon the marginal portion of the figure, as would be expected from what we have already said.

The conditions presented by the emergence of only one optic axis are rather simpler than those obtaining when both axes emerge; and as the explanation of the effect follows much the same lines as that already given, we need not elaborate the matter further. It should be pointed out, however, that in the case of a single optic axis the figure is liable to be much less symmetrical than is the case with an acute bisectrix. This is particularly the case for variations of direction in the optic axial plane, especially when the axial values of $\mathfrak{c}$ and $\mathfrak{a}$ are appreciably different, and when the observation is made with a nicol having its short diagonal along the optic axial plane. In brown phlogopite these values are much the same, and the effects on either side of the optic axis in the optic axial plane are not perceptibly dissimilar. In epidote, however, the difference can be clearly seen.

6. Interference-effects in absorption-figures (idiophany).

The conditions under which interference-effects are observed in absorption-figures, and the agency by which they are produced, are matters about which there has been much discussion. The difficulty is one which appears not to have been satisfactorily settled.

In discussing this subject it is necessary to be precise as to the conditions under which the observation is to be made. It must be stipulated that the portion of the plate examined should be free from such twinning planes or other internal complications as would develop idiophanous interference-figures. The light used should not be appreciably polarized.[1] It has been argued in this connexion that the eye functions as an analyser, but its effects in the case of absorption-figures can be ignored as quite imperceptible. Of all these disturbing factors, the most important from a practical standpoint is naturally polarized light; and, as already mentioned, care should be taken to avoid its use when non-polarized light is required. These matters attended to, it will be found that an absorption-figure, seen in a convergent beam of ordinary light the axis of which is normal to the plate, shows no interference-effects;[2] whereas

[1] The mirror of an ordinary microscope is unable to produce any appreciable degree of polarization. The polarization so often noticed in the light reflected from the metallic mirror of a microscope is polarized skylight. It should also be noticed that some forms of artificial light are substantially polarized.

[2] According to Groth ('Physikalische Krystallographie,' 3rd edit., 1895, p. 159), andalusite shows the interference-rings in plates cut normal to an optic

when the observation is made by means of one nicol, either analyser or polarizer, interference-curves are seen. Why is this? When Bertin raised this question,[1] he answered it erroneously by saying that absorption-figures were due entirely to interference depending upon absorption-polarization in the plate itself. According to him, the action of a nicol was merely an intensification of what was already an interference-phenomenon ; 'il faut considérer les lames biaxes perpendiculaires qui donnent des houppes comme placées naturellement dans une mauvaise pince à tourmalines parallèles.'[2] In advocating this view Bertin seems to have had no supporters. The view is not without plausibility, though as a matter of fact it is quite erroneous.

It was rightly claimed by Mallard and others that the figure seen in convergent ordinary light was due to absorption alone. Mallard allowed, however, that interference-effects were obtained by using only one nicol; and these he explained by saying that, 'avant de passer de l'air dans le cristal, ou de sortir du cristal dans l'air, le rayon lumineux traverse une couche de très-faible épaisseur qui sert comme de couche de transition entre les deux milieux.' He assumes that this thin transitional layer, or atmosphere which surrounds a crystal, enables it to exert a polarizing effect upon the light which enters into and emerges from the crystal. Hence 'lorsqu'on place un polariseur derrière la lame, la surface antérieure de celle-ci joue le rôle d'analyseur, et que lorsqu'on place un analyseur derrière la lame, la surface postérieure de celle-ci joue le rôle de polariseur'.[3]

It is curious that Mallard should have considered it necessary to make such an assumption, and it seems quite unnecessary to put the matter as mysteriously as he did. The interference-effects to be accounted for are feeble. The rays yielding them are obliquely incident, and consequently must be, to a slight extent at least, refraction-polarized, both at incidence and emergence. If, therefore, we replace Mallard's assumption of a mysterious transitional polarizing layer by the fact of reflection-polarization, we get what is probably the correct explanation of the interference-effects observed when absorption-figures are examined by means of one nicol or its equivalent.

axis and examined in clear skylight; but this is presumably true only when the skylight is polarized.

[1] A. Bertin, 'Sur les houppes des cristaux polychroïques,' Bull. Soc. Min. France, 1879, vol. ii, pp. 54–66.

[2] A. Bertin, loc. cit., p. 66.

[3] E. Mallard, Bull. Soc. Min. France, 1879, vol. ii, p. 77.

It might, however, be claimed that, if this explanation be correct, the interference-effects should be seen in ordinary light. And if theoretically possible, why is it that, except perhaps to the eye of imagination, they are not as a rule perceptible? The reason for this is that reflection-polarization alone, for small angles of incidence, is too feeble to produce any appreciable interference; the effect becoming appreciable only when the figure is examined in a strongly polarized beam. At the best, however, the interference-effects seen with the microscope when only one nicol is used are feeble in comparison with those seen between two nicols, and are in many instances scarcely discernible. It is evident that if, on account of weak pleochroism, the plate has to be thick to show the absorption-figure, then the interference-rings may be too closely crowded to be perceptible. This is especially the case when, as in the case of epidote, the birefringence is considerable.

These interference-effects with one nicol only can be best observed by using the naked eye, and polarizing the light which traverses the plate by means of a principal section of tourmaline. In this way we get a large field and good illumination, and the effects can often be seen by this means when they are almost imperceptible under the microscope.

The explanation given above of the interference-effects, seen when absorption-figures are examined by means of a single nicol, has one important corollary. If the explanation be correct, it follows that interference-effects should also be visible when a non-pleochroic biaxial crystal plate, showing the emergence of an optic axis, is examined with one nicol; especially if the emergence can be secured on a plate so disposed as to produce a considerable degree of reflection-polarization. Fortunately this is a point which can be tested in the easiest possible manner.

Take a basal cleavage plate of quite clear and colourless topaz about two millimetres thick. Hold it close to the eye, and, with the optic axial plane in the plane of incidence, tilt it until one of the optic axes lies along the line of sight. The interference-figure for parallel nicols can then often be seen, when there is no appreciable degree of polarization in the skylight, without using a polarizer at all. It becomes quite pronounced when the skylight is appreciably polarized, and still more pronounced when the light entering the plate is polarized by means of a nicol or a tourmaline section.

If this observation be made on a plate of brown phlogopite, it will be found that the interference-effects are not appreciable in ordinary light. This may be due to some extent to the masking influence of absorption;

but it is presumably due in far greater measure to the fact that, owing to the smaller axial angle of the phlogopite, the angle of incidence is much smaller when an optic axis is lying along the line of sight, than it is in the case of topaz, and the amount of reflection-polarization consequently less.

These observations prove that the idiophanous interference-effects accompanying absorption-figures arise from reflection-polarization, as explained above; and that they are not peculiar to pleochroic plates. According to Voigt (see p. 27), non-pleochroic crystals should not yield these idiophanous interference-effects with one nicol only, let alone ordinary light; whereas pleochroic crystals should. It would, however, be difficult to find a pleochroic crystal showing a more pronounced idiophanous interference-figure than that referred to above as seen in a cleavage plate of colourless topaz.

Evidence of idiophanous interference-effects can also be very readily seen by examining a quartz-wedge with one nicol only, in parallel rays. The wedge should be tilted so as to effect reflection-polarization, and held with its vibration-directions diagonally to the plane of incidence and short diagonal of the nicol. Under these conditions the interference-bars on the wedge can be seen quite distinctly.

7. Historical résumé.

Observation in parallel rays.—There is a considerable amount of literature on the subject of pleochroism; but the only records which the writer has been able to find relating to the behaviour of pleochroic plates in parallel rays of variable incidence are those by Sir David Brewster and W. von Haidinger. Both deal with the case of mica. It is not clear exactly which variety was used by Brewster, but it was probably a biotite. Haidinger's mica was apparently a muscovite. Brewster remarks that 'another crystal (of mica) which in one direction was as transparent as ordinary specimens of olivine, would not admit, through a thickness of 0·1 of an inch, a single ray of the meridian sun on the 20th May, when it passed along the axis of the prism. The ordinary ray, which was entirely lost in one direction, became gradually visible in thin plates and at last of equal intensity to the other ray, as the ordinary light formed a greater angle with the laminae.'[1]

[1] D. Brewster, 'On the phenomena of dichroism,' Edinburgh Phil. Journ., 1820, vol. iii, p. 244.

Haidinger is presumably referring to the same phenomenon when he remarks: 'Sieht man senkrecht durch die Basis A hin, so ist das Glimmerblatt, namentlich bei der Varietät von Utön (Winkel der Axen nach Grailich 72° 30′) bei einer gewissen Dicke, etwa von einer Linie, weniger durchsichtig, als wenn man schief dagegen hindurchsieht, weil bereits die Einwirkung des weniger absorbirten Tones der Axe *a* beginnt.'[1]

There can be little or no doubt that the phenomenon referred to by Brewster and Haidinger, in the passages cited above, is identical with the phenomenon described on p. 7 of the present paper as pseudo-pleochroism arising from the action of the cleavage rifts. It is perhaps not surprising that Brewster should have failed to recognize this fact, since he appears to have made his observation on a dark biotite, the intense pleochroism of which would lead one to expect that it might act in the way Brewster thought it should. We have seen, however, that black biotite shows practically no change when it is comparatively free from cleavage rifts; whereas phlogopite, which is almost colourless, shows a pronounced change when the cleavage rifts are numerous.

Haidinger had less reason for attributing the phenomenon to true pleochroism, since he appears to have made the observation on muscovite, which shows little or no pleochroism, especially in the sense implied by his observation.

Brewster seems to have been aware that minerals with a platy structure could act like a pile of plates. Indeed, it was in consequence of his observation that a cleavage plate of mica polarizes transmitted oblique rays more effectively than does a single glass plate, that he was led to construct a pile of plates in glass. It appears, however, that in his later work he failed to realize the bearings of this fact with regard to the pleochroism and pseudo-pleochroism of the micas in ordinary light.

The writer has not been able to find any record of the extremely interesting case of the behaviour of brown phlogopite in obliquely incident parallel rays.

Absorption-figures.—Brewster appears to have been the first to describe absorption-figures.[2] His first observations seem to have been made on basal cleavage plates of exceptionally fine blue topaz, but he describes the phenomenon in several other minerals, including mica and cordierite.

[1] W. Haidinger, Sitz. Akad. Wiss. Wien, 1854, vol. xiii, p. 812.
[2] D. Brewster, Phil. Trans., 1819, vol. cix, p. 17.

His observations on these figures were made with polarized light; but with regard to mica he remarks that the figure is seen quite distinctly in ordinary light. Although the mica which he refers to in this connexion was probably brown phlogopite, he seems not to have been aware that there was any difference between the figure seen in ordinary light and that seen in polarized light with the plane of polarization at right angles to the optic axial plane.

Brewster rightly regarded absorption-figures as features due to pleochroism, though he apparently made no observations on the presence of interference-effects when they are examined in polarized light. This is the more surprising because he had already recorded the fact that interference-effects could arise as a consequence of polarization by reflection and refraction.[1]

Herschel[2] made a study of the absorption-figures in biaxial crystals as described by Brewster, and explained them as due entirely to interference-effects. He was struck with the similarity of their form and position to those of the interference-figures seen with a polariscope. He inferred that the absorption-brushes resulted from the overlapping and consequent blurring of interference-rings; and this he attributed to 'a slight degree of confusion of structure' in the crystals. He tells us that the brushes ('cloudy fan-shaped spaces') can only be seen in 'limpid crystals' by examining them between a polarizer and analyser; and further, that they can be seen in a pleochroic crystal without polarizer and analyser, in consequence of the absorption-polarization of the plate itself, which enables it to act as an analyser towards the emergent ray. Erratic as is this explanation by Herschel, it is of some interest, especially on account of its near affinity to explanations which were advocated later, notably that by Bertin.

[1] See particularly 'On the affections of light transmitted through crystallized bodies', Phil. Trans., 1814, vol. civ, p. 203, where Brewster describes the interference-figure seen when ordinary light is sent obliquely through a plate of topaz, using an agate or a pile of plates as an analyser. I had already completed the observations embodied in the present paper before I found this record by Brewster, an earlier knowledge of which would have saved me much trouble. From the manner in which Brewster made his observation on topaz, it does not follow that polarization by reflection and refraction was the cause of the figure he saw, unless he took special precautions to see that there was no appreciable polarization in the 'ordinary light' which he used. His observation is, however, closely similar to that on colourless topaz which is given on p. 21 of the present paper.

[2] 'Light,' by Sir John F. W. Herschel; Encyclopedia Metropolitana, 1827, vol. iv, p. 557. The Encyclopedia as a whole was not published until 1845.

It was Herschel who applied the term 'idiocyclophanous'[1] to crystals which Brewster had described as showing interference-figures, in consequence of their self-polarizing action.

In 1844, Haidinger announced his discovery of the fact that when a beam of plane-polarized light falls on the eye, two small yellow 'Büschel' are seen lying parallel to the plane of polarization.[2] He pointed out that these can be seen not only in the nicols prism and dichroscope and certain polarizing plates of minerals, but also in polarized skylight. In his later papers these were referred to as 'Polarisationsbüschel'. Their cause was the subject of much discussion and very numerous papers by Haidinger and others. It appears to have been decided from the outset that these polarization-brushes were subjective phenomena; and we should have no need to refer to them here, had not Haidinger confused them in his first paper with the absorption-brushes originally described by Brewster. It was natural that, having apparently made his discovery before he had studied absorption-brushes, Haidinger should regard the latter as due to the same cause as his 'Polarisationsbüschel'. Certain micas, for instance, exhibited absorption-polarization, and he seems to have inferred that the 'Büschel' which they exhibited were due to this polarization.

Brewster, however, seems to have perceived from the first that Haidinger's brushes had nothing to do with absorption-brushes.[3] In his later papers, Haidinger also keeps the two phenomena quite distinct. In his papers on pleochroism in 1854 he refers to absorption-brushes not as 'Polarisationsbüschel', but simply as 'Büschel', describing the phenomena under the name of 'Idiostaurophanie', and attributing their discovery to Brewster.[4] As we have already mentioned, Haidinger's early confusion of 'Polarisationsbüschel' with 'Absorptionsbüschel' is still maintained in some modern textbooks.

The study of absorption-brushes was revived by Bertin,[5] whose ex-

[1] J. F. W. Herschel, loc. cit., p. 562.

[2] W. Haidinger, 'Ueber das directe Erkennen des polarisirten Lichts und der Lage der Polarisationsebene,' Ann. Chem. Phys. (Poggendorff), 1844, vol. lxiii, pp. 29–39.

[3] D. Brewster, 'On the coloured houppes or sectors of Haidinger,' Phil. Mag., 1859, vol. xvii, p. 323.

[4] See particularly W. Haidinger, 'Pleochroismus an einigen zweiaxigen Krystallen in neuerer Zeit beobachtet,' Sitz. Akad. Wiss. Wien, 1854, vol. xiii, pp. 306–331.

[5] See particularly A. Bertin, Bull. Soc. Min. France, 1879, vol. ii, p. 54, followed by a discussion, to which Mallard, Bertrand, and others con-

planation of them we have already referred to (p. 20). Bertin's explanation is, in part at least, a revival of Herschel's, as may be gathered from the quotation already given (p. 20) and his further statement that 'Les houppes sont formées par des segments d'anneaux, qui ne sont pas apparents parce qu'ils sont noyés dans la lumière naturelle'.[1] According to Bertin, absorption-brushes are only seen in pleochroic biaxial crystals.

Bertrand, in his contribution to the discussion appended to Bertin's paper, claimed that 'houppes' were also seen in uniaxial crystals; but the instances he referred to were those in which marginal modifications (halos, &c.) were to be observed under the conditions mentioned in Cases I (*a*) and I (*b*) of the present paper. These, as we have seen, are usually slight among minerals; and it was perhaps scarcely just on the part of Bertrand to regard these as 'houppes' in the sense in which Bertin and previous workers had used the term, though they might fairly be included with 'houppes' under the general name of absorption-figures.

It was in his excellent contribution to this discussion on Bertin's paper, that Mallard gave the true explanation of genuine absorption-brushes, i.e. those which depend upon the coexistence of emergent optic axes and absorption-polarization in the same plate. The explanation given in the present paper is essentially that adopted by Mallard. We have already (p. 20) noted the curious fact that Mallard, perceiving that the interference-effects which accompany absorption-brushes were due to polarization on incidence and emergence at the surface of the plate, made a false assumption to account for it, and overlooked the fact of reflection-polarization which renders his assumption unnecessary.

Liebisch[2] studied absorption-figures and described them as seen in various minerals in which they had been already observed by Brewster, Haidinger, Bertrand, and others. According to Liebisch, 'uniaxial' biotite yields an absorption-figure similar to that of penninite. According to the present writer's observations, however, 'uniaxial' biotite does not show genuine absorption-figures, but only pseudo-absorption figures, as described on p. 13 of the present paper.

tributed. Also A. Bertin, 'Sur les cristaux idiocyclophanes,' Ann. Chim. Phys., 1878, ser. 5, vol. xv, pp. 396–430.

[1] A. Bertin, loc. cit., p. 66.

[2] T. Liebisch, Nachr. Ges. Wiss. Göttingen, 1888. See also Liebisch's 'Physikalische Krystallographie', 1891, and 'Grundriss der physikalischen Krystallographie', 1896.

Absorption-brushes were studied by Tolstopiatow. His paper[1] is chiefly characterized by an exhaustive study of epidotes, of which he had an extensive collection. He preferred to make his observations on entire crystals rather than on plates, and he shows that the figures seen in this way in epidote are sometimes complicated by 'epoptic figures'[2] due to twinning, an effect similar to that described by Erman, who observed it in the complex twins of aragonite.[3] This complication due to twinning in epidote, to which Tolstopiatow devoted so much attention, had been already noticed by Klein,[4] and again by Voigt.[5] The fact that Tolstopiatow restricted his observations largely to epidotes, and examined them in such a way as to ensure a maximum of complication due to twinning, led him to exaggerate the importance of these complications, and made his general conclusions on absorption-brushes of little value.

The subject of absorption-figures has been treated mathematically by Voigt.[6] A later paper was published by Voigt in 1902,[7] and summarized by him in the Philosophical Magazine of that year.[8] According to his theory, light is not propagated through a pleochroic crystal in the same way as it is propagated through an 'ordinary or active transparent crystal'. In the former case he tells us that the transmitted light consists of 'two elliptic vibrations which have the same sense of rotation', whereas in the latter the 'two linear or two elliptic similar but crossed vibrations are of oppositely directed sense'. In the former case he informs us that his theory demands interference-rings when the observation is made in polarized light, whilst in the latter case his theory demands no interference-rings; and he claims, strangely enough, that 'experiment is in complete accord with this, and thus proves the

[1] M. Tolstopiatow, 'Notes sur les phénomènes des houppes,' Recherches Minéralogiques, Édition Posthume, Moscou, 1893.

[2] Erman's 'epoptic figures' are cases of 'idiocyclophany'. He was apparently unaware of Herschel's term, and of Brewster's earlier observations of similar effects.

[3] P. Erman, 'Ueber die epoptischen Figuren des Arragonits ohne vorläufige Polarisation,' Ann. Chem. Phys. (Poggendorff), 1832, vol. xxvi, pp. 302–307.

[4] C. Klein, 'Die optischen Eigenschaften des Sulzbacher Epidots,' Neues Jahrb. Min., 1874, pp. 1–21.

[5] W. Voigt, 'Erklärung der Farbenerscheinungen pleochroïtischer Krystalle,' Neues Jahrb. Min., 1885, vol. i, pp. 119–141.

[6] W. Voigt, loc. cit.

[7] W. Voigt, Nachr. Ges. Wiss. Göttingen, 1902, p. 48.

[8] W. Voigt, 'On the behaviour of pleochroitic crystals along directions in the neighbourhood of an optic axis,' Phil. Mag., 1902, ser. 6, vol. iv, p. 90.

existence, hitherto not established, of these pairs of waves with vibrations of the kind described'.[1]

It would appear, however, from the evidence considered in the present paper that reflection-polarization is a quite adequate cause of these interference-effects which are requisitioned by Voigt as the only experimental evidence available to support his theory; and if so, then Voigt is scarcely entitled to claim that his theory is supported by experimental evidence.

In concluding this historical résumé, one feels tempted to suggest that the use of the terms 'epoptic figures' and 'idiocyclophanous crystal' should be discontinued. Erman's 'epoptic figures' as seen in aragonite constitute a special case of 'idiocyclophany', and should be treated as such, as is done by Groth.[2] 'Idiocyclophany' is, however, a rather clumsy word, and was put forth somewhat apologetically by Herschel. Moreover, the contracted form 'idiophany', which has been used by Voigt and others, is decidedly preferable. Hence it seems desirable that one should use the terms 'idiophany' and 'idiophanous figures'[3] to signify the phenomenon of interference-effects arising in consequence of the polarizing action of the crystal itself, whether this be due to reflection-polarization at the surface, or to internal complications such as twinning lamellae.

8. Summary.

An examination of pleochroic plates in parallel rays shows that polarization by reflection and refraction is an important factor in determining the behaviour of the plates in some cases. Under certain conditions, which are exemplified in a remarkable manner by brown phlogopite, axial pleochroism arising from reflection-polarization is the predominant feature in the effects to be observed when the plate is examined in parallel rays of sufficiently oblique incidence. Reflection-polarization not only influences the phenomena to be observed in genuinely pleochroic plates; but under certain conditions, again exemplified by mica, it is capable of producing strong pseudo-pleochroism.

Since absorption-figures (Absorptionsbüschel) represent the effects of

[1] W. Voigt, Phil. Mag., 1902, ser. 6, vol. iv, p. 96.

[2] P. von Groth, 'Physikalische Krystallographie,' 3rd edit., 1895, p. 398.

[3] E. S. Dana apparently describes absorption-figures as idiophanous figures ('System of Mineralogy,' 6th edit., 1892, pp. 420, 497, and 518. Also 'Textbook of Mineralogy', by E. S. Dana, 1908, p. 219); but there seems to be no justification for the use of the phrase 'idiophanous figures' in this sense.

normal and oblique incidence simultaneously, it is desirable to consider them in the light of the behaviour of pleochroic plates in parallel rays. The two sets of phenomena fall naturally together under the head of the pleochroism of plates in light of variable incidence. Hence reflection-polarization is a factor to be reckoned with in dealing with absorption-figures, as is proved by the detailed consideration of the behaviour of brown phlogopite in a convergent beam. We have, therefore, to admit its action as a possible cause of the interference-effects observed when absorption-figures are examined in polarized light.

These interference-effects are theoretically inevitable as a result of reflection-polarization, whether the absorption-figures be examined in ordinary or polarized light. In practice, however, they are imperceptible with a convergent beam of ordinary light when the axis of the beam is normal to the plate; but they become perceptible when examined with a nicol. If the axis of the convergent beam of ordinary light is sufficiently inclined to the plate they may be seen without the agency of any polarization other than that arising by reflection and refraction at the surface of the plate.

If we make due allowance for this action of polarization by reflection and refraction, the explanation of idiophanous interference-effects demands no extraordinary assumption, such as that made by Mallard of a transitional polarizing atmosphere around crystals; or that made by Voigt with regard to the condition of the rays traversing the crystal. Both absorption-figures and idiophanous figures can be explained in a comparatively simple manner, on exactly the same basis as that employed for the explanation of the ordinary effects of pleochroism and interference.