A universal goniometer.

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[Read January 24, 1911.]

THE instrument to be described in the following pages is a goniometer of the suspended type. It is intended primarily for the examination of small crystals, and by its aid all the usual crystallographic and optical determinations can be readily carried out. In its design the attempt has been made to combine efficiency with simplicity and strength of construction, together with adaptability to very various purposes. The instrument was completed in the spring of 1899, and has been in continuous use in the Mineralogical Laboratory at Cambridge ever since.[1] Other instruments of the same general type were in existence at the time,[2] or have been described during the past twelve years, and several features which were novelties when it was first constructed can no longer lay claim to originality. It has, however, proved itself a serviceable piece of apparatus, and has met with approval from several friends who have examined its capabilities. It is owing to their representations that the following account of it has been prepared in the hope that it may be found useful by other workers.

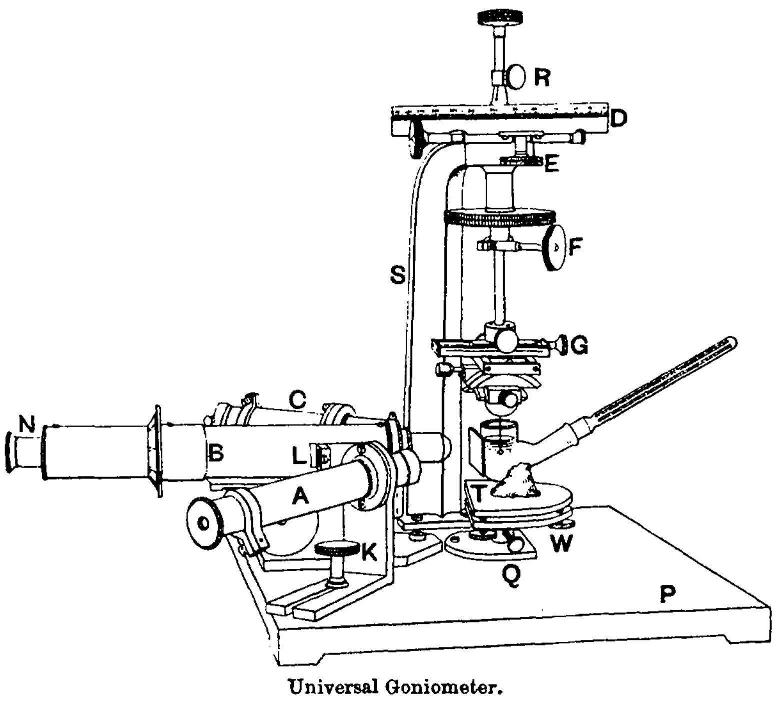
Description.—A circle *D*, five inches in diameter, graduated to ½ degrees and reading by a vernier to minutes is supported by a stout bracket *S*, at a height of ten inches above a flat base-plate *P*, eleven inches square. The circle is provided with a slow-motion attachment, and can be clamped by the screw *E*. A steel rod, which can be clamped at any convenient position by the screw *F*, passes through the centre of the circle and carries, at its lower end, the ordinary centring and adjusting arrangements shown at *G*. A loose collar, which can be clamped to

[1] The instrument was constructed by Messrs. Troughton and Simms, 138 Fleet Street, London, at an approximate cost of £30. It has been briefly described in A. E. H. Tutton's 'Crystallography and Practical Crystal Measurement', 1911, p. 765, fig. 630.

[2] Vide H. A. Miers, Brit. Assoc. Report, 1894, 654; Zeits. Kryst. Min., 1904, vol. xxxix, p. 223; C. Leiss, Zeits. Kryst. Min., 1899, vol. xxx, p. 363.

the rod by the screw R, gives the means of raising the adjusting head and of again lowering it to its former position.

A telescope A, and a collimator C, are securely clamped to the base-plate in the manner shown at K, a number of holes being provided for this purpose at convenient positions. The object-glasses of the telescope and collimator are $\frac{3}{4}$ inch in diameter and about 4 inches in focal length. Their tubes are carried by collars, provided with adjusting screws. An additional lens of $2\frac{1}{2}$ inches focus is also supplied. This can be slipped



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into position in front of the objective of the telescope, thereby converting the latter into a microscope of low power with which the crystal can be examined.

The telescope and collimator are placed at any convenient angle to one another (some angle between 60° and 90° will be found suitable), and the microscope B is arranged so that its optical axis bisects the angle between them. The microscope-tube, which is eight inches long, is moved by an ordinary coarse adjustment actuated by a pair of milled heads, one of which is seen in the figure just below the telescope. At one end it carries a centring nose-piece into which the objectives are screwed, those of $\frac{1}{2}$ inch and of 2 inches focal length will be found most generally useful, but those of $\frac{1}{4}$ inch and of 1 inch focus can sometimes be employed with advantage. At the other end a nicol N slips on over the eye-piece; the latter and the nicol-holder are slotted to admit of the insertion of a quartz-wedge or mica-plate. A Bertrand-lens L slides into the body of the microscope.

An adjustable table T, which can be levelled by the screws W, is carried by a steel rod which can be clamped by the screw Q; a loose collar clamped to the rod by a screw enables the table to be rotated when supported at any convenient height. On this table can be placed a tank, when it is desired to observe the crystal immersed in a liquid.

Two extra fittings, not shown in the figure, are also provided. Both are similar in shape to that which carries the telescope. One enables a short tube containing a nicol and a condensing lens to be placed opposite the objective of the microscope. The other can be clamped to the graduated circle: at its lower end it carries a collar into which the telescope A can be screwed, thus enabling the latter to be supported at the same height above the base-plate ($3\frac{1}{4}$ inches) as the collimator and microscope.

Adjustment of the instrument.—The construction of the instrument is such that all adjustments are under the full control of the observer. They are best made in the following order:—

In the first place the short-focus lens is slipped on in front of the objective of the telescope, which is then placed temporarily in the position to be subsequently occupied by the microscope. A small plate of plane-parallel glass is attached by wax to the crystal-holder. On one surface of this glass plate a fine line has been ruled with a diamond point. By manipulating the screws of the adjusting head this line is brought into coincidence with the axis of rotation of the circle, and the telescope is then arranged to focus it sharply in the centre of the field. The extra lens is next removed from the telescope, and by means of the screws in the collar which carries it, the optical axis of the telescope is made perpendicular to the axis of rotation of the circle. To accomplish this, auto-collimation is employed: the image of the illuminated cross-wires being reflected, first from one side of the parallel glass plate, and then from the other. The illumination of the cross-wires can be effected by means of a special auto-collimating eye-piece, but a plate of glass held in front of the eye-lens in such a way as to reflect into it the light of a lamp placed on one side of the observer will answer the purpose quite as well. The focusing of the telescope for infinity can also be conveniently carried out at this stage.

As soon as the telescope is in position, the collimator is set up immediately opposite and adjusted until its slit—of the Websky pattern as modified by Miers—is clearly seen on the cross-wires of the telescope. The latter can now be removed and the microscope set up in its place, with the $\frac{1}{2}$-inch objective of N.A. 0·5 screwed on to the nose-piece. If the Bertrand-lens be now pushed in, it will be found that a bright diminished image of the collimator-signal can be seen. It is important that the optical axis of the microscope should be so adjusted that an object brought into the axis of rotation of the graduated circle should remain steady in the centre of the field of view of the $\frac{1}{2}$-inch objective during a complete revolution of the circle, and that on introducing the Bertrand-lens a sharp image of the collimator-signal should be seen on the cross-wires. By moving the microscope and by manipulating the screws of the centring nose-piece these adjustments can be effected.

During these operations the plane-parallel glass plate has remained untouched, standing perpendicular to the axis of the collimator, and therefore to that of the microscope also. A reading of the graduated circle is now taken, and it is then turned through some definite angle, 35° say, to the right (counter-clockwise) and there clamped. The telescope is then adjusted by the method of auto-collimation until its axis is perpendicular to the glass plate and is firmly clamped in position, as shown in the figure. The circle is then turned back to its original reading, carrying with it the glass plate, which is now once more standing perpendicular to the axis of the microscope. The final step is to move the collimator to the left of the microscope and adjust it till the image of its signal reflected from the glass plate is seen on the cross-wires of the telescope. When this is the case the optical axis of the microscope bisects the angle between those of the collimator and telescope respectively. To adjust the analyser and polarizer, the condenser should be removed from the tube containing the latter and it should be set up in its stand opposite the microscope. A suitable crystal of quartz or natrolite should then be mounted on the crystal-holder and viewed with the 2-inch objective. When the long axis of the crystal is brought into coincidence with the axis of rotation, a pair of its faces can be set perpendicular to the axis of the microscope and the polarizer and analyser adjusted to give extinction.[1]

[1] An excellent account of the method of adjusting a goniometer was given by

The instrument can now be used for any of the following purposes:—

I. As an ordinary goniometer for the measurement of angles.

II. As an axial-angle apparatus.

III. As a Kohlrausch total-reflectometer.

IV. For determining refractive indices by the prism method.

I. *Use as a goniometer.*—The telescope and collimator are employed in the ordinary way. The microscope fitted with a 2-inch objective is useful for examining small crystals, while the reflections from very minute or dull faces can be conveniently observed by means of the ½-inch objective employed in conjunction with the Bertrand-lens, this combination giving a bright diminished image of the collimator-signal. The 1-inch objective can also be used for the same purpose, if provided with an adapter, to support it at the proper distance in front of the Bertrand-lens.[1]

II. *Use as an axial-angle apparatus.*—A fitting similar to that which carries the telescope, but not shown in the figure, is placed on the base-plate. Into it is slipped a tube containing a nicol and a plane-convex condensing lens. This is clamped opposite the microscope which is furnished with a lens of short focus. The ½-inch objective of N. A. 0·5 will be found the most generally useful; occasionally a ¼-inch, N.A. 0·85, may be employed, but in this case an extra lens should be arranged in front of the condenser provided in the nicol-tube, to render the light more highly convergent.

A crystal plate suspended from the central axis can now be rotated between crossed nicols in convergent polarized light and the value of its optic axial angle measured, either in air, or in any suitable liquid contained in a parallel-sided tank mounted on the table *T*. The crystal-plate is adjusted by means of the telescope and collimator. When it is so placed that it reflects the image of the collimator-signal on to the cross-wires of the telescope it must be perpendicular to the optical axis of the microscope, for this was arranged to bisect the angle between the axes of the collimator and telescope. This adjustment is made with great ease, and permits of the determination of the angle at which an optic axis emerges from any face without the necessity of resorting to auto-

M. Websky, Zeits. Kryst. Min., 1880, vol. iv, p. 545. The essential points have been reproduced by A. E. H. Tutton in his work 'Crystallography and Practical Crystal Measurement', 1911, p. 32.

[1] The use of the Bertrand-lens for this purpose has also been recommended by V. de Souza-Brandão, Zeits. Kryst. Min., 1904, vol. xxxix, p. 583, and by A. Hamberg, ibid., 1907, vol. xlii, pp. 13, 280.

collimation, a great advantage when small crystals are under examination. If an immersion liquid is to be employed, the tank containing it can be rapidly adjusted in the same fashion by rotating the table and by manipulating its levelling screws.

III. *Use as a Kohlrausch total-reflectometer.*—The indices of refraction of quite small crystals can be readily determined by total reflection, and in recent times attention has been repeatedly called to the special advantages of the method originally devised by Kohlrausch.[1] The apparatus now described will be found very convenient for this purpose. The crystal, mounted on a pin, or fastened to some form of rotating holder, such, for example, as that devised by T. Liebisch, is attached to the head *G*, and by means of the telescope and collimator the face to be employed is brought into position. It is then surrounded by a highly refractive liquid contained in a small tank, provided with a thermometer graduated to $\frac{1}{10}$° C., and mounted as shown in the figure.[2] The plane face of this tank is adjusted to be perpendicular to the axis of the microscope as described above. The front of the ½-inch objective is now brought as near as may be to the plane surface of the tank without actually touching it, and the Bertrand-lens pushed in. On illuminating the tank from the side with a convergent beam of monochromatic light focused on it by a lens, the limits of total reflection can be observed with great ease. Plates 2 to 3 mm. square will be found amply large enough, and if the face is bright, an area 1 mm. square gives limits which can be readily distinguished. The plate is turned till the limit of total reflection is brought to the cross-wires of the microscope and the circle reading taken. The tank is then illuminated on the other side and the observation repeated. The difference between the two readings gives twice the critical angle.

It has been found that the illumination of the tank can be most conveniently effected by means of a convex lens of about 2¼ inches diameter and 5 inches focal length, mounted at the proper height in front of a Bunsen-burner. The latter is screwed to a flat board, which likewise supports an arm, by means of which a bead of sodium carbonate or other salt can be held in the flame. This arrangement enables lens and flame

[1] Vide K. Zimányi, Zeits. Kryst. Min., 1894, vol. xxii, p. 321. A. J. Moses and E. Weinschenk, ibid., 1896, vol. xxvi, p. 150. C. Leiss, ibid., 1899, vol. xxx, p. 368. V. de Souza-Brandão, ibid., 1908, vol. xlv, p. 326.

[2] The tank can be procured from Mr. H. Helm, 66 Hatton Garden, London. The thermometer is best arranged to enter it at one side, and not, as shown in the figure, at the back.

to be moved readily to the proper position, and it will be found desirable to provide this apparatus in duplicate, one set being used for observations with the light on the right, the other on the left. The visibility of the limit will often be increased if a second lens is interposed between the flame and the tank. This lens may be of about 1½ inches diameter and about 2½ inches in focal length. It is supported on the base-plate of the instrument by a heavy foot.

The best immersion liquid is methylene iodide in which sulphur has been dissolved. Should this attack the substance under examination, a concentrated solution of potassium iodide and mercuric iodide (Thoulet's solution) may be tried. The former is available for substances of which the refractive index does not exceed 1·77.[1] The maximum value of the index obtainable in the case of Thoulet's solution is 1·73.[2] For substances of which the refractive index is less than 1·65, α-monobromonaphthalene may be employed with advantage. In any case it is essential that the index of the liquid should be determined immediately after the observations on the crystal have been completed. This is best done by finding the critical angle for some substance, such as glass or fluorite, of which the optical properties are accurately known.[3] Owing to the rapidity with which the refractive indices of the liquids employed change with temperature, the observations on the crystal and on the control piece should be made at the same temperature, or, if this is impracticable, then at known temperatures. Care should be taken to avoid heating the tank by the proximity of flames, and no time should be lost between the observations. If, however, a double set of illuminating apparatus is available, it will be found easy to complete a set of observations within a temperature range of 0·5° C.; and, with care, results accurate to two or three units in the fourth place of decimals can be obtained, even in the case of quite small crystals.

[1] It is said that with this liquid an index of 1·83 can be attained; see Schroeder van der Kolk, 'Tabellen zur mikroskopischen Bestimmung der Mineralien,' 1906, p. 13. Personally I have not been able to go beyond 1·785.

[2] Directions for the preparation of Thoulet's solution and an exhaustive account of its physical properties have been given by V. Goldschmidt, Neues Jahrbuch Min., 1881, Beil.-Band i, pp. 179-238.

[3] The following device will be found convenient:—A narrow strip (20 mm. × 3 mm.) of thin glass of known optical properties is taken, one side polished plane and the other side ground. The crystal is attached at one end of the strip to the ground side, and the strip arranged vertically from the adjusting head *G*. After the critical angle for the crystal has been found, the plate is turned round, till the polished side of the glass becomes the reflecting surface and the critical angle is again determined.

It may be of interest to notice here the effect on the index of refraction of any inaccuracy in setting the limit of total reflection on the cross-wires. This is shown in the following table, in which are given

(1) The critical angle θ (to the nearest minute), for solids of which the indices of refraction range from 1·7500 to 1·5000, when observed in liquids of indices 1·8000, 1·7500, and 1·7000 respectively.

(2) The indices of refraction calculated for these solids on the assumption that θ has been read 1′ too high in each case.

Index of Solid.	Liquid μ = 1·8000.		Liquid μ = 1·7500.		Liquid μ = 1·7000.	
	θ	Index for $\theta+1'$.	θ	Index for $\theta+1'$.	θ	Index for $\theta+1'$.
1·75	76° 27′	1·75012	—	—	—	—
1·70	70 48½	1·70017	76° 16′	1·70012	—	—
1·65	66 26½	1·65021	70 32	1·65017	76° 4′	1·65012
1·60	62 44	1·60024	66 6	1·60021	70 15	1·60017
1·55	59 26½	1·55027	62 20	1·55024	65 45	1·55020
1·50	56 26½	1·50029	59 0	1·50026	61 55½	1·50023

IV. *Use as a refractometer.*—In order to measure indices of refraction by the prism method, the centring and adjusting head is removed from the goniometer axis and attached instead to the rod which supports the table on which the tank rests. The fitting in which this rod slides is clamped to the base-plate by three screws passing through holes in the base of the fitting. As these holes are somewhat larger than the screws, the fitting can be moved slightly laterally, and we have the means of adjusting this rod so that its axis coincides with the prolongation of the axis of rotation of the circle. The telescope is removed from its holder and screwed into the extra fitting which can be clamped to the upper side of the disk which carries the graduated circle. The collimator is left in position. On turning the circle, the telescope can be adjusted by means of the collar to view the collimator-signal. The crystal can now be mounted on the head *G*, adjusted, and rotated until it is in the position of minimum deviation. The amount of the latter is then determined in the ordinary way by means of the telescope.

The utility of the instrument can be further increased by the addition of two accessories—a micrometer eye-piece for the microscope, and a Stöber circle to be clamped to the axis.

A convenient form of micrometer-ocular can be made by substituting for the cross-wires of the microscope eye-piece a glass plate ruled with two systems of lines at right angles to one another and 0·1 mm. apart. Every fifth line is ruled stronger than the rest, and every tenth line stronger still. The two lines which intersect at the centre are made particularly distinct, and serve instead of the cross-wires.[1] The field of view, which in the eye-piece supplied is 15·4 mm. in diameter, is thus divided into small squares, and by their aid the angular position of an eccentrically placed image can be determined.

The addition of Stöber's circle, as constructed by the firm of Fuess at Steglitz, converts the instrument into a two-circle goniometer.[2] It is readily clamped to the central rod, and by a slight alteration it is possible to arrange a pivot to support it underneath, thereby increasing its stability.

In conclusion, it may be pointed out that besides fulfilling the purposes for which it was designed, this instrument lends itself readily to the exigencies of experimental work, for any other apparatus which it may be found desirable to employ in connexion with a graduated circle can be speedily clamped to the base-plate in any position required, and can be as easily removed.

[1] Similar eye-pieces suitable for use with petrological microscopes are supplied by Messrs. J. Swift & Son, 81 Tottenham Court Road, London, and will be found useful for a variety of purposes.

[2] F. Stöber, 'Ueber ein einfaches Theodolitgoniometer,' Zeits. Kryst. Min., 1898, vol. xxix, p. 25.