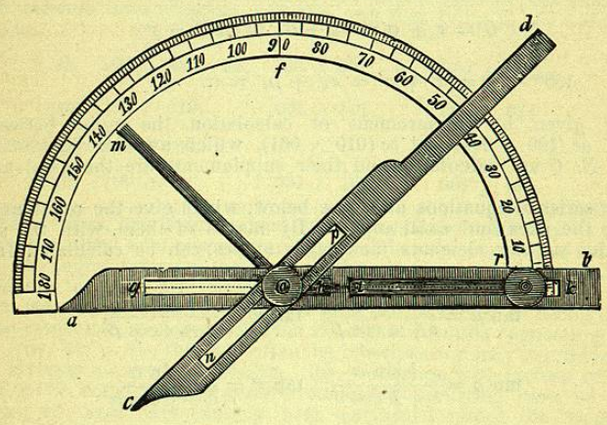
MEASUREMENT OF THE ANGLES OF CRYSTALS.

208. Hand-Goniometers.—The interfacial angles of crystals are measured by means of instruments which are called *goniometers*.

The simplest form is the hand-goniometer, represented in Fig. 342. It consists of an arc, graduated to half-degrees or finer, and two movable arms. In the instrument figured, one of the arms, *ab*, has the motion forward

342.



and backward by means of slits *gh*, *ik*; the other arm, *cd*, has also a similar slit, and in addition it turns around the center of the arc as an axis. The faces whose inclination is to be measured are applied between the arms *ao*, *co*, and the latter adjusted so that they and the surfaces are in close contact; further, the arms must be exactly at right angles to the intersection-edge. This adjustment must be made with care, and when the instrument is held up to the light none must pass through between the arm and the face. The number of degrees read off on the arc between *k* and the left edge of *d* (this edge being in the line of the center, *o*, of the arc) is the angle required. The motion to and fro by means of the slits is for the sake of convenience in measuring small or embedded crystals. In a better form of the instrument the arms are wholly separated from the arc; and the arc is a delicately graduated circle to which the arms are adjusted after the measurement.

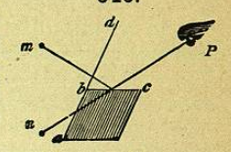
The hand-goniometer is useful in the case of large crystals and those whose faces are not well polished; the measurements with it, however, are seldom accurate within a quarter of a degree. In the finest specimens of crystals, where the faces are smooth and lustrous, results far more accurate may be obtained by means of a different instrument, called the reflecting goniometer.

209. Reflecting Goniometer.—This instrument, devised by Wollaston (1809), has been much improved in its various parts since his time by Mitscherlich and others. The principle on which it is constructed may be understood by

reference to the following figure (Fig. 343), which represents the section of a crystal, whose angle, *abc*, between the faces *ab*, *bc*, is required.

The eye at *P*, looking at the face of the crystal, *bc*, observes a reflected image of *m*, in the direction of *Pn*. The crystal may now be so changed in its position that the same image is seen reflected by the next face and in the same direction, *Pn*. To effect this, the crystal must be turned around, until *abd* has the present direction of *bc*. The angle *dbc* measures, therefore, the number of degrees through which the crystal must be turned; it may be measured by attaching the crystal to a graduated circle, which turns with the crystal.

343.



This angle is the supplement of the interior angle between the two faces, or in other words is the *normal angle*, or angle between the two poles (see Art. 41, p. 28). The reflecting goniometer hence gives directly the angle needed on the system of Miller here followed.

Many different forms of reflecting goniometer of simple type are in use. The accompanying figure (Fig. 344) will suffice to make clear the general character of the instrument, as well as to exhibit some of the refinements added for the sake of greater exactness of measurement.

The circle, *C*, is graduated, in this case, to twenty minutes, and by means of the vernier at *v* the readings may be made to minutes and half-minutes. The crystal is attached by means of wax to the little plate at *k*; this may be removed for convenience, but in its final position it is, as here, at the extremity of the axis of the instrument. This axis is moved by means of the wheel, *n*; the graduated circle is moved by the wheel, *m*. These motions are so arranged that the motion of *n* is independent, its axis being within the other, while on the other hand the revolution of *m* moves both the circle and the axis to which the crystal is attached. This arrangement is essential for convenience in the use of the instrument, as will be seen in the course of the following explanation. The screws, *c*, *d*, are for the adjustment of the crystal, and the slides, *a*, *b*, serve to center it.

The method of procedure is briefly as follows: The crystal is attached by means of suitable wax at *k*, and adjusted by the hand so that the direction of the combination-edge of the two faces to be measured coincides with the axis of the instrument; the wheel, *n*, is turned until an object (*e.g.*, a window-bar) reflected in one face is seen to coincide with another object not reflected (*e.g.*, a chalk-line on the floor); the position of the graduated circle is observed, and then both crystal and circle revolved together by means of the wheel, *m*, till the same reflected object now seen in the *second* face again coincides with the fixed object (that is, the chalk-line); the angle through which the circle has been moved, as read off by means of the vernier, is the normal angle between the two faces.

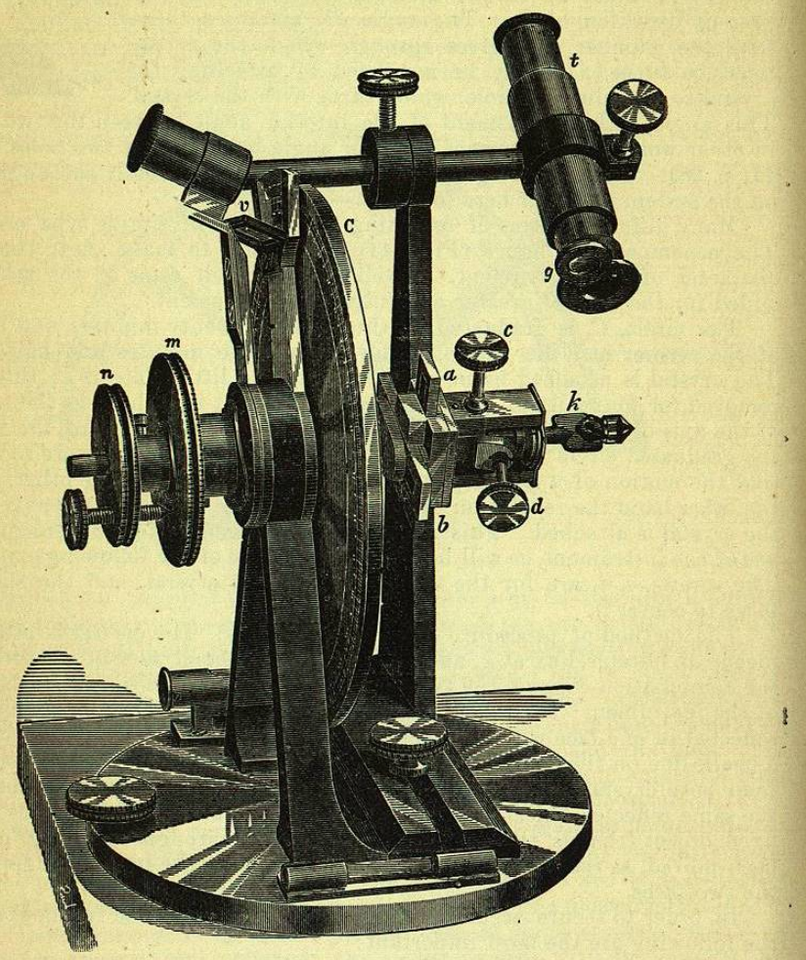
In order to secure accuracy, several conditions must be fulfilled, of which the following are the most important:

1. The position of the eye of the observer must remain perfectly stationary.
2. The object reflected and that with which it is brought in coincidence should be at an equal distance from the instrument, and this distance should not be too small.
3. The crystal must be accurately *adjusted;* this condition is satisfied when the line seen reflected in the case of each face and that seen directly with which it is in coincidence are horizontal and parallel. It can be true only when the intersection-edge of the two faces measured is exactly in the *direction*

of the axis of the instrument, and perpendicular to the plane of the circle. The adjustment is accomplished roughly by the hand and accurately by the screws *c* and *d*.

4. The crystal must be *centered* as nearly as possible, or, in other words, the same intersection-edge must *coincide* with a line drawn through the

344.



revolving axis. This condition will be seen to be distinct from the preceding, which required only that the two *directions* should be the same. The error arising when this condition is not satisfied diminishes as the object reflected is removed farther from the instrument, and becomes zero if the object is at an infinite distance. In the centering of the crystal the slides *a* and *b* are employed.

The first and second conditions are both satisfactorily fulfilled by the use

of a telescope, as *t* (Fig. 344), with slight magnifying power. This is arranged for parallel light, and provided with a hair-cross in its focus. It admits also of some adjustments, as seen in the figure, but when used it must be directed exactly toward the axis of the goniometer. This telescope has also a little magnifying-glass (*g*) attached to it, which allows of the crystal itself being seen when mounted at *k*. This latter is used for the first adjustments of the crystal, and then slipped aside, when some distant object which has been selected must be seen in the field of the telescope as reflected, first by the one face and then by the other as the wheel *n* is revolved. When the final adjustments have been made so that in each case the object coincides with the center of the hair-cross of the telescope, and when further the edge to be measured has been centered, the crystal is ready for measurement.

This telescope, obviously, can be used only when the face is smooth and large enough to give distinct and brilliant reflections.* In many cases sufficient accuracy is obtained without it by the use of a window-bar and a white chalk-line on the floor below for the two objects; the instrument in this case is placed at the opposite end of the room, with its axis parallel to the window; the eye is brought very close to the crystal and held motionless during the measurement.

The best instruments are provided with two telescopes. The second stands opposite the telescope, *t* (see figure), the centers of both telescopes being in the same plane perpendicular to the axis of the instrument. This second telescope has also a hair-cross in the focus, and this when illuminated by a brilliant gas-burner (the rest of the instrument being protected from the light by a screen) will be reflected in the successive faces of the crystal. The reflected cross is brought in coincidence with the cross in the first telescope, first for one and then for the other face. As the lines are delicate, and as exact coincidence can take place only after perfect adjustment, it is evident that a high degree of accuracy is possible. Still more than before, however, are well-polished crystals required, so that in many cases the use of the ordinary double telescopes is impossible. Very often the hair-cross of the second telescope may be advantageously replaced by a bright line or cross, the light shining through a cross cut in tin-foil (Schrauf), or as given by the analogous Websky signal. This light-signal is visible in the first telescope even when the planes are extremely minute, or, on the other hand, somewhat rough and uneven; even if the image is not perfectly distinct, it may be sufficiently so to admit of fairly good measurements (*e.g.*, within two or three minutes).

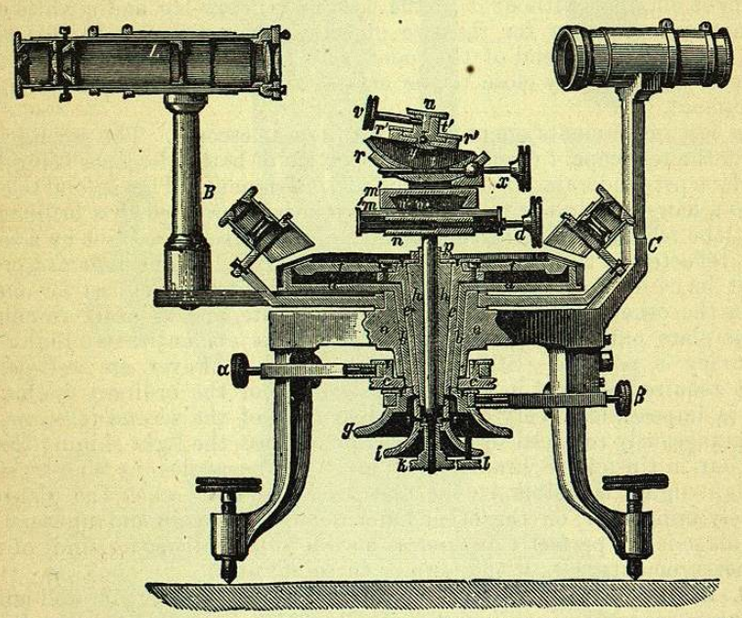
210. Horizontal Goniometer.—A form of reflecting goniometer well adapted for accurate measurements is shown in Fig. 345. It is made on the Babinet type, with a *horizontal* graduated circle; the instruments of the Mitscherlich type, just described, having a vertical circle. The horizontal circle has many advantages, especially when it is desired to measure the angles of large crystals

* When planes are rough and destitute of luster the angles can often best be obtained by use of a candle-flame, the diffuse reflection of which in the given face takes the place of more distinct images. For embedded crystals, and often in other cases, measurements may be very advantageously made from impressions in some material, like sealing-wax. Angles thus obtained ought to be accurate within one degree, or even less, and suffice for many purposes. It is sometimes of advantage to attach to the planes to be measured, when quite rough, fragments of thin glass, from which reflections can be obtained; this must, however, be done with care, to avoid considerable error. Occasionally dusting the surface with graphite makes a "shimmer" measurement with the candle-flame possible, or, again, covering it with a thin film of gum arabic.

or those which are attached to the rock. This particular form of instrument here figured * is made by R. Fuess in Berlin.

The instrument stands on a tripod with leveling screws. The central axis, *o*, has within it a hollow axis, *b*, with which turns the plate, *d*, carrying the verniers and also the observing telescope, the upright support of which is shown at *B*. Within *b* is a second hollow axis, *e*, which carries the graduated circle, *f*, above, and which is turned by the screw-head, *g*; the tangent screw, α, serves as a fine adjustment for the observing telescope, *B*, the screw, *c*, being for this purpose raised so as to bind *b* and *e* together. The tangent screw, β, is a fine adjustment for the graduated circle. Again, within *e* is the third axis, *h*, turned by the screw-head, *i*, and within *h* is the central rod, which carries the support for the crystal, with the adjusting and centering contrivances mentioned below. This rod can be raised or lowered by the screw, *k*,

345.



so as to bring the crystal to the proper height—that is, up to the axis of the telescope; when this has been accomplished, the clamp at *p*, turned by a set-key, binds *s* to the axis, *h*. The movement of *h* can take place independently of *g*, but after the crystal is ready for measurement these two axes are bound together by the set-screw, *l*. The signal telescope is supported at *C*, firmly attached to one of the legs of the tripod. The crystal is mounted on the plate, *u*, with wax, the plate is clamped by the screw, *v*. The *centering* apparatus consists of two slides at right angles to each other (one of these is shown in the figure) and the screw, *a*, which works it; the end of the other corresponding screw is seen at *a'*. The *adjusting* arrangement consists of two cylindrical sections, one of them, *r*, shown in the figure, the other is at *r'*; the cylinders have a common center.

* The figure here used is from the catalogue of Fuess.

The circle is graduated to degrees and quarter degrees, and the vernier gives the readings to 30″, but by estimate they can be obtained to 10″. The signals provided are four in number, each in its own tube, to be inserted behind the collimator lens; these are: (1) the ordinary telescope with the hair-cross, to be used in the case of the most perfect faces; (2) the commonly used signal, proposed by Websky, consisting of two small opaque circles, whose distance apart can be adjusted by a screw between them; the light passing between these circles enters the tube in a form resembling a double concave lens; also (3) an adjustable slit; and, finally, (4) a tube with a single round opening, very small. There are four observing telescopes of different angular breadth of field and magnifying power, and hence suitable for faces varying in size and in degree of polish.

The methods to be employed, both in making the preliminary adjustments required by every instrument before it can be used and in the actual measurement of the angles of crystals, have been described by Websky * with a fullness and clearness which leave nothing to be desired, and reference must be here made to his memoir.

211. Theodolite-Goniometer.—A form of goniometer † having many practical advantages has two independent circles; it can be used in a manner analogous to that of the ordinary theodolite, as will appear below. Instruments of this type have been devised independently by Fedorow, Czapski, and Goldschmidt. In addition to the usual graduated horizontal circle of Fig. 345, and the two accompanying telescopes, a second graduated circle is added which revolves in a plane at right angles to the first; to the latter the crystal to be measured is attached, with the addition of suitable adjusting and centering contrivances.

By this instrument, instead of the interfacial angles being measured directly, the position of each face is determined independently of others by the measurement of its angular co-ordinates. These co-ordinates are the angles (ϕ and ρ of Goldschmidt) measured, respectively, in the vertical and horizontal circles from an assumed pole and meridian, which are fixed, in most cases, by the symmetry of the crystal. In practice the crystal is usually so mounted that the prismatic zone is perpendicular to the vertical circle and a pinacoid in this zone is the zero point. For example, with an orthorhombic crystal, for the face 111, the angle ϕ is equal to 010 $\wedge$ 110 and ρ to 001 $\wedge$ 111 for the given species. Goldschmidt has shown that this instrument is directly applicable to the system of indices and methods of calculation and projection adopted by him, which admit of the deducing of the elements and symbols of a given crystal with a minimum of labor and calculation.‡ Fedorow has also shown that this instrument, with the addition of the appliances devised by him, can be most conveniently used in the crystallographic and optical study of crystals.

* See Websky, Zs. Kryst., **3**, 241, 1879; **4**, 545, 1880; also Liebisch, Bericht über die wissenschaftlichen Instrumente auf der Berliner Gewerbeausstellung im Jahre 1879, pp. 330–332.

† Fedorow, Universal or Theodolit-Goniometer, Zs. Kryst., **21**, 574, 1893; **22**, 229, 1893; Czapski, Zeitschr. f. Instrumentenkunde, 1, 1893; Goldschmidt, Zs. Kryst., **21**, 210, 1892; **24**, 610, 1895; **25**, 321, 538, 1896. On the method of Goldschmidt, see Palache, Am. J. Sc., **2**, 279, 1896. A simplified form of the theodolite-goniometer is described by Stüber, Zs. Kryst., **29**, 25, 1897.

‡ Goldschmidt's latest contribution to this subject is his work, Krystallographische Winkeltabellen (432 pp., Berlin, 1897). This gives the angles required by his system for all known species. See also Zs. Kryst., **29**, 361, 1898.