XLIV. Optical combinations of crystalline films

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To cite this article: Lewis Wright (1883) XLIV. Optical combinations of crystalline films , Philosophical Magazine Series 5, 15:95, 301-309, DOI: [10.1080/14786448308627355](https://doi.org/10.1080/14786448308627355)

To link to this article: <http://dx.doi.org/10.1080/14786448308627355>

Published online: 28 Apr 2009.

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THE
LONDON, EDINBURGH, AND DUBLIN
PHILOSOPHICAL MAGAZINE
AND
JOURNAL OF SCIENCE.

—◆—
[FIFTH SERIES.]

—
MAY 1883.
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XLIV. *Optical Combinations of Crystalline Films.*
By LEWIS WRIGHT*.

[Plate VI.]

THE object of the following experiments is to illustrate the facility with which simple combinations of mica-films, such as can be readily put together by any one with the aid of Canada balsam dissolved in benzol, may be made to demonstrate not only the simpler chromatic phenomena of polarized light, but also the more beautiful and complicated appearances encountered at a more advanced stage of study. The colours obtainable from such mica-films are more delicate and intense than the usual selenite preparations, because while in selenite those films which produce the lower and more intense orders of Newton's colours are so thin as to be split with difficulty, in mica they can be obtained with the greatest facility. Some of the preparations are also, as demonstrations, superior in themselves.

Let us take first the simplest case, of different retardations produced by different thicknesses of crystal, counteracted or not by opposite retardations caused by another crossed film. It has been usual to demonstrate these by two selenite wedges, rotating one over the other. A simpler and more effective demonstration is given by two wedges, each built up of similar mica-films superposed, and cemented together, like those on the

* Communicated by the Physical Society.

screen (Pl. VI. fig. 1). The series of flat steps or tints are both more conspicuous and more readily understood; and if the two wedges are properly matched, when crossed the diagonal row of squares will be black when the Nicols are crossed. When the thick edge of one is superposed over the thin edge of the other, with the mica axes parallel, we have an even tint; and when the thick edge is superposed over the other thick edge, with the mica axes crossed, the retardations or colours produced by the first wedge are all destroyed by the second, and the field is all black. I wish to remark here, as I have done elsewhere, that the idea of wedges and other designs, built up in this way of thin flat films, is not due to me, but to my friend Mr. Fox, F.R.M.S., from whom both this pair of wedges and the next one are simply copied.

Here is another preparation of the same character, built up of twenty-four films, each of a thickness causing exactly $\frac{1}{8}\lambda$ of retardation for yellow light. Of course the thickness must be very exact to bear multiplication twenty-four times without sensible error. Now if we superpose on this wedge a flat plate of mica with its axis* crossing that of the wedge, and of a thickness equal to the middle stripe, that central stripe must appear black when the Nicols are crossed (fig. 2), while Newton's first order of colours and half the second order appear symmetrically on both sides of the black stripe. On one side of the stripe the wedge itself gives greater successive thicknesses; while on the other side the plate of mica does the same.

Such a wedge has further and real optical uses. It shows at a glance the precise composition of every successively increased $\frac{1}{8}\lambda$ of retardation for the first three orders of Newton's colours. When extinction is complete for yellow light, we know that a little of both red and blue must be unextinguished, the two giving us at the end of the first order the opaque plum-colour known as the "tint of passage." As the red at a given distance from the end of the spectrum is visually more conspicuous than the blue, at the end of the second and third orders this "tint of passage" must become more and more red, as we see on the screen is the case. The precise composition of the light destroyed and that remaining, we may demonstrate by placing a slit across the wedge and throwing its spectrum on the screen (fig. 3), when we see the shifting of the bands in steps for each $\frac{1}{8}\lambda$ of retardation. The wedge alone shows only the first three orders; but it is obvious that by superposing a plate of mica 1λ in thickness, the spectrum

* Throughout this paper the "axis" of the mica is supposed to be that one of its two polarizing planes which passes through the two optic axes.

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.

Fig. 6.

would give us from the second to the fourth orders, and so on. I have not here the plates to show this in detail; but I have brought a thick plate of selenite, not measured, but hurriedly mounted for this afternoon. We throw its spectrum on the screen first: from the seven or eight dark bands it appears to be from eight to ten waves in thickness; it is at all events so thick as to show no colour. But now superposing the wedge, the shifting of the bands shows the precise composition for every successive $\frac{1}{3}\lambda$ of retardation even in this high order of interferences. It is all rendered by spectrum analysis. Another great use of such a wedge is for gauging the thickness of films in making other preparations, for which I use it constantly: we only have to superpose the film to be gauged with its axis crossing that of the wedge, and the stripe that is nearest extinction when the Nicol is crossed gives the thickness.

The *rotatory* colours of films are also beautifully shown by mica preparations. We all know that if a film $\frac{1}{4}\lambda$ thick (the terms "thick" or "thickness" of course mean in retardation of the slowest ray, throughout this paper) is adjusted with its polarizing planes at 45° with the plane of polarization, we obtain a single circular vibration. But if we adjust in this position a film giving colour next the polarizer, and introduce after that the $\frac{1}{4}\lambda$ plate, with its planes at an angle of 45° with those of the colour-film, both the two rays which emerge from the first film are converted into rays circularly polarized, but in opposite directions; and hence we get approximately the rotatory colours of quartz as the analyzer is rotated. The geometrical figure I now insert is thus circularly polarized, and will illustrate not only the beautiful rotational phenomena of the colours, but also that superior delicacy and intensity of these lower-order colours which has been alluded to: it would be exceedingly difficult to get colours like these in selenite. Again, we take the 24-section wedge used just now, and superpose upon it a $\frac{1}{4}\lambda$ plate made in two halves, one of which has its planes reversed as compared with the other; on rotating the analyzer the colours appear to pass along the wedge in opposite directions, as if it were made in two halves of right- and left-handed quartz.

My friend the Rev. P. R. Sleeman lately suggested to me another preparation, which was in turn suggested to him by a beautiful one in quartz belonging to the President of the Royal Society. This is a quarter-wave plate divided into twelve sectors. In the position now on the screen the polarizing planes are all perpendicular and horizontal; but the principal plane or "axis" is *reversed* (as in fig. 4) in every alternate sector. If we superpose this upon a mica-film giving

uniform colour, on rotating the analyzer we get, as you see, the contrary quartz rotations. But it lately occurred to me that a still more beautiful demonstration of these rotational colours would be obtained by another combination, which deserves perhaps to be called an "optical chromatrope." We place first in the stage next the polarizer a large even-tint film in a rotating frame; next to that a concave selenite plate showing Newton's rings; next to that again our quarter-wave plate in sectors. As we rotate the analyzer, one set of alternate sectors of the rings approach the centre, while the intermediate sectors recede from it; and if we now at the same time rotate the even-tint plate, we simultaneously vary the colour phenomena in an exquisitely beautiful manner.

A $\frac{1}{4}\lambda$ plate divided into four sectors or quadrants, with their planes alternately reversed in the same way (fig. 5), enables us to demonstrate the nature of the curious modifications of the rings and brushes in a plate of crystal when circularly-polarized convergent light is employed. Here, for example, are the rings and cross of calcite: interposing a $\frac{1}{4}\lambda$ plate, the black cross disappears into a grey nebulous one, and on opposite sides of each arm the quadrants of rings appear dislocated, the dark rings of one quadrant opposing the light rings of its neighbours. Interposing another $\frac{1}{4}\lambda$ plate on the other side, on rotating the analyzer one opposite pair of quadrants contracts while the intermediate ones expand, so that in two complementary positions we have unbroken circles. The same phenomena precisely are exhibited by this disk of chilled glass in parallel light, the gradually decreasing elasticity of the glass as we recede from the centre having the same effect as the increasing convergence of the rays has in the calcite. Now it is pretty easy to explain this phenomenon to a student by such a diagram as this (fig. 6) representing our crystal or glass with the Nicols crossed. The circularly-polarized ray we know is, on entering the glass, decomposed into its two plane-polarized components, of which one (let us suppose that denoted by the arrow-heads) is retarded a quarter of a wave. But the calcite or glass, beside this, itself also retards either the radial or the tangential vibration more than the other component—in calcite the radial. Taking, then, any originally-circular ring caused by the calcite retardations alone, we see that in two opposite quadrants the $\frac{1}{4}\lambda$ plate retards the radial vibrations a further quarter-wave, while in the alternate quadrants it accelerates them a quarter-wave. The result must obviously be a half-wave dislocation. As I have just observed, such a diagram sufficiently explains it all; but it seems to me better actually to represent it optically, by introducing the

composite quarter-wave plate, with its planes at 45° with the plane of polarization, before a film ground concave to show Newton's rings. Here we have, in an analogous way, in opposite quadrants retarded one of the component vibrations a quarter-wave before entering the selenite, while in the alternate quadrants we retard the other component; and we get similar dislocations. Again, letting the concave selenite come first, and superposing a $\frac{1}{4}\lambda$ plate cut in quadrants with their planes alternately horizontal and vertical, we now have the contracting and expanding quadrants, with the perfect circles in two positions, as in the calcite. We may make the demonstration complete by reversing the process, and superposing our last composite $\frac{1}{4}\lambda$ plate on the disk of chilled glass*. We now are applying in each quadrant all the retardations equally to either the tangential or radial vibrations; and hence the rings remain perfectly concentric, while they expand or contract as the analyzer is rotated: there is no dislocation at all. Finally, either the quadrant or 12-sector $\frac{1}{4}\lambda$ plate superposed on this *square* of chilled glass gives us a very beautiful demonstration that the dislocation of the crystal rings is entirely due to the $\frac{1}{4}\lambda$ plate retarding one component ray in the crystal on one side of the plane of polarization or that at right angles to it, and accelerating the same component on the other side of those planes. Here we have the square perpendicularly adjusted, with the composite plate superposed. When the analyzer is rotated, the reversal of the sectors on the lines of the black cross keeps the figure symmetrical, as in the last experiment. But you observe that the *diagonals* of the square are covered, each by a single plate or sector; and a mere glance at the screen makes it obvious that if, *in this position*, these diagonals were covered—as the black cross now is, by the junction-line between two contrary sectors, they would be dislocated, the colours on one side of the line approaching the centre, and those on the other receding when we rotate the analyzer. But we will now bring these diagonals of the square into the planes of polarizer and analyzer crossed, and superpose the sectors again upon the glass, junction-lines now covering the diagonals. You observe that the state of things is exactly reversed; and the contrary sectors now do keep the figure symmetrical on each side of the diagonals, while, on the other hand, the single $\frac{1}{4}\lambda$ plates which now cover the bisecting diameters of the square preserve the

* In private experiment we can of course do this with a plate of calcite; but in a projecting instrument it is rather difficult to ensure the precise axial coincidence of all the arrangements with the axis of the convergent light, without which the experiment fails.

symmetry there also. It is not necessary to add details of explanation which will be familiar to all.

Allow me next to illustrate the beautiful phenomena of crossed films of mica in highly convergent light, such as will take in biaxial angles of, say, 50° . Our starting-point will be Norremberg's beautiful discovery, worked out entirely from theory, that by crossing films of biaxial mica of gradually increasing number and proportionately diminished thickness, there was a gradual approach to the rings and cross of a uniaxial crystal. He found three wave-lengths of retardation the best approximate unit. Here is a single plate of mica—the ordinary biaxial lemniscates; and here are two such plates crossed at right angles—the ordinary figure of a “crossed” crystal, in which we get the black cross. With four plates crossed we get the first approach towards rings, each of the “eyes” being now bisected by a straight fringe placed as a tangent to the figure. Norremberg's next preparation was eight films crossed; but I add one of six, which gives a single perfect though nearly square ring, while eight films give two rings. Twelve give three rings and signs of a fourth; while twenty-four, as you see, are absolutely undistinguishable from a calcite. The whole series will be thus:—

$$\frac{1}{3\lambda}, \quad \frac{2}{3\lambda}, \quad \frac{4}{\frac{3}{2}\lambda}, \quad \frac{6}{\frac{1}{2}\lambda}, \quad \frac{8}{\frac{3}{2}\lambda}, \quad \frac{12}{\frac{1}{4}\lambda}, \quad \frac{24}{\frac{1}{8}\lambda}.$$

Now there is no necessity for an *exact* total thickness of three wave-lengths in constructing this series; but an approximation to it is necessary, to preserve the gradation of the phenomena and the gradual passage to the uniaxial figure. So far Norremberg ascertained; but he does not seem to have carried his experiments with mica any further. Let us now do so. The eight films gave us two rings, the outer one squarish in figure. But if we combine eight very *thin* films (say $\frac{1}{8}\lambda$ thick, as in this preparation), you observe that we get perfectly circular rings at once; and in fact even four very thin films will give them; and twelve thin films give us quite fine circles. Now, on the other hand, let us employ four and eight *thick* films—in this case over 1λ thick (we thus more than double Norremberg's thicknesses); and observe that the rings now have altogether disappeared, and the curved fringes are all turned the reverse way, their convex sides to the centre. The same thing is still more evident in this splendid figure, produced by twelve crossed films $\frac{3}{4}\lambda$ in thickness. We see easily enough that it must be so, if we follow in our minds the decompositions and recompositions of the vibrations in traversing the successive films; but it is very interesting to notice how,

with the same number of micas crossed in exactly the same way, but of different thicknesses, the phenomena appear actually reversed in character. Having seen this, we abandon simply crossed films, and the following will be composed of films superposed at angles of both 90° and 45° . Here another cause of variety comes into play, since all films whose thickness contains an odd $\frac{1}{2}\lambda$, when superposed at 45° will circularly polarize the light. Moreover we also know that if two such films are superposed at an angle of 45° , the effect is to rotate the plane of polarization itself (as shown for instance by the rotation of a calcite cross) 45° from the original plane. Hence the variety and scope for combination here are endless, the phenomena always being beautiful; but I must only show you a very few of such preparations. The first four are all composed of films $\frac{1}{2}\lambda$ in thickness, and each contains the same number of twelve films, and the lines show the successive positions of the mica "axis." In the first they are

| \ | — \ — | \ | — \ —

Thus all the diagonal axes lie the same way. Now this second preparation has the very same individual films differently placed, thus:—

| \ — | \ — | / — | / —

You see the total difference in effect produced by the difference in crossing.

The next one is thus arranged:—

|| — || — | = | =

This is an interesting combination, because the wave-decompositions indicate that the light should be nearly extinguished when the Nicols are crossed, not only in the original black cross, but also along the diagonals between. You see that it is so; but this result is still more completely brought out by the next preparation,

| — | — | — — | — | — |

where we get a nearly perfectly black square crossed by nearly black diagonals as well as by the black cross. The next set of five are all built of films one wave in thickness, as follows:—

No. 1. 8 micas | — | × | — |

2. 10 „ + + × + +

3. 12 „ + + × × + +

4. 8 „ + × + ×

5. 8 „ | / — \ | / — \ (i. e.
successively rotated 45°).

This last figure is interesting, because we can see that the result must be some polygonal or roughly circular central figure with some sort of a cross, surrounded by eight detached figures or eyes. I am sorry I cannot work this out mathematically; but with whole-wave and somewhat greater retardations it is pretty easy to trace it in one's own mind. It is so, as you perceive; and you also see that the preparation and figure can be rotated without very sensible change, which also follows from theory, and is a somewhat remarkable result, after what we saw at the commencement, with such thick films. And now, to show the effect of thickness, here is a precisely similar preparation of eight films superposed at a successively rotated angle of 45° , but built up of $\frac{3}{4}\lambda$ films. Circular polarization here comes into play; and the effect is totally different in every way. The last of these crossed micas is built up of twelve $\frac{3}{4}\lambda$ films, thus—

$$\times + + + + \times$$

You see the total difference in figure from any thing before, and the scope for endless variety, which I must not further pursue.

Still more beautiful, but perhaps less interesting, are the combinations of mica- and selenite-films discovered experimentally by Norremberg. As he observes, if we call the three axes of elasticity in any crystal x, y, z , then selenite-films contain x and z , while mica on the other hand contains y and z ; and it is easy to see that if preparations are built up of both elements, very fine coloured fringes must result, differing very greatly in character according to whether the x of the selenite is parallel to the z of the mica or crosses it. As far as I remember, however, Norremberg and Reusch seem to have said that the characters of the fringes defy all prediction. This is perhaps hardly true, even apart from mathematical analysis, which I am unable to give, and which the mere beauty of these combinations is scarcely worth. For it is easy to perceive that if a single selenite be placed between two thick micas, we must have very nearly the usual biaxial figure, with some little modification in the eyes or rings, but chiefly distinguished from the simple mica by rich colour. That is so here. But if we alternate several parallel selenites between parallel micas of less thickness, so as to give the selenite functions of elasticity more comparative influence, then it is evident that the modified lemniscate curves, or what is still traceable of them, must be either brought nearer together or more widely separated, and that we shall thus obtain curved fringes having their approximate origin in the original

optic axes of the mica, but reversed in character according as the x of the selenite crosses or is parallel to the mica z . This is the simplest analysis I can give, and it follows on consideration from Norremberg's data. Here are two such preparations, in each of which four selenites are alternated between five $\frac{1}{2}\lambda$ micas. In the first the modified lemniscates are wider apart than in the mica, but the resulting fringes originate approximately in the mica axes. In the second the selenites are at right angles with their former position, and the fringes still centre in the axes, but the curves are reversed; and the resulting "palm-tree" pattern is perhaps one of the most beautiful, both in colour and figure, which it is possible to behold.

The few other preparations here are built up of either four or six ternary elements constructed on Norremberg's system, each consisting of two parallel micas, with a selenite between them either crossed or parallel. In the first you readily recognize the "palm-tree" character of the last figure, "crossed." It is needless to describe the others; for here, too, variety is boundless; but I purposely reserve for the last, two combinations composed of exactly the same arrangements of both mica and selenite, and all the micas the same ($\frac{1}{2}\lambda$) thickness, but the selenite films in one slightly thicker than in the other. The difference in effect is purposely not so great as to prevent your recognizing the same general figure in both, but is still conspicuous and interesting. Let me, in conclusion, hope that the beauty of these preparations constructed after Norremberg's method, and the facility with which they can be prepared, may make them better known.

[At the conclusion of the paper Mr. Wright described and exhibited an adaptation to the microscope by Messrs. Swift and Son, by the aid of which all the preparations and crystals requiring highly convergent light could be shown on the stage of any microscope constructed with a draw-tube.]

XLV. *On Permanent Magnetism.*

By R. H. M. BOSANQUET.

To the Editors of the Philosophical Magazine and Journal.

GENTLEMEN,

IN a former paper I have proposed to follow out Faraday's analogy between magnetism and electricity; and the following is a summary of the resulting point of view.

Magnetic induction, or the number of lines of force through unit area, is the quotient of magnetomotive force by resistance, in magnetic circuits.