PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

An Instrument of Precision for Producing Monochromatic Light of any Desired Wave-Length, and Its Use in the Investigation of the Optical Properties of Crystals

A. E. Tutton

Phil. Trans. R. Soc. Lond. A 1894 **185**, 913-941
doi: 10.1098/rsta.1894.0015

XV. *An Instrument of Precision for Producing Monochromatic Light of any desired Wave-length, and its use in the Investigation of the Optical Properties of Crystals.*

By A. E. TUTTON, *Assoc. R.C.S., Demonstrator of Chemistry at the Royal College of Science, South Kensington.*

Communicated by Prof. THORPE, *F.R.S.*

Received January 11,—Read February 1, 1894.

IN the optical investigation of crystals it is of great advantage to command a ready means of illuminating the field of the observing instrument with light of any desired wave-length. The red, yellow, and green monochromatic light emitted by incandescent salts of lithium, sodium, and thallium has hitherto been considered sufficient for most crystallographical investigations. The disadvantages of employing such a source of monochromatic illumination are threefold. In the first place it is difficult to remove the last traces of the relatively more powerfully illuminating sodium from the lithium salt employed. The admixture of yellow with the red light is a very great inconvenience when determining refractive indices by the method of total reflection and when measuring the optic axial angle of biaxial crystals by observations of the separation of the hyperbolic brushes of the interference figures. In the latter case, owing to more or less dispersion of the axes for light of different wave-lengths, the effect of the admixture of even a little of the highly illuminating yellow sodium light with the red lithium light is to diminish the definition of the brushes, the interference figures for the two colours being superposed, and thus to destroy the possibility of accurate measurement of the separation of the axes for lithium light. In the second place, the poisonous nature of the fumes of the volatile thallium salts renders it imperative that the green flame should be produced in a draught cupboard, and all observations conducted in front of it, a condition which it is frequently inconvenient to fulfil. The third and most weighty objection to this mode of producing monochromatic light is that it confines the observations to three wave-lengths, at considerable intervals apart, ceasing, however, with the yellowish-green, and leaving the blue end of the spectrum out of consideration altogether. For substances whose crystals exhibit very slight dispersion of the optic axes this may, perhaps, be conceded to be sufficient, although, even in these cases, the observations cannot be considered as complete. For the numerous substances, however, whose crystals are endowed with sufficient dispersion to exhibit considerable differences of optic axial angle, and (in crystals belonging to the two systems of least symmetry) differences in the directions of stauroscopic extinction, observations with light of only these three wave-lengths are insufficient. Moreover, in the cases occasionally met with—such as the rhombic form of titanium dioxide known as brookite, the rhombic triple tartrate of sodium potassium and ammonium, and the monoclinic ethyl-triphenylpyrrholone described three years ago by the author,*—in which the dispersion is so large that the axes for red light lie in a plane perpendicular to that which contains them when illuminated by blue light, observations with lithium, sodium, and thallium light are totally inadequate to enable us to follow the change which must occur as the wave-length of the light is altered, and, except by mere fortuity, afford no means whatever of observing the interesting point when the wave-length is such that the axes coincide in the centre of the field and the biaxial crystal simulates a uniaxial one.

It is evident, therefore, that for the complete investigation of the optical properties of crystals, an arrangement for procuring monochromatic light must be adopted which will enable us to illuminate the field of the observing instrument with the whole of the spectrum colours in succession. A step towards supplying such a requirement has been made by FUESS, the well-known crystallographical optician of Berlin, in his larger axial angle goniometer. In front of the objective of the polariscope are placed a small prism and a collimating tube, arranged at such an angle to the polariscope that the light from a lamp passing through the slit of the collimator is dispersed by the prism into a spectrum, the whole of which is seen in the field on observing through the polariscope. The prism is capable of rotation, the amount of which is registered by a micrometer. It is intended that the readings of the micrometer shall be recorded for the coincidences of the vertical cross-wire of the polariscope with the principal lines of the solar spectrum, so that light of any particular wave-length may be brought into the centre of the field when using any artificial source of white light In practice, however, the author finds this arrangement unsatisfactory. The smallest amount of "backlash" in the working of the endless screw and wheel by which the rotation of the prism is effected introduces a considerable error in the reproduction of the setting for any solar line. But, even assuming the construction perfect at first and to remain so after use, the arrangement labours under the great inconvenience that the whole, or, when the second power is employed, almost the whole, of the spectrum is visible at once. Although it may be true that a fair approximation to the value of the optic axial angle for any wave-length may be obtained in cases where the dispersion of the axes for different colours is not considerable, by bringing light of that wave-length to the vertical cross-wire (or between the pair of cross-wires) to which the hyperbolic brushes are also successively adjusted, still the rings and lemniscates surrounding the axes are distorted more or less according to the amount

* 'Journ. Chem. Soc.,' 1890, 733; 'Zeitschrift für Krystallographie,' XVIII., 563.

of dispersion by the other portions of the spectrum in the field of view. In cases where the dispersion of the axes is great the method fails altogether, for the interference figures become perfectly unintelligible.

From the above discussion of the methods hitherto adopted, it will be apparent that the ideal arrangement must be one by means of which *the whole field* of the optical instrument is evenly illuminated with light of as nearly as practicable one wave-length, which may be rapidly varied, as desired, from one extreme of the spectrum to the other. The apparatus now described enables these conditions to be fulfilled. It was suggested by the arrangement described by ABNEY,* and employed in his researches, in conjunction with FESTING,† upon colour photometry.

ABNEY'S arrangement consists essentially of a spectroscope with two prisms, but with the eye-piece of the observing telescope replaced by a screen, upon which the spectrum is received, and which is perforated by a movable and adjustable slit, through which any desired portion of the spectrum may be allowed to escape. This slit of monochromatic light is allowed to fall upon a lens of comparatively large diameter, and of such convenient focal length that an image of the nearest surface of the second prism may be thrown upon the screen which it is desired to illuminate, in the form of a uniform patch of light involving fewer wave-lengths the narrower the slit. The position of the screen with relation to that of the lens is such that the successive patches of colour all illuminate the same space upon the screen.

The arrangement now described, while similar in principle to that of ABNEY, differs from it in certain important particulars rendered necessary by the exigencies of crystallographical optical work. The chief differences and innovations are as follows :—

1. Instead of desiring to illuminate an opaque screen, to be observed by reflection, it is desired to employ the beam of monochromatic light in directly illuminating the field of an optical instrument, the polariscope of an axial angle goniometer for instance. Hence the large lens, so conveniently used by ABNEY to direct the coloured light upon a screen, is discarded, and the objective of the observing instrument is brought to within an inch or so of the exit slit, thus utilising the whole of the issuing coloured light and economising space.

2. Instead of a movable slit, which, the lens being discarded, would necessitate a corresponding but highly inconvenient movement of the observing instrument in order that the issuing light for all the different colours should always pass along its optical axis, the exit slit is fixed.

3. The different colours of the spectrum are caused to pass the fixed exit in succession by rotation of the dispersing apparatus. This latter consists, instead of two prisms as employed by ABNEY, of one large 60° prism whose faces are capable of receiving almost the whole of the light from the collimating lens of two inches

* 'Phil. Mag.,' 1885, vol. 20, p. 172.

† 'Phil. Trans.,' vol. 177, p. 423.

aperture, and of filling the similar lens of the exit tube with the dispersed beam. The convenience of employing a single prism when rotation is required will be obvious. The disadvantage of less dispersion is avoided by constructing the prism of glass endowed with as high dispersive power as can be obtained without introducing colour and consequent absorption of the violet end of the spectrum.

4. By placing an eyepiece in front of the exit slit, the optical tube carrying the latter may be temporarily converted into a telescope, for the purpose of observing solar or metallic lines. The jaws of the exit slit when nearly in contact (their normal position when the instrument is being used to produce monochromatic light), are clearly focussed by the eye-piece and act precisely like a pair of parallel vertical cross-wires, midway between which any solar or metallic line may be adjusted by suitable rotation of the prism. A fine graduation of the circle which carries the latter, aided by a vernier, enables this position, for as many lines as it may be desired to observe, to be once for all recorded in a table, and graphically expressed by a curve. The collimator and telescope remaining fixed, it is only necessary in order at any subsequent time to produce light of any desired wave-length to set the prism circle to the reading recorded for that wave-length, to remove the eye-piece and to illuminate the slit of the collimator by the rays from any source of light whatsoever. The light issuing from the exit slit will then be of the wave-length desired.

5. The narrow band of monochromatic light issuing from the exit slit, when allowed to pass directly along the optical axis of the instrument to be illuminated, appears, upon looking through the latter, as a brilliant coloured line forming the vertical diameter of the field of view. By the simple device of placing a plate of finely ground glass immediately in front of the objective of the observing instrument, the line of light is diffused so that the whole field of the instrument is evenly and brightly illuminated with monochromatic light of the very few wave-lengths which are permitted to escape through the exit slit.

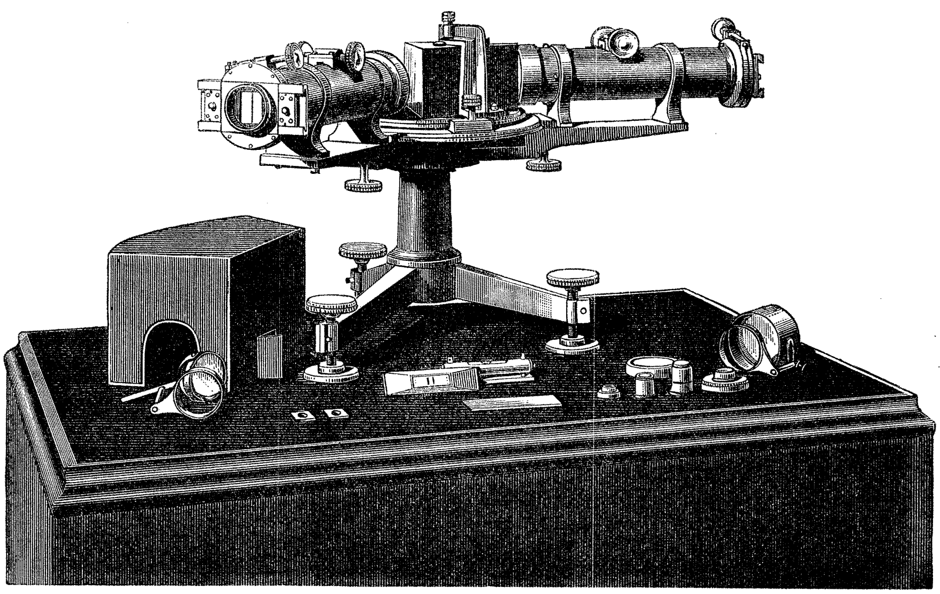
The essential constructive details will now be given.

Construction of the Instrument.

The whole arrangement is devised so as to pass as much light as possible, in order that when the two slits are almost closed, using the oxy-coal gas lime-light or other equally powerful illuminant as source of light, the small fraction of the spectrum emerging may still afford ample illumination of the field of the observing instrument, after diffusion by the ground glass, to enable accurate observations to be made with light as far as G in the bluish-violet, and as far as F when a less powerful illuminant, such as an incandescent gas-light burner, is employed. The instrument and its various accessories are represented in fig. 1.

The two optical tubes are precisely similar in all respects, so that either may be employed as collimator. They are each about nine and a half inches in length, the slit in each case being placed at the focus of the achromatic lens combination of nine inches focal length and two inches aperture. The lens combination of each consists of two lenses, one hard crown and the other dense flint, both perfectly colourless. The lenses are not cemented together by balsam or other mounting medium, but are held in metal mounts and slightly separated from each other by a brass ring, so that they include between them an air space. By adopting this arrangement there is no risk of the setting being disturbed by the long-continued passage of the heat rays from a powerful source of light; and there is consequently no necessity for the troublesome interposition of a cell containing alum or any other liquid for the purpose of filtering out the heat rays. The spherical aberration was approximately corrected by making the outside surface of the crown-glass lens to deviate slightly from the spherical figure, and the final corrections for both spherical and chromatic aberration were effected by adjustment of the amount of separation of the two lenses. The

Fig. 1.



comparatively large aperture of two inches, together with the short focal length of nine inches, allows of the passage of a large amount of light while rendering the instrument compact.

The slit of each optical tube is carried at the end of an inner tube, capable of the necessary amount of motion in and out of the wider tube which carries the lens combination, by means of a rack and pinion worked by a milled head. The slit is specially adapted for the purpose in view by being constructed so that the two jaws move equally in opposite directions on each side of the central line of contact. This is essential in order that, for different amounts of opening to suit crystal plates or prisms of different degrees of transparency or sources of light of different intensities,

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

the light of the wave-length for which the prism circle has been set shall always remain in the central line between the two jaws. The manner in which this object has been attained will be apparent from figs. 2, 3, and 4, which are reduced to about one-half the actual size.

Fig. 2.

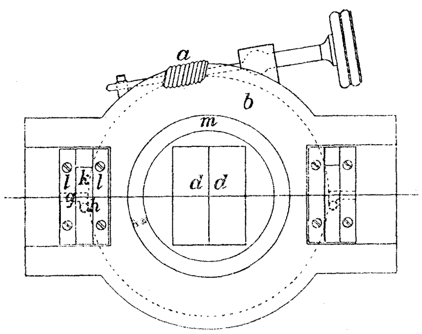


Fig. 3.

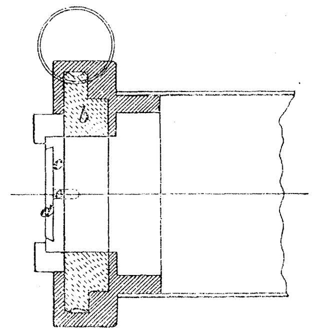
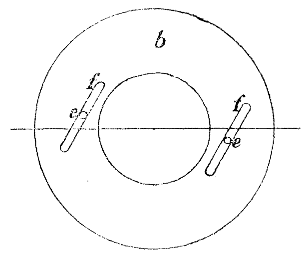


Fig. 4.



The principle lies in the adoption of an endless screw and wheel, in which latter two similar grooves are cut upon opposite sides of the centre, which, by means of sliding-pins connected with the jaws, bring about the desired equal and opposite movement of the latter. Fig. 2 is a front elevation of the slit-box, showing the endless screw *a*, which, for the sake of clearness, is not dotted and its nut-cap is omitted, and (dotted) wheel *b*. Fig. 3 represents a section of the box, showing the wheel *b* in its setting in the rigid framework of the box, the slide *c*, which carries the hard white metal bevelled jaws *d*, and the pin *e*, fixed in the slide, and whose motion is directed by the slots in the wheel. Fig. 4 is an elevation of the wheel, showing the slots *f* which move the slides by means of the pins. The "pitch" of the slots is equal to one-half the total opening of which the slit is desired to be capable, which is adjusted so that the jaws may be sufficiently withdrawn to enable an unobstructed field of view to be obtained when the optical tube is used as a telescope for observing the solar or other spectrum.

It is further provided that the white metal jaws may be removed altogether, in order that the single slit may be replaced by two or more whenever it is desired to employ composite light taken from definite parts of the spectrum. This is useful in order to be able to study the effect of such composite light upon the interference figures afforded by crystals whose dispersion of the optic axes for different colours is so great that the axes for red and blue light lie in planes at right angles to each other. The study of such figures in composite light is of assistance in appreciating the nature of the remarkable figures observed when white light is employed. It is for this purpose that the jaws themselves are not directly moved, by the wheel; they are held in close contact with the slides *c*, which are directly moved, by being made to slide in a dove-tailed recess cut out of the latter, as shown in fig. 3, and when their knife-edges are brought just beyond the edges of the slides they are locked firmly to them by means of a simple locking arrangement, shown in fig. 2. In the slide *c* an L-shaped groove *g* is cut, in which slides a pin *h*, carried by the jaw. This pin is not fixed into the jaw itself, but into a short slider *k*, furnished with bevelled edges, which is capable of sufficient vertical motion between two guides *l* (one edge of each of which is likewise bevelled, so as to form together a dove-tail in which the slider is supported), to enable the pin to be raised to the level of the horizontal part of the groove, when the jaw may be readily withdrawn. In order to place the jaw in position again it is only necessary to slide it into its dove-tailed recess, until the pin reaches the end of the horizontal part of the groove; it is made to slide quite smoothly, without jamming, by fitting a short curved spring in a suitable niche in the upper horizontal edge, so as to press slightly against the upper guide; the slider *k* is then lowered so as to bring the pin down the vertical portion of the groove, when the jaw will be firmly locked to the slide *c*. The pin and groove are so well fitted that precisely the same position is always occupied by the jaw, when locked, with respect to the slide.

When it is desired to utilise the above arrangement for the purpose of replacing the single slit by two or more, it is found more convenient to construct them permanently in a simple but highly accurate manner, which will be described under the heading, "Mode of Production and Use of Composite Light," than to employ an elaborate metal arrangement of several movable and adjustable slits, such as is so admirably adapted to ABNEY's form of apparatus, but upon which inconvenient limitations are necessarily imposed, and which would require re-adjusting by means of the solar or a metallic spectrum for every variation.

The full width (using this term in its current sense denoting the longest dimension of the opening) of the slit of each optical tube is one inch; this relatively large width is not intended to be generally utilised, but is provided for use in observations with imperfectly transparent crystals, when, subject to limitations to be presently specified, it is of great advantage as it transmits a correspondingly large amount of light. It is of course impossible with a slit of one inch width to avoid a slight curvature of the spectral lines. W. H. M. CHRISTIE* has shown that this curvature cannot be eliminated by adjustment of the prism or prisms, and that it increases with the number of prisms; hence it is least with a single prism as used in this arrangement. The lines are slightly concave towards the normal to the surface of incidence of the prism. Particular care has been taken in the setting of the lens combinations that such curvature should not be accentuated by any slight want of parallelism in the incident light. The slight deviation from perfect monochromatism in the light issuing from the exit slit, consequent upon this slight curvature of lines of light vibrating with the same wave-length, is found in practice to be no detriment whatever in the measurement of the optic axial angles of crystals whose dispersion of the axes for the red and blue does not exceed 5°, and the brilliant illumination of the field by use of the one-inch slit is a very great advantage when dealing with sections

* 'Roy. Astron. Soc. Monthly Notices,' 1874, 263.

of crystals of imperfect transparency. For use with clear sections and for all cases where the dispersion amounts to or exceeds the limit just specified, and also for use in all determinations of refractive index by means of prisms, a series of four stops, perforated by circular apertures of $\frac{5}{8}$-inch, $\frac{1}{2}$-inch, $\frac{3}{8}$-inch, and $\frac{1}{4}$-inch diameter respectively, are provided by which the width of the slit may be suitably diminished. The stop most frequently employed by the author is the one of $\frac{3}{8}$-inch diameter, which affords spectral lines which are apparently perfectly straight. This definite mode of reducing the width of the slit is found more convenient than by use of the usual >-shaped arrangement, and it is more satisfactory to have the ends perpendicular to the length of the opening. The stops are fitted with a light spring at one side to keep them in position in the rectangular recess in front of the slit. Two of them are shown in fig. 1 lying on the base-board. The illumination of the field of the observing instrument, when the slits are nearly closed and the quarter-inch stop is placed in front of the receiving slit, is still sufficiently good, when the lime-light is the source of light, to enable excellent measurements of axial angles or refractive indices to be carried out with F light, and when the sections or prisms are clear with G light. If it is inconvenient to employ the lime-light, excellent measurements may still be obtained as far as F light by substituting for it in the lantern the improved form of incandescent gas-light burner, as described in the preceding communication, and slightly increasing the opening of the receiving slit.

The slit frame at the end of each optical tube terminates in a slightly projecting annulus, *m* in fig. 2, of one and-a-half inch diameter, carrying on its outer surface a screw-thread upon which can be screwed the small eye-piece tube, which serves as a carrier for either of three eye-pieces, magnifying respectively two, four, and six diameters. The tube and its three eye-pieces are shown slightly to the right of the centre of the base-board in fig. 1. The eye-pieces are constructed to focus the closely approximated jaws of the exit slit immediately in front of them, so that when the spectral lines are focussed by means of the rack and pinion movement which adjusts the distance between the lens combination and the slit, the knife-edges of the slit jaws are likewise in focus, and serve all the purposes of a parallel pair of vertical cross-wires between which the spectral lines may be adjusted by suitable rotation of the prism.

Each optical tube is capable of independent rotation round the axis of the instrument, by means of the counterpoised arms. Each may be fixed in any position, by means of clamping-screws, to the lower circle which carries the vernier and which is rigidly fixed to the central pillar of the strong stand, and whose plane is accurately perpendicular to the axis of rotation of the optical tubes and of the prism. The prism is carried upon a rotating table parallel to the lower circle, and which is graduated for 180°; the graduations read directly to half-degrees, and, with the aid of the vernier, to single minutes. This rotating circle may be fixed for any reading by means of the clamping arrangement seen in front of the prism in fig. 1. A fine adjustment is provided for the circle, and it is made readily detachable, so that it may be arranged at any convenient position on the limb, or may be removed altogether if not required. It is shown in position in fig. 7. It is constructed in two parts. A double elbow-piece, fitting closely to the circle-plate, and capable of being tightly clamped to it by means of two milled-headed screws passing through the upper plate of the piece, carries an outwardly projecting arm; the latter is pressed between the ends of a long milled-headed screw of fine thread and a spring piston, similar to those employed in the fine adjustment of the circle of the instrument described in the preceding communication. The tangent-screw and piston are carried by a second elbow-piece enveloping a segment of the limb of the lower fixed circle; the upper plate of this elbow-piece is sufficiently short (radially) to permit the upper elbow-piece to move past it without touching; but the lower plate is longer, in order to afford a rigid grip, and carries the two clamping-screws, by which it may be fixed from underneath to the circle. The graduated surface of the movable circle is protected from the upper clamping-screws by means of a thin intermediate plate of hard white metal, lined next to the graduated surface with chamois leather. The distance between the ends of the nut of the tangent-screw and the cylinder of the piston is sufficiently great to enable the projecting arm, and with it the circle, to be moved by rotation of the tangent-screw through a little more than 7° of arc, sufficient to enable the whole spectrum, from A to a little beyond G, to be brought past the exit slit. The prism is firmly fixed to the rotating circle by means of an angle bracket and screw, which latter is prevented from injuring the top of the prism by causing the pressure to be applied to a slightly convex hard white metal plate, shaped like a three-rayed star, the three terminations of which rest upon the top of the prism; the centre of the plate is perforated with a small hole, into which the rounded end of the screw fits without being able to pass through it. The lower portion of the strengthening rib of the angle bracket may be conveniently utilised as a handle, with which to effect the rotation of the prism and circle, whenever the fine adjustment is not in use.

The 60° prism is larger than usual, having sides of four-and-a-half by two-and-a-half inches, in order to be able to utilise as much of the light from the two-inch collimating lens combination as possible. The heavy flint-glass, which was supplied by Messrs. CHANCE, possesses as high a dispersive power as it was possible to obtain without introducing colour, in order that the dispersion shall not suffer much by the use of only one prism. There is a limit to the dispersion which can be employed, for if it is excessive, as by use of some of the very dense glasses now available, it is found that the whole of the spectrum cannot be brought to pass the exit slit by rotation of the prism without serious loss of light by reflection from the receiving surface, owing to the large angle through which the prism requires to be rotated. The essentials of the prism are, therefore, that it shall be free from colour in order that it may fully transmit the blue end of the spectrum, and that it shall possess the highest possible dispersion which will still enable the whole of the spectrum, from A to H′, to be brought between the nearly closed jaws of the exit slit by rotation of the prism without materially sacrificing the light by reflection. The heavy colourless glass supplied by Messrs. Chance satisfies these conditions, its dispersion being higher than that of ordinary flint, while not too great to be a disadvantage. Very great care has been taken to make the two utilised surfaces truly plane, and at right angles to the base. The high cost of so large a prism of heavy glass, truly worked, is amply compensated by the advantage gained in the large amount of light transmitted. The definition of the solar and metallic lines afforded by this prism and the lens combinations previously described, is of very high quality up to the extreme end of the violet. With the lowest power eye-piece, magnifying two diameters, the two D lines of sodium are clearly separated; the second eye-piece, magnifying four diameters, exhibits them half a millimetre apart; and the third eye-piece, magnifying six diameters, separates them by quite an apparent millimetre.

For convenience in viewing the solar lines a small mirror is provided, which is capable of the four motions necessary for the reflection of sunlight along the axis of the collimator. Its carrier is attached to an annulus furnished with a milled flange, and carrying a screw thread upon its inner surface of the same pitch as that of the eye-piece carrier, so that it may be firmly screwed to the projecting annulus, *m* in fig. 2, of the slit frame of that optical tube which is chosen for convenience as collimator, just as the eye-piece carrier is screwed to the similar annulus of the other optical tube which it is desired to use as telescope for the purpose of observing the solar lines. The mirror and its carrier are represented at the left-hand corner of the base-board in fig. 1.

The ground glass screen which is employed for the purpose of diffusing the line of monochromatic light escaping from the exit slit, in order that the whole field of the observing instrument may be evenly illuminated, is conveniently held in a small carrier forming an attachment in front of the exit slit similar to that just described. This attachment is shown at the right-hand corner of the base-board in fig. 1. It consists of an annulus provided outside with milled flange and inside with a screw thread capable of engaging with that upon the projecting annulus of the slit frame, exactly similar to that which carries the adjustable mirror; to the arm carried by the annulus is fixed at right angles, that is horizontally, a strong rod of square section and $2\frac{1}{2}$ inches long. Upon this rod slides easily a short tube of similar square section and bore, which supports, by means of a short upright, the tube of two inches diameter and two inches length which carries within it the ground glass screen. The slider can be fixed in any position along the rod by means of a clamping screw. Two ground glass screens are provided, one of the texture of fine photographic focussing glass, and the other still more finely ground. They are mounted in circular metal frames like lenses, and the frames are of such a size as to be capable of sliding fairly tightly in the carrying tube. In the illustration one screen is represented in position inside the tube, and the other lies on the base-board just behind the eye-pieces. Either screen may be employed according to its ascertained suitability for use with the particular optical instrument to be illuminated, and the screen chosen may be placed in any position in the carrying tube, best with the ground surface nearest the slit in order to avoid loss of light by reflection from the smooth surface. For certain work it is best to have it right at the end nearest the slit, so that by sliding the whole tube along the rod the screen may be brought close up to the slit frame; while for other classes of work it is advantageous to remove it as far from the slit as possible by placing it at the other end of the tube and sliding the latter away from the slit as far as the length of the rod permits. For most purposes, however, it is best to place it in the centre of the carrying tube, when it is shaded on both sides from extraneous light, and the half of the carrying tube furthest from the slit serves as a dark box into which the end of the observing instrument may be pushed until its objective almost touches the screen.

The whole instrument is mounted upon a strong base-board, upon which it can be levelled by means of three strong levelling screws resting in toe plates. The base-board is conveniently covered with black velvet so that, with the aid of suitable folding screens constructed of strong cardboard and covered inside also with black velvet and outside with dark red cloth, the whole apparatus may be readily enclosed whenever desired (on account of imperfect transparency of the crystal under examination) in a dark chamber and thus effectively shaded from stray light from the lantern. In ordinary cases, with good transparent crystals, it will be found sufficient to cover the prism and the ends of the optical tubes at which the lenses are placed with a dark box of the kind shown in fig. 1, also constructed of cardboard and covered inside with velvet and outside with dark red cloth, and in which a small movable door is left through which the rotation of the prism can be effected. The base-board is in turn mounted upon a strong daïs, of such a height above the table upon which the whole arrangement stands that the plane of the axes of the optical tubes is raised to the level of the eye when the observer is seated. This daïs is conveniently covered with the same dark red cloth, which enables the base-board, whose under surface is smooth, to be easily moved over the daïs and rotated 90° upon it, as will be subsequently shown to be desirable in order to be able to approach certain observing instruments sufficiently near to the slit, the daïs otherwise being in the way of the support of the observing instrument. Moreover, if the table has a polished surface, the daïs base-board and instrument can be readily moved *en bloc* to any required position. The instrument is so heavy, being so solidly constructed, that these apparently trivial arrangements are of considerable moment. The base-board is grooved around its margin for the reception of a rectangular protective glass shade when the instrument is not in use.

Determination of Circle Readings for the issue of Light of Definite Wave-lengths.

The determination of the prism circle readings for the passage of light of certain wave-lengths through the exit slit, in order that light of any wave-length may at any subsequent time be reproduced, is carried out as follows :—

The reflecting mirror is attached in front of the slit of that optical tube which is to be used as collimator, and the eye-piece holder carrying one of the eye-pieces, perferably the second one magnifying four diameters, is attached in front of the slit of the other optical tube so as to convert the latter into a telescope. Sunlight is then reflected along the axis of the collimator, and the jaws of the slit of the latter are approached until the best definition of the solar lines is obtained upon looking through the telescope and arranging the prism and telescope for minimum deviation of the refracted rays. The exit slit in front of the eye-piece should be opened wide in order to obtain an unobstructed view of the whole field, when about one-half of the spectrum is included in the field at once, and by moving the telescope the whole spectrum may be observed. It is manifestly impossible, however, with the prism set for minimum deviation to bring the whole of the colours of the spectrum into the centre of the field by rotation of the prism, the telescope being fixed. But if while the prism is arranged for minimum deviation the telescope is moved round some little angular distance, so as to pass the whole of the spectrum from red to blue, and is fixed in a position when the centre of the field is just past the extreme violet, a wave length in the ultra-violet being thus set centrally at minimum deviation, it will then be possible by movement of the prism in either direction to bring the whole of the colours of the spectrum in succession past the vertical diameter of the field. That one of the two directions of movement of the prism is chosen in which the greater loss of light by reflection from the receiving surface of the prism occurs when the red end of the spectrum is brought to the centre of the field, and the lesser loss when the feebler illuminating violet end is central ; by this choice the illuminating values of the different colours are rendered less unequal than they usually are with a fixed prism, while if the other direction is chosen the inequality is intensified. The definition of the solar lines for this setting is still admirable, the focussing being achieved by means of the milled head in connection with the rack and pinion.

Having firmly clamped the telescope to the fixed lower circle, the solar lines for which it is desired to record the prism circle readings are well noted while the exit slit is still widely open. The jaws of this slit are then brought so closely together that the interval between their knife-edges, which are clearly defined by the eye-piece, is only very slightly greater than that between the two sodium D lines, that is, not greater than two-thirds of an apparent millimetre. The desired solar lines are then in turn brought, by rotation of the tangent screw of the fine adjustment, midway between the two edges of the slit, which thus act like a pair of vertical cross-wires. The exact distance of the jaws apart is of no consequence so long as it is sufficiently small to permit of accurate adjustment of the lines to the central line between them, as the jaws move equally on each side of this central line. If the whole width of the receiving slit is employed the lines are very slightly curved as previously stated, but as the centre of the line is the part adjusted there is no real necessity to stop the slit down with one of the smaller stops. If, however, the $\frac{3}{8}$-inch or $\frac{1}{4}$-inch stop is placed before the receiving slit the lines are then apparently quite straight and fall wholly in the central line between the two jaws when adjusted.

The readings of the prism circle are then taken, with the aid of the vernier, for each of the lines so adjusted by suitable movement of the prism, and recorded in a table. This table should be supplemented by a curve, in order that the readings for intermediate wave-lengths may be obtained by interpolation. The readings for the solar lines of hydrogen may be confirmed, if considered desirable, by use of a hydrogen Geissler tube illuminated by means of four Grove's cells and an induction coil. It is also convenient to confirm the sodium readings, and to extend the observations by recording the readings for the red lithium and the green thallium line. For this purpose it is convenient to have at hand a metal-lined box, fitted with a window in front and a door behind, a chimney above and air holes in the raised base, containing a Bunsen lamp and an arrangement for bringing one of three platinum spoons, containing respectively a supply of a sodium salt, a lithium salt, and a smaller quantity of a thallium salt, into the flame as desired by means of a rotating arrangement manipulated from outside by means of a lever. This arrangement is also very convenient for confirming the circle readings before and after every important investigation, in order to be quite certain that no movement of any of the parts of the instrument shall have occurred. For this purpose it is sufficient to ascertain whether the reading for the double sodium line remains the same. It is thus only necessary to use the poisonous thallium vapour for a few seconds during the first determination of the reading for that wave-length. Although the exit slit frequently requires slight opening or closing, to suit the lesser or more perfect transparency of the crystals examined, the readings for the sodium and hence for all the lines have never been found to vary by more than two minutes of arc.

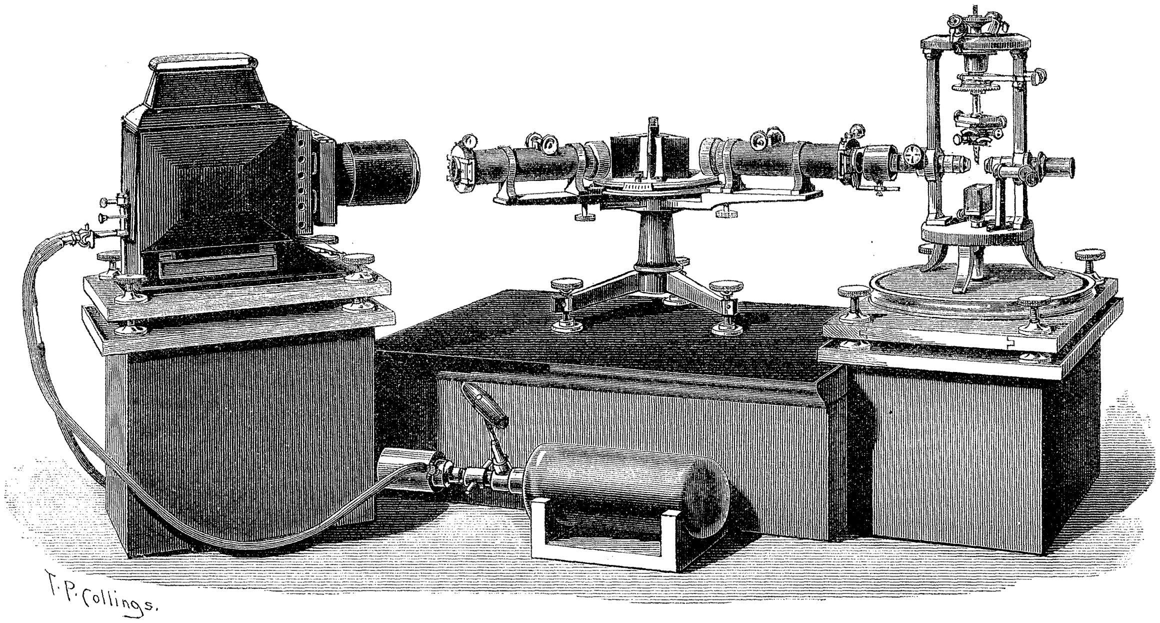
After thus determining the relation between the wave-length of the issuing light and the prism circle readings, the mirror and the eye-piece are removed from before their respective slits, and it is only necessary, when at any time monochromatic light of any specific wave-length is required, to set the prism so that the circle reading is identical with that recorded in the table, or obtained by interpolation from the curve, for light of the wave-length in question, and to illuminate the slit of the collimator with a sufficiently powerful artificial source of light. Tho oxy-coal gas lime-light affords ample illumination with slits nearly closed, and if the observer is sufficiently fortunate to have an electric arc lamp at his disposal the openings of the slits may be so fine that the slightest further movement of the milled head of the tangent screw closes them altogether. If the receiving slit is opened to the extent of a third of a millimetre and the exit slit to about a quarter of a millimetre, sufficiently good illumination may be obtained with wave-lengths up to F by employing the incandescent gas-light previously referred to in the lantern instead of the lime or electric light, retaining the condensers of the lantern to concentrate the rays upon the slit.

The wave-lengths mostly employed by the author in crystallographical investigations are those corresponding to the red lithium line, the red hydrogen line C, the yellow pair of sodium lines D, the green thallium line, the greenish-blue hydrogen line F, and the bluish-violet hydrogen line G, supplemented by other well marked intermediate solar lines in cases of extreme optic axial dispersion. The angular difference between the circle readings for the lithium and G lines is 6° 10′ in the author's instrument, and as the readings can be made directly to minutes, and a deviation of one minute from the setting between the edges of the slit is readily perceived, it will be at once apparent that light of any wave-length can be produced with a very high degree of accuracy.

Use of the Instrument in the Measurement of Optic Axial Angles.

The whole arrangement for the measurement of optic axial angles—by the observation of the separation of the hyperbolic brushes of the interference figures afforded by a pair of sections perpendicular to the first and second median lines respectively in convergent light, and with nicols crossed at 45° from the horizontal

Fig. 5.



and vertical positions—is shown in fig. 5. The lantern and the axial angle goniometer are conveniently mounted upon firm box supports of rectangular shape and covered with dark red cloth like the daïs of the monochromatic light apparatus, in order that they may be easily moved over the polished table into any required position. The block supports should carry levelling tables, each consisting of two mahogany boards, framed and with flush panels in order to increase their rigidity;

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

the lower of these boards is screwed down upon the top of the basal support, and carries four toe-plates in which rest four strong levelling screws working through nut-plates screwed to the upper board. The height of the blocks is so arranged that the optical axis of the light issuing from the condensers of the lantern, and that of the polariscope of the axial angle goniometer, may be adjusted by means of the levelling screws to exactly the same plane as that in which the axes of the optical tubes of the monochromatic light apparatus lie, that is to the level of the observer's eye when seated.

The axial angle goniometer may conveniently rest upon a circular base-board with grooved margin for the reception of a protective glass shade, rather than directly upon its levelling table; for the under surface of the base-board can be covered with cloth or felt, and the heavy instrument, together with the base-board, can then be readily moved about upon the polished levelling table, and the adjustment is facilitated.

The crystal plate perpendicular to the first median line is first attached to the crystal holder, and adjusted by means of the adjusting and centering motions provided upon the goniometer. The section itself is either mounted upon a circular glass plate, as described in the preceding communication, or is suspended unmounted by means of a strip of thin glass, to which it is fixed at some point on its edge by means of a little marine glue or other cement which is not attacked by the highly refractive liquid to be employed, and which is held by the crystal holder. Sections prepared by use of the instrument described in the preceding memoir may always be suspended unmounted provided the specified time has been bestowed upon the final polishing, and the observations are then unaffected by slight errors due to the cover glass or want of parallelism in the cementing film. The adjustment is carried out in ordinary white light, so that the monochromatic light apparatus may not be unnecessarily used on these preliminaries. For this purpose the goniometer and its base-board are rotated through a right angle upon the levelling table, and the polariscope is illuminated by the goniometer lamp described in the foregoing paper.

Having adjusted the section in white light so that the hyperbolic brushes and the rings and lemniscates are bisected by the horizontal cross-wire of the polariscopical eye-piece, the short tube carrying in its centre the more coarsely ground of the two diffusing screens is attached in front of the exit slit of the monochromatic light apparatus, so that the ground glass surface is distant about one and a half inches from the slit, the goniometer is rotated until its axis forms a continuation of that of the exit tube of the latter instrument, and moved up towards the ground glass screen until the end of the polarising tube enters the diffusing tube and all but touches the screen. The prism and the ends of the optical tubes are then covered by the dark box and the circle set to the reading recorded in the table for light of the wave-length to be first employed, usually that corresponding to the passage of red lithium light through the exit slit. The light is generated in the lantern, and the observations are commenced by rotating the section in the usual manner so that the two hyperbolic brushes are in turn brought between the pair of vertical cross-wires, and observing the corresponding angular readings recorded by the goniometer circle and pair of verniers. After repeating the observations with light of the same wave-length once or twice, according to the definition of the brushes afforded by the particular section, the prism is rotated until light of the next desired wave-length is allowed to pass the exit slit, when the observations are repeated, and so on for as many wave-lengths as are desired. When once used to the arrangement a series of observations for the six wave-lengths mentioned at the close of the last section may be carried out in triplicate in less than half-an-hour. Employing the lime-light, the slits need only be opened so that the D lines would appear just coalesced if the entrance slit were illuminated by a sodium flame, and the spectrum were observed by placing the eye-piece in front of the exit slit. The illumination for D light is then as bright or brighter, even when the entrance slit is stopped down to $\frac{1}{4}$ inch, than when the polariscope is placed directly in front of a good sodium flame, and the illumination for lithium light is vastly superior to that obtained by use of a lithium flame. Moreover, the illumination is quite evenly distributed over the field, and the interference figures are wonderfully sharp. Results only slightly inferior are obtained by using the incandescent gas-light with a receiving slit of about twice the opening.

After the conclusion of the measurements of the apparent angle (2E) in air, the glass cell containing a colourless oil, or preferably the highly refractive liquid bromine derivative of naphthalene, α-monobromnaphthalene, is raised until the crystal is fully immersed in the liquid, and a similar series of measurements are made of the apparent acute angle (2 Ha) in the highly refractive liquid. The light may then be temporarily extinguished in the lantern while the section is removed from the crystal holder, and the second section, perpendicular to the second median line, is placed there in its stead, and adjusted in white light by means of the goniometer lamp, whose by-pass has been left burning in order to save time in re-ignition of the lamp. The measurements of the apparent obtuse angle (2 Ho) of the optic axes in the same highly refractive liquid are then carried out for light of the same wave-lengths, and in a precisely similar manner as in the case of the first section.

By thus carrying out the complete series of measurements with the two sections at one sitting, a process which need only occupy about an hour, all risk of any perceptible change in the refractive index of the liquid is avoided. The results thus obtained in so comparatively short a space of time, by the aid of the monochromatic light apparatus now described, enable the true value of the optic axial angle (2V a) and the mean refractive index β, for six different wave-lengths, to be immediately calculated, and, if considered desirable, the value of these constants for any wave-length may be further expressed by embodying the results in a general formula of the type of that of CAUCHY. Moreover, provided the sections are afforded by naturally-occurring largely developed faces, or are prepared by means of the apparatus described in the preceding communication, the accuracy of the values furnished is of the very highest order.

Use of the Instrument with the wide-angle Polariscope, with particular reference to the study of Crossed Axial Plane Dispersion.

It is frequently desired to employ a wide-angle polariscopical goniometer, such as the well-known instrument forming part of the universal apparatus constructed by Fuess, of Berlin, at the instance of Groth. The aperture of the polariscope of this instrument is considerably larger than that of the more accurate instrument reading to thirty minutes of arc represented in fig. 5, and which is employed, as previously described, in the actual measurement of optic axial angles. The convergent system of lenses is also so powerful, consisting of several lenses of very short focus, that a very wide angle is included in the field of view, so that the rings and lemniscates surrounding both optic axes of most biaxial crystals are visible through a section perpendicular to the first median line. This instrument is, therefore, very convenient for studying the nature of the interference-figures, especially in cases of strongly-marked dispersion of the optic axes for different colours. The optical tube which carries the analysing nicol is provided, in addition to cross-wires, with an etched scale, which enables a rough estimation of the separation of the axes to be effected without rotating the section, and thus permits the convergent lenses of the two optical tubes carrying the polarising and analysing nicols respectively to be brought almost in contact with the two surfaces of the crystal plate, when the full aperture of the instrument is utilised. When desired, however, the tubes may be withdrawn sufficiently apart to permit of the rotation of the crystal plate, and of measurement of the separation of the axes by means of the circle and vernier, which read to minutes, but, of course, a smaller field and angle of view is presented.

Even the comparatively large field of this instrument, whose objective has an aperture of $1\frac{1}{2}$ inches, is fully and evenly illuminated upon placing it in front of the coarser ground-glass screen of the monochromatic light apparatus. The diffusing-tube is sufficiently wide to admit the end of the polarising-tube, so that the latter may be brought close up to the screen. It is not necessary to use more than the $\frac{3}{8}$-inch slit so that the monochromatism can be made as perfect as when using the more delicate instrument with smaller objective.

The investigation of cases of such extreme dispersion as to result in the optic axes for red and blue lying in different planes, may be very beautifully carried out with the aid of the instrument for producing pure monochromatic light now described. The whole phenomena may be traced with the utmost precision, from the extreme separation of the axes for the first rays of red, through the gradual approach of the axes with diminishing wave-length, until they unite in the centre of the field; and subsequently as they re-diverge along the diameter of the field perpendicular to the one which previously contained them, right up to their maximum separation for the last visible rays of violet. The exact position of the axes for any wave-length is at once obtained by setting the prism circle to the reading corresponding to the passage of light of that wave-length through the exit slit; and, in particular, the exact wave-length may be readily determined for the interesting case in which the two axes coincide in the centre of the field, when the rings and lemniscates become circles, and the biaxial crystal becomes apparently uniaxial. If it is desired to accurately measure the apparent angles for different wave-lengths the more delicate polariscopical goniometer is of course employed, the crystal being rotated 90° in its own plane after the measurements on one side of the central uniting point have been carried out in order to effect the remainder. For the purpose of merely studying or demonstrating the phenomena, however, the wide angle goniometer is employed, as the complete series of figures may then be observed in succession without moving the section, but simply by rotation of the prism of the monochromatic light apparatus.

It is the author's intention to communicate subsequently the results of a detailed investigation of a number of cases of crossed axial plane dispersion, illustrated by a series of photographic reproductions, which it is comparatively easy to produce with the aid of the apparatus now described in conjunction with a good camera.

Mode of Production and Use of Composite Light.

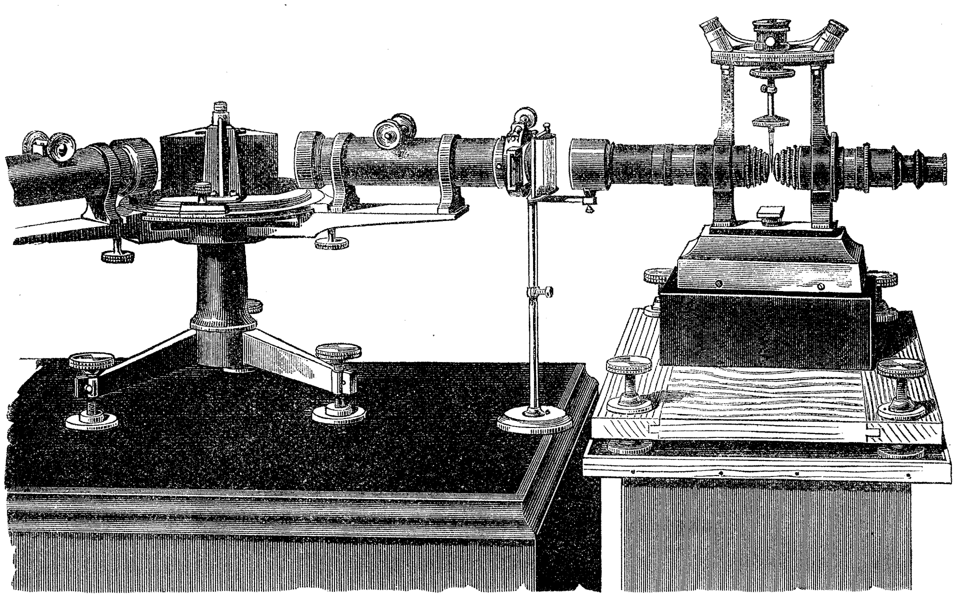
In the investigation of such cases of extreme optic axial dispersion it may be desired to supplement the measurement of the axial angle for different wave-lengths by observations of the interference-figures exhibited in mixed light taken from any two or more known regions of the spectrum. For this purpose the jaws of the exit slit are removed and their place occupied by a diaphragm pierced by two or more slits so arranged as to permit of the exit of light vibrating with the desired wave-lengths. It is found preferable in practice to construct such diaphragms in the following simple and permanent manner, ready for immediate use at any time, rather than to employ an adjustable arrangement. The slide with three movable and adjustable slits employed by Abney, and so convenient for use with a fixed spectrum, is unsuitable when the spectrum is movable.

There is provided with the instrument a slip of glass, finely ground upon one side, whose edges are bevelled and which is of the right size to be capable of sliding readily into the dove-tailed recess vacated by the slit jaws. When the slides *c* (fig. 3) are withdrawn, as far as possible, by rotation of the milled head in connection with the tangent-screw, the ground-glass surface may be employed to receive the solar spectrum or the spectra of metallic lines. Having decided what wave-lengths are to be permitted to escape through the two or three slits, the spectrum is brought into such a position by rotation of the prism that the lines corresponding to the two wave-lengths, or if three are required to the two outside wave-lengths, are about equidistant from the centre of the aperture. The lines are then clearly focussed, and a tracing of them made by means of a fine blacklead pencil upon the ground surface (which is nearest the observer) of the glass itself. Slits corresponding to the traced lines can then be cut as finely as desired in a diaphragm of stout tin-foil, the relative openings of the slits being varied slightly in the inverse proportion to that of the relative illuminating power of the light which is to pass through them. The tin-foil diaphragm is conveniently supported in a slider of hard wood, whose edges are bevelled, and which is likewise of the right size and sufficiently thin to slide into the dove-tailed recess after removal of the slip of ground glass. By employing a very hard variety of wood, such as box-wood, hard olive, or ebony, the slide may be constructed out of a single piece, and is then quite as durable and rigid as metal, and is preferable to the latter, as it is incapable of wearing the bevelled guides of the recess. It is shown in fig. 1, leaning against the spirit-level. It is furnished with two guiding-grooves, cut with a fine fret-saw, along which the tin-foil diaphragms are capable of sliding, and its central portion is cut away in order to permit the spectrum to impinge directly upon the diaphragm. By making several such diaphragms for the combinations which are likely to be required, and indelibly numbering them so as to ensure identification, any desired one may be placed in the frame at any time to furnish light of the required composition. The accuracy with which the slits have been cut should be tested at the time they are made, by placing the lowest power eye-piece in position in front of the slit-frame and observing whether the focussed lines, from a tracing of which the slits were cut, can be brought by suitably moving the slider to simultaneously occupy the centres of the slits. In order to avoid having subsequently to set the selected diaphragm to the correct place in the spectrum by the aid of Fraunhofer or metallic lines, the following simple device is adopted :—

A pair of fine marks, forming a continuation of the same vertical line as that in which the knife edges of the slit-jaws meet, have been made on the rigid framework of the slit-box immediately above and below the slit. A similar pair of marks are also made upon the guides of the wooden slider. After the diaphragm has been tested as above with the eye-piece and found to be satisfactory, the slider is adjusted in the recess so that the marks upon it are in the same vertical line with those upon the rigid framework. Maintaining the slider in this position the diaphragm, if not already so arranged, is then moved in the guiding-grooves of the slider until the same position as before is attained, when the lines are seen simultaneously focussed in the centres of the slits. A vertical mark is then likewise made upon the tin-foil diaphragm by means of a fine needle, exactly in the same line as the other marks. The reading of the prism circle is observed while so adjusted, and recorded. It is then only necessary at any subsequent time, when it is desired to employ that particular diaphragm, to place it in the slider with the mark in line with the two marks on the latter, then to place the slider in the recess so that these marks are also in line with those on the slit-frame, and to set the prism circle to the reading previously recorded for this setting of the particular diaphragm ; on illuminating as usual by means of the lantern, light of the desired wave-lengths will emerge from the slits.

The wide-angle polariscope alluded to in the last section is of course employed as observing instrument, in order that the whole figure may be visible in the field at once. Having selected the diaphragm to be used, and placed it in position as above described, and set the circle to the reading recorded for the diaphragm, the diffusing-tube is attached in front of the slit-frame and moved as far from the latter as is allowed by the length of the rod, and the ground-glass screen is placed right at the end furthest from the slit. A cylindrical lens of short focus, carried on a convenient stand, is then introduced between the diffusing-tube and the slit-frame, its plane side towards the latter, in such a position that the two or more lines of light are directed upon the same space in the centre of the ground-glass screen, where they are well

Fig. 6.

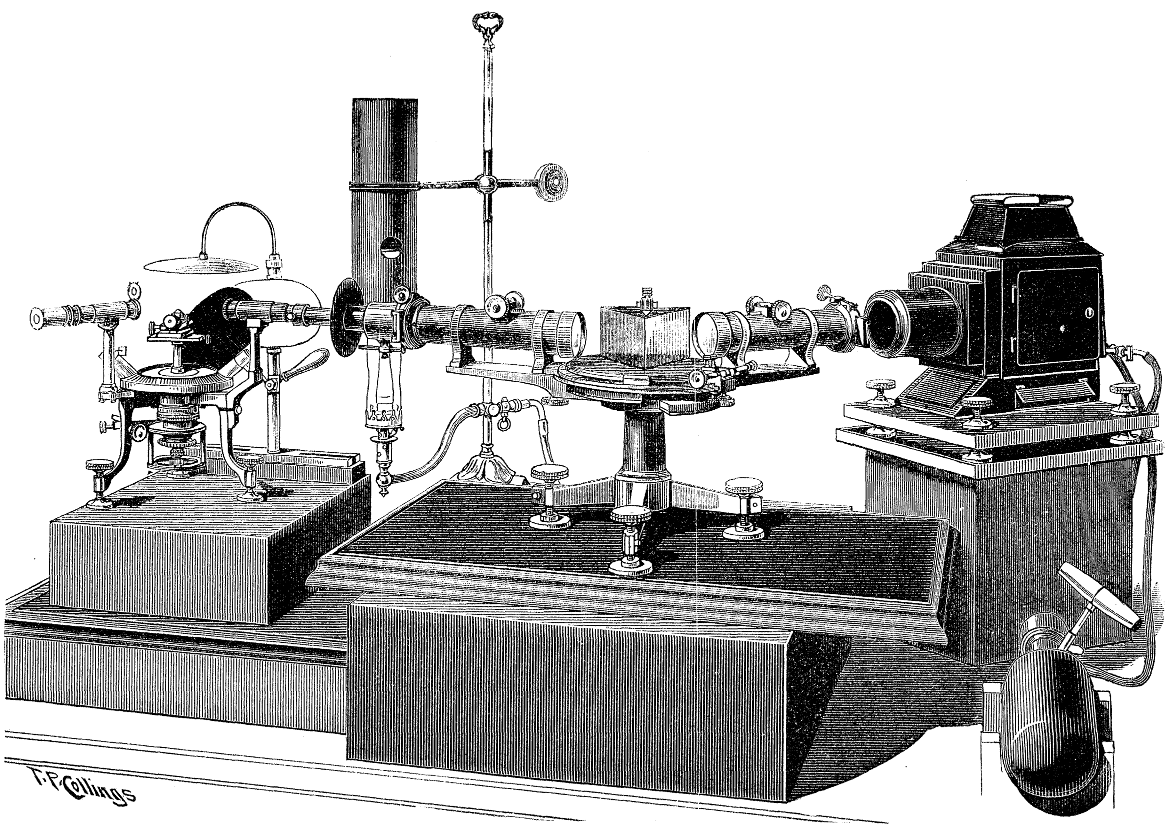


mixed and diffused. It is quite easy in this way to produce a patch of white light upon the screen, by employing a diaphragm pierced by two slits of the necessary apertures, through which yellow and blue rays of the requisite wave-lengths are transmitted and afterwards properly blended by the cylindrical lens. Upon bringing the polariscope close up to the diffusing-screen the field is brilliantly illuminated with light of the colour produced by the admixture of the pure colours emanating from the two or more slits, and if a section of a crystal exhibiting the phenomenon of crossed axial planes is introduced between the converging-lens systems the composite interference-figure will be observed. The arrangement is represented in fig. 6.

Use of the Instrument in the Determination of Refractive Indices.

The instrument now described is admirably adapted for supplying the monochromatic light necessary for refractive-index determinations, either by the method of refraction, or by the method of total reflection. The results in either case are, to say the least, quite as accurate as are afforded by the direct employment of lithium, sodium, and thallium flames, or the light from incandescent rarefied hydrogen; and the observations are immensely facilitated by the much more brilliant illumination of the images of the slit, and the better definition of the limiting line of total reflection, and by the ease with which the change from one wave-length to another can be effected. Moreover, the observations may be supplemented, as in the case of optic axial angle determinations, by observations for as many other wave-lengths as it may be considered desirable to employ.

Fig. 7.



For the determination of the minimum deviation of rays refracted by prisms, furnished by suitably inclined existing faces upon the crystal, or prepared by grinding, the disposition is shown in fig. 7. The highly accurate and in every way admirable horizontal circle goniometer, reading to thirty seconds of arc, constructed by Fuess of Berlin, is used as refractometer. This instrument, and the supporting stand which raises it so that the optical tubes are brought to the level of the eye, are placed in front of the diffusing tube of the monochromatic light apparatus, just as were the axial angle goniometer and its stand. The form of stand shown in the illustration is particularly convenient, both for ordinary goniometric and spectrometric observations. The lower and broader base of polished mahogany, covered beneath with cloth, so as to be easily moved over the polished table, serves as support for a protective glass shade when the instrument is not in use. Upon this rests a second base of smaller surface but of about the same height, about four inches, and of similar polished mahogany; it may with advantage carry a drawer in which the accessories of the instrument may be kept, and is covered underneath with cloth so that it can be moved easily over the larger base. The levelling screws of the goniometer rest in toe plates, also covered underneath with cloth, placed upon the surface of the smaller base. The weight of the instrument is ample to prevent movement during the observations, while this mode of mounting enables the goniometer to be placed in any convenient position upon the upper base, and the latter as well as the lower base to be independently arranged in the most convenient positions for the work in hand.

The illumination tube supplied with the goniometer, to be placed in front of the slit of the collimator, and which consists of a tube about five inches in length carrying at its further extremity a condensing lens of $1\frac{1}{4}$-inch aperture, is very convenient, not so much on account of any increase in the intensity of illumination, which is usually but slightly augmented by it, as because the source of light may then be employed with equal advantage at a further distance from the slit.

Before commencing the observations a folding screen of three folds, lined inside with black velvet, and made of such a size as to rest in the outer groove of the lower base-board, is placed behind and on either side of the spectrometer. A circular aperture is cut in the middle fold, somewhat to the right of the centre, of sufficient size to permit of the passage of the illumination tube of the spectrometer. A second aperture of somewhat larger size is also cut at the same height in the middle fold near the left corner, and is provided with an easily moving door so that it may be closed when not required. Behind this larger aperture is placed the goniometer lamp described in the preceding communication, and which is shown in the background in the illustration, from which the screen is omitted for obvious reasons.

In order to adjust the prism and to measure its angle, the spectrometer is arranged with the illumination tube of the collimator directed towards or passing just through the larger aperture, so as to receive the light from the goniometer lamp. The door may be partially closed so as to shut off most of the light from the observer while adjusting the images of the slit to the cross wires.

The prism is first adjusted and centred by means of the circular and rectangular motions provided for the purpose, and the angle is then measured in the usual goniometrical manner. For the adjustment a white background is an advantage, in order that the crystal may be well seen when using the telescope as a microscope by rotating the movable lens into position in front of the object-glass. But for the accurate adjustment of the images of the slit, reflected by the faces of the prism, to the cross-wire of the telescope when measuring the angle of the prism, just as in making ordinary goniometrical measurements, a dark background is required. In order to supply either background as desired, and with the minimum of trouble, the little arrangement shown behind the goniometer in the illustration serves admirably. It consists of a strong brass pillar screwed into a bevelled foot-plate which is capable of sliding in a dove-tailed groove in the heavy metal base, so that the pillar may readily be brought opposite the telescope when this cannot be done by movement of the whole without bringing the base partly over the edge of the supporting box. The pillar is pierced by an axle at about a third of its height, to the front end of which is attached an arm which carries the dark background in the form of an ebonite sector. The axle is easily moved by a lever handle attached to the axle at the back of the pillar. The amount of rotation is limited by cutting a piece out of the axle nut into which the arm is screwed, and fixing a pin into the bearing, so that the axle can only be moved round a little more than 45° from the position in which the arm is vertical, when its motion is arrested by the stop-pin. The white background is formed by a similar sector of white xylonite fixed to the pillar. When the movable arm is vertical the ebonite sector completely covers the white background; when the lever is touched the ebonite sector moves over to the left, and a large portion of the white xylonite sector is exposed. In order to screen the crystal and the objectives of the collimator and telescope from any overhead light, a thin metallic canopy, darkened underneath, is suspended over the goniometer from a bent brass rod resting loosely in a socket drilled into the top of the pillar which carries the backgrounds, so that it may be rotated out of the way while reading the verniers.

Ample light for reading the verniers may be obtained from the goniometer lamp by temporarily opening widely the door of the aperture.

Having measured the angle of the prism, the direct reading of the slit of the collimator may be taken at once while the goniometer lamp with protective cylinder is in position, and the position of minimum deviation of the spectrum produced by the crystal prism also found, so that time may be saved when using the monochromatic light arrangement. The Websky slit employed in the preliminary goniometrical observations is retained for the measurement of minimum deviation. This slit is formed by using as jaws the adjacent portions of two circular discs, whose circumferences almost touch, the aperture thus produced combining the advantage of a narrow middle portion which can be accurately adjusted to a cross-wire, with broader ends which pass so much more light.

It will be observed in fig. 7 that the daïs of the monochromatic light apparatus is rotated under the base-board for a right angle; this is advisable in order that the large base of the goniometer may be pushed for a little distance under the base-board, so that the goniometer may be approached closely to the monochromatic light apparatus without leaving an inconvenient amount of the lower base projecting towards the observer. After completion of the above preliminaries the goniometer is rotated into the position shown in the illustration, when the axis of the collimator of the goniometer forms a continuation of that of the exit-tube of the monochromatic light apparatus, and the illumination tube passes through the smaller aperture in the screen and enters the diffusing tube, its objective nearly touching the ground-glass screen. The more finely-ground screen affords the best illumination of the Websky slit. The goniometer lamp is used during the observations of minimum deviation in order to illuminate the verniers, which it does very brilliantly when the door of the aperture is temporarily opened.

Upon generating the light in the lantern, setting the prism circle to the reading recorded for light of the first wave-length to be employed, and observing through the telescope of the goniometer, the two images of the Websky slit (supposing the crystal to be bi-refringent) in the colour corresponding to the desired wave-length, and corresponding to the two indices of refraction afforded by the particular prism, will be observed in the field of the telescope. These images are then to be accurately arranged for minimum deviation, brought to the cross-wire by movement of the telescope, and the readings of the goniometer circle taken in the usual manner. In order to determine the direction of vibration of the rays corresponding to these refracted images it is usual to interpose a nicol prism somewhere in the path of the ray. Such a nicol is supplied with the goniometer for insertion in the illuminating tube; it is more convenient, however, to employ it as an adjunct of the telescope, placed in front of the eye-piece. It can then be readily removed if it is desired to observe both images in the field at once, or to avoid loss of light while placing the images; it need only be employed in order to determine their planes of vibration, and to extinguish each in turn while placing the other to the cross-wire in cases of feeble double refraction when the images are so close as to almost or quite overlap. Such a nicol is supplied by FUESS for use with the Liebisch total-reflectometer; it is mounted in front of a telescope similar in power to the one most frequently employed for goniometrical work, but fitted with a silvered indicating circle, against which the graduated circle of the nicol rotates, and the nicol itself is constructed with flat ends, which pass more light.

The brightness of the images obtained by use of the monochromatic light apparatus now described is far superior to that obtained by illuminating the slit with coloured flames, and the images observed with C, F, and G light are immensely brighter than those afforded by the use of a hydrogen Geissler tube. Of course the actual brightness depends upon the individual crystal prism with which the observations are being carried out. In case the practice is followed of increasing the transparency of the prisms and obliterating any slight distortion of the faces by cementing thin glass plates over the faces, with a solution of balsam in benzene, the definition and brightness of the images is always admirable. The ground and polished faces furnished by the instrument described in the preceding communication, however, are so plane and brilliant that excellent images are obtained without the use of glass-covering plates.

Having recorded the two pairs of readings of the goniometer-circle verniers for the two images afforded by light of the first wave-length, similar observations are made for the remaining wave-lengths by setting the prism circle of the monochromatic light apparatus to the proper readings. The whole series of observations are then repeated with the telescope arranged upon the other side of the direct reading of the slit, and the light incident upon the other face of the crystal prism; the mean values derived from observations with the same wave-length in the two series are then taken as representing the true angular values of the minimum deviation for light of those wave-lengths.

When it is desired to make determinations of refractive index at different temperatures the larger goniometer of FUESS, the micrometer of which reads to ten seconds of arc, is employed, together with the heating apparatus provided with it. It is arranged in connection with the monochromatic light apparatus, precisely like the goniometer above referred to. The advantage of employing the form of monochromatic light apparatus now described is here particularly evident, for it is possible to complete the whole series of observations for any one temperature in a very brief interval of time compared with that taken up by observations with flames and Geissler tubes, during which the temperature can more easily be maintained constant. This larger instrument may, of course, be employed for determinations at the ordinary temperature if such a course is considered desirable, but usually the somewhat smaller and much more handy instrument is preferable.

In order to employ the monochromatic light apparatus for the purpose of the determination of refractive indices by means of the total-reflectometer of LIEBISCH, the crystal holder of the goniometer is replaced by the total-reflectometer, which may be either the smaller instrument used with the goniometer No. 2A, or the larger type employed with the large goniometer No. 1. The crystal plate is gently pressed by means of the delicate arrangement provided for the purpose, terminating in a series of Cardani rings whose inner disc carries the crystal, against one face of a highly refracting heavy glass prism, whose angle and whose refractive indices for different wave-lengths are known. Any minute inequalities in the surface of the crystal plate preventing absolute contact between it and the prism are rendered of no consequence by introducing a film of a highly refractive liquid such as α-monobromnaphthalene between the two surfaces. In the prisms supplied by FUESS with the total-reflectometer the face upon which the light is to be incident is ground, so that the incident light is sufficiently diffused without the necessity of interposing a diffusing screen between the source of light and the prism.

It is only necessary, therefore, to arrange the goniometer so that the ground face of the prism receives the monochromatic light issuing from the exit slit. The most convenient distance of the prism from the slit is about eight inches. The diffusing tube is removed from in front of the exit slit, and the direct light from the latter may then be concentrated upon the ground face of the prism by means of a condensing lens of three or four inches focus, an ordinary microscope condenser on stand fitted with ball and socket joint serving admirably. The illumination is much greater than when the condensed light from coloured flames is employed, and the limiting line of total reflection can be more readily adjusted to the cross-wire of the telescope. The latter is accurately adjusted for parallel rays, and carries a nicol prism in front of the eye-piece in order to extinguish one of the limits in the case of doubly refracting substances, while rendering the other limiting line more distinct. Care must be taken to avoid the admission of light into the objective of the telescope other than that which emanates from the surface of contact between crystal and prism, in order that the limiting line shall be as distinct as possible. For this purpose the small tube supplied with the instrument, which adapts on to the objective end of the telescope, is used. This tube is made to terminate, as close to the crystal as is compatible with the necessary amount of rotation of the total-reflectometer, in a cap pierced by a rectangular aperture of suitable small size. As the illumination by the monochromatic light apparatus now described is so good, the author uses a cap with an aperture only half the size of the smallest supplied by FUESS, namely, about one-and-a-half by one millimetre, thus being quite certain of the exclusion of other light than that from even a small crystal. By moving the condenser after finding the limiting line, so as to alter the angle of incidence, a position will be found for which the greatest difference of illumination on the two sides of the line is apparent, when it may be most accurately brought to the cross-wire.

The adjustment of the crystal upon the total-reflectometer, and of the prism of the latter with respect to the goniometer, and also the determination of the position of the normal to the face of the prism from which the totally reflected light emerges, should first be carried out in white light in the manner described by LIEBISCH,* employing the goniometer lamp.

The determination of the angle or angles of total reflection is then carried out by bringing the limiting line or lines of total reflection to the cross-wire of the telescope, employing light of each desired wave-length in turn. During these operations the circle is maintained clamped to the crystal carrier as it was when determining the position of the normal to the prism face, in order to be able to ascertain the angular difference between that position and the direction of the various limits of total reflection, from which, together with the knowledge of the angle and refractive indices of the prism, the required angles of total reflection can be calculated. Having taken two sets of such observations if the crystal is bi-refringent, with the aid of the nicol, for the two limiting lines corresponding to the first desired position of the crystal, the whole series are repeated with the crystal rotated in its own plane by means of

* 'Zeitschrift für Instrumentenkunde,' 1884, 185, and 1885, 13.

the small graduated circle of the total-reflectometer, for as many positions (having reference to the axes of optical elasticity) of the crystal as it is desired to record observations for.

Use of the Instrument in Stauroscopical Observations.

The determination of the directions of extinction for different colours, exhibited by plates of crystals belonging to the monoclinic and triclinic systems of symmetry in parallel polarised light between crossed nicols, in order to ascertain the directions of the principal optical planes, by means of the stauroscope or a microscope arranged as such, may very readily be carried out with the aid of the monochromatic light apparatus described in this communication. It is only necessary to place the stauroscope or microscope in front of the exit slit, so that the mirror usually carried by either of the instruments mentioned receives the line of monochromatic light at such an angle as to reflect it up along the axis of the instrument. The nearer the mirror is to the slit, the better the illumination. The diffusion into an even field of light is effected by use of a ground-glass diffuser carried as a cap at the lower end of the stauroscope, or fixed on the end of the polarising prism of the microscope.

As, however, the use of the mirror causes some loss of light, by absorption at the back surface, the author prefers to conduct stauroscopical measurements with the stauroscope or microscope arranged horizontally, so as to be able to utilise the ordinary diffusing-tube of the monochromatic light apparatus, and to thus make use of the whole of the light issuing from the exit slit. Of course this necessitates that the crystal plate shall be firmly held on the stage, which is now vertical. Monochromatic light, however, is only required when making the actual measurements of the angles of extinction, during which the crystal plate is cemented upon the small rectangular glass plate provided for the purpose, one of whose edges coincides with a known reading of the circle and makes a goniometrically-ascertained angle with an edge of the crystal plate. Hence, for stauroscopical measurements there is no necessity for a vertical arrangement of the observing instrument, and the horizontal arrangement has the further advantage that the observer is then enabled to make the observations while seated, with the eye looking forwards at the normal height, a condition in which he is far better able to appreciate minute differences of light and shade in the two halves of the Calderon double-calcite plate, which is now generally employed in order to increase the accuracy of determinations of extinction, than when a vertical arrangement is employed.

As the best crystallographical microscopes are provided with a swing arrangement which enables them to be placed horizontally, there is no difficulty in so employing them for stauroscopical observations. It is only necessary to rotate the mirror out of the way, and to bring the instrument close up to the monochromatic light apparatus so that the end of the tube which carries the polarising nicol almost touches the ground-glass diffusing screen, carried as usual in the tube mounted in front of the exit slit, and to make the axis of the microscope a continuation of that of the exit tube of the monochromatic light apparatus.

In order to use horizontally the stauroscope forming part of the universal apparatus supplied by FUESS, a very simple addition in the form of a supporting stand of wood is all that is required. The stauroscope is supported horizontally upon the base-board by utilising the metal foot, upon which the instrument usually stands, as one support, and a similar one of hard wood firmly fixed to the base-board as support for the other end of the rod of triangular section along which the optical tubes slide, and from which they now depend. The opening between the two toes of the metal foot is ample to permit of the full aperture of the instrument being employed, and the toes are prevented from slipping off the base-board by means of a low protective rib of similar wood fixed to the latter. A piece is cut out of the wooden support in order to permit of the free movement through it of the optical tube carrying the analysing nicol and the half-shadow calcite plate, the aperture being left sufficiently wide to enable the vernier and circle to be easily read through it with the aid of a pocket lens. Although the amount of rackwork provided with the analysing tube will not permit the objective of the polarising tube to be conveniently brought close up to the ground-glass diffusing screen of the monochromatic light apparatus, as the crystal would then appear very small when observed through the analysing tube, still the illumination suffers little from this cause, and is superior to that which is obtained by employing the diffusing screen in the form of a cap fitting on the end of the polarising tube. When the whole arrangement is moved up so that the metal foot is within a quarter of an inch of the end of the diffusing tube, and the two optical tubes are likewise approached as near as the rackwork will permit, an excellent illumination is obtained on generating the light in the lantern, far more brilliant than is usually obtained from a sodium flame, and ample to permit of the most accurate determinations of the directions of extinction for light of any wave-length from that of lithium up to that corresponding to G of the solar spectrum. Of course the arrangement is equally applicable when any other form of stauroscopical plate, such as that devised by BREZINA, is employed instead of the half-shadow Calderon plate.

For merely studying the phenomena exhibited by loose crystals or crystal plates in parallel polarised monochromatic light, the vertical arrangement first mentioned is naturally employed.

The foregoing represent only a typical few of the applications of the apparatus for producing monochromatic light described in the earlier part of this communication. Its use may be extended to all other cases in which it is desired to illuminate the whole field of an optical instrument, or any portion of it, with light of any wave-length or of any definite composition whatsoever.

The instrument has been admirably constructed by Messrs. TROUGHTON and SIMMS, and the author is particularly indebted to Mr. JAMES SIMMS for the success of the optical portion of the apparatus. The author desires further to express his indebtedness to the Research Fund Committee of the Chemical Society for their grant to defray the cost of the instrument.