THE MULTIPLE CRYSTAL XRAY SPECTROGRAPH

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By Jesse W. M. DuMond and Harry A. Kirkpatrick

ABSTRACT

The need for improvements in scattered x-ray spectroscopic technique along the lines of increased intensity and contrast is discussed and a new instrument composed of fifty small units, each a Seeman Spectrograph in itself cooperating to form a single spectrogram, is described in detail. The technique of adjusting the instrument is also described.

The limiting factor in many research problems in x-ray spectroscopy today is found in the difficulty of obtaining the necessary intensity. Generally either the photographic film or the ionization chamber is the detecting or measuring instrument. If photography is used, the study of such problems as the Compton Effect, in which the initial x-radiation suffers two serious reductions of intensity, once by scattering and once by selective reflection on a crystal surface, is limited both by the inordinately long photographic exposures required and by the impossibility of obtaining the necessary contrast between the effect sought and the general fogging. If the ionization chamber is used as a detector, even with the most sensitive electrometers such as the Compton or the Hoffman the difficulty of insufficient contrast between the effect and such spurious disturbances as penetrating radiation, electrical leaks, etc. imposes a limit on the work.

Much remains to be cleared up on the Compton Effect and related problems of x-ray scattering. In the authors' opinion further progress is possible only through some radical improvements in experimental technique permitting increased intensity and contrast in x-ray spectroscopy. Such improved technique should permit the investigator to purify experimental conditions without prohibitive sacrifice of intensity. For example, it should permit much greater homogeneity of scattering angle, greater spectral resolution, an investigation of the question of multiple scattering by the comparison of the effect from very thin scattering bodies with that from thicker ones, the study of the Compton Effect from scatterers heretofore prohibited by intensity limitations, and many other questions still remaining open. The authors are especially interested in the question of the diffuse spectral distribution surrounding the position predicted by Compton for the well known "shifted line." Previous work by one of us[1] suggests strongly the existence of an important correlation between the breadth, or more accurately the

[1] J. W. DuMond. Phys. Rev., *33*, No. 5, pp. 643–658; May 1929.

structure of this diffuse distribution and the statistical mechanics of so-called free or conduction electrons in the scattering body (and possibly also the bound electrons). It seems possible to establish *by direct experiment* the applicability of the new Fermi statistics to such conduction electrons and to contradict the applicability of the Maxwell-Boltzman statistics. In fact the study of the structure of scattered x-radiation holds the promise of opening into the new field of the study of electron momentum distributions just as the study of x-ray spectroscopy has lead to energy levels and distributions.

The multiple crystal spectrograph is one attempt then to improve experimental x-ray spectroscopic technique along the lines mentioned above.

At first sight it would seem quite impossible to apply the principle of the concave Rowland grating to x-ray crystal spectroscopy. Let us start, for simplicity, with the two-dimensional case. If, as in Fig. 1,
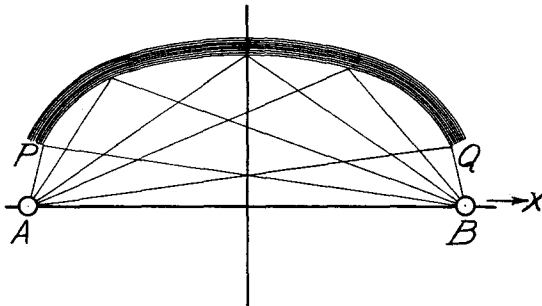

FIG. 1. *Flexible crystal Rowland grating.*

A is a point source of composite x-rays and B a point image of one narrow wave-length band of wave length λ in the spectrum of source A we may set ourselves the geometrical problem of finding the curve defined by the equation $y = f(x)$ such that a flexible crystal surface (as mica for example) conforming to this curve would by Bragg reflection over a large area take x-radiation from A and focus it selectively at B. *If the atomic crystal planes are parallel to the reflecting boundary of the crystal it is immediately evident that no curve can satisfy the conditions for Bragg reflection all over a finite area.* Bragg reflection imposes *two* conditions at every point of the surface PQ. (1) At all points on the surface the angles of incidence and reflection referred to the reflecting atomic planes must ·be equal. (2) At all points on the surface the angle of deviation of the reflected beam (twice the grazing angle) must be a constant (depending on the wave length selected at B). We thus have two mathematical

conditions and only one equation $y = f(x)$ to satisfy them.

dictates the *direction* of the curve $y = f(x)$ at every point.

dictates the position of each point on the curve. It is an

show that the two conditions are not compatible in this case for the definition of any continuous smooth curve.

The situation is not as hopeless as it appears, however, *if we do not insist on having the atomic reflecting planes parallel to the reflecting boundary of the crystal.* Condition (1), it should be noticed, dictates the direction of the atomic reflecting planes but imposes no condition on the reflecting boundary of the crystal. Condition (2) dictates the position of every point on the reflecting boundary but demands nothing of the
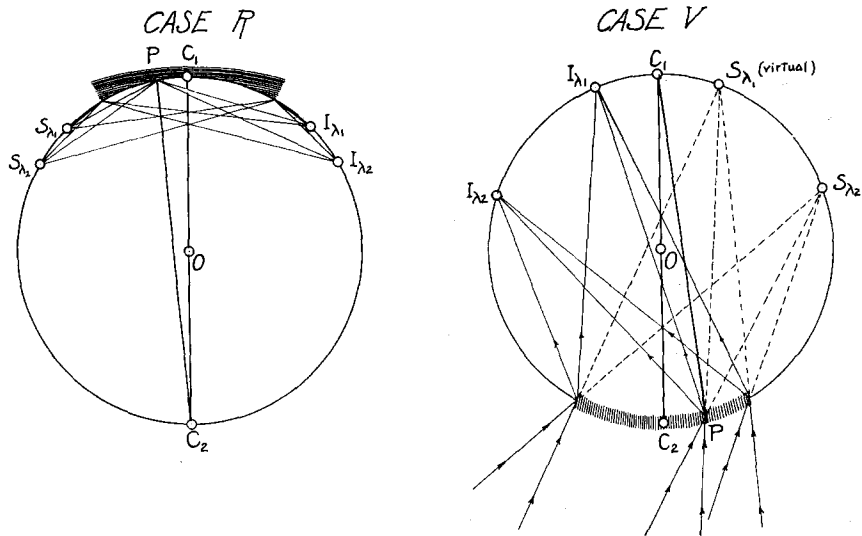

FIG. 2. *Two solutions of problem of selective X-ray focussing.*

atomic reflecting planes. If we arrange matters as in Fig. 2 R or V it is evident that our theoretical problem is completely solved. At R a crystal is shown whose reflecting boundary coincides with part of the circle of center O. The atomic reflecting planes of this crystal however are bent so that they coincide with concentric circles centered on the *circumference* of circle O at the point C.

For all points P of the surface condition (1) is seen to be fulfilled since the equal arcs SC and IC now measure twice the angles of incidence and reflection on the reflecting atomic planes whose normal is PC. Condition (2) is seen to be fulfilled since the arc SI measures twice the angle of deviation of the beam for all points P. It is also evident that the

locus along which the spectrum is focused lies on the circle of center O.

At V the crystal may be thought of as being used in transmission rather than reflection. The short reflecting planes traversing the thin lamellar crystal may either be thought of as short concentric circular arcs with center at C_2 or as planes which if produced would intersect in C_1 diametrically opposite C_2. Case (V) is not geometrically distinct from case (R) save for the fact that case (V) requires a virtual source (or image) while case (R) requires a real source and a real image. As will be presently seen, for many reasons case (V) is the best adapted for practical realization.

DESIGN OF INSTRUMENT

It is of course impracticable to cut and bend large single crystals in the forms shown at R and V, Fig. 2, with the extremely high degree of accuracy required for spectroscopy. The instrument was therefore designed to consist of fifty small units disposed on the arc of a circle of about one meter diameter, each unit consisting of a Seeman type spectrograph with a tiny slip of calcite having a good cleavage surface confronted with a sharp but obtuse brass wedge. The units are each cylindrical, externally being only $1/4''$ in diameter, and the crystal cleavage surface coincides with a diametrical plane of the cylinder. The active reflecting portion of the crystal surface just beneath the edge of the wedge lies exactly in the axis of the cylinder. Fig. 3 is a
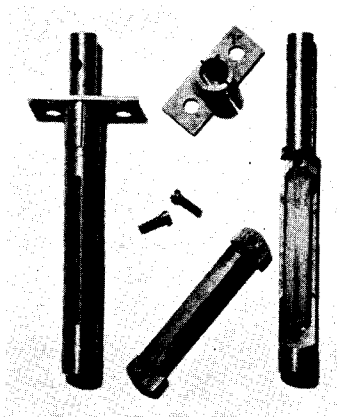

FIG. 3. *Crystal holders; before and after assembling.*

photograph of one of these holders, while Fig. 4 shows their internal design. Very ingenious shop methods for rapidly and economically

producing large numbers of these crystal holders all exactly alike have been worked out by Mr. Julius Pearson, at this Institute. The calcite crystals are cleaved into little rhombohedral slivers with two edges about 1/4″ long and a third edge about 1″ long. Specimens of these slivers are then chosen having one excellent cleavage surface free as far as possible from steps and striae. This cleavage surface is then cemented on a 45° bevel surface cut off the edge of a small square steel block. The crystal sliver is then lapped down with emery on an ordinary lapping wheel until it has two faces flush with the two mutually perpendicular faces of the steel block. The ends of the crystal are then finished off by a special method to conical shape so as to fit the depression provided for

Hole for adjusting pin
Split sleeve for clamping
Calcite cleavage face
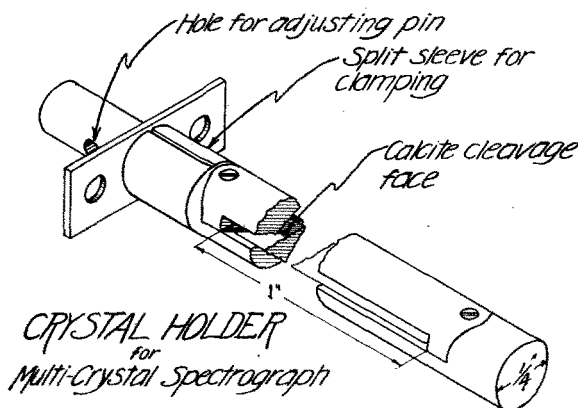1″
1/4
CRYSTAL HOLDER for Multi-Crystal Spectrograph

Fig. 4.

the crystal in the crystal holder. Mr. Julius Pearson so cleverly developed the technique of cleaving and grinding these small crystals that he can produce a dozen or more in a day which in the authors' opinion is a feat meriting the highest praise. Owing to the fragility of calcite a very appreciable percentage of the small ground crystals crack slightly in the lapping process and subsequently break after they have been mounted in their holders a few days. Difficulty has also been encountered in securing the crystal in its holder so as to completely prevent shifting without producing strains which spoil the sharpness of the spectral lines. These questions are discussed in the latter part of this paper.

Figs. 5, 6 and 6A show general views of the instrument both with and without the lead protecting box. The sides and cover of this box can be removed in several pieces without disturbing the set-up. Fig. 7 shows the plan and elevation views of the instrument. The small crystal
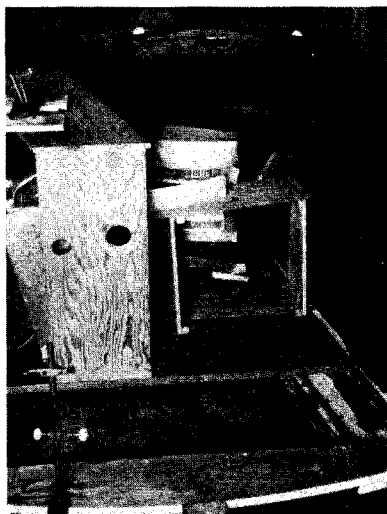
FIG. 5. *Spectrograph in lead box with tube and paraffin block mounted for 90° scattering.*
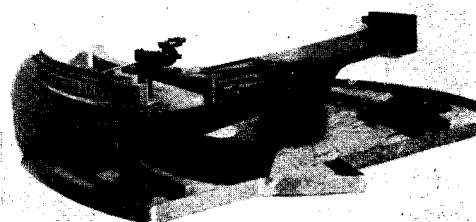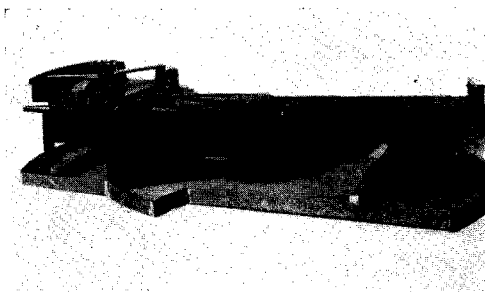

FIG. 6. *The multi-crystal spectrograph.*

FIG. 6a. *The multi-crystal spectrograph.*

holders, fifty in number, fit accurately in fifty holes bored as close to-
gether as was consistent with mechanical strength in a single bronze
casting. These holes are accurately located on a circular arc which forms
part of the major circle of the instrument. The curved casting has two
channels milled out on either side to such a depth that the holes open
into the channels so as to form two elongated rectangular windows on
diametrically opposite sides of each hole. The x-rays pass through these
windows. The hour glass cross-section of the bronze casting which re-
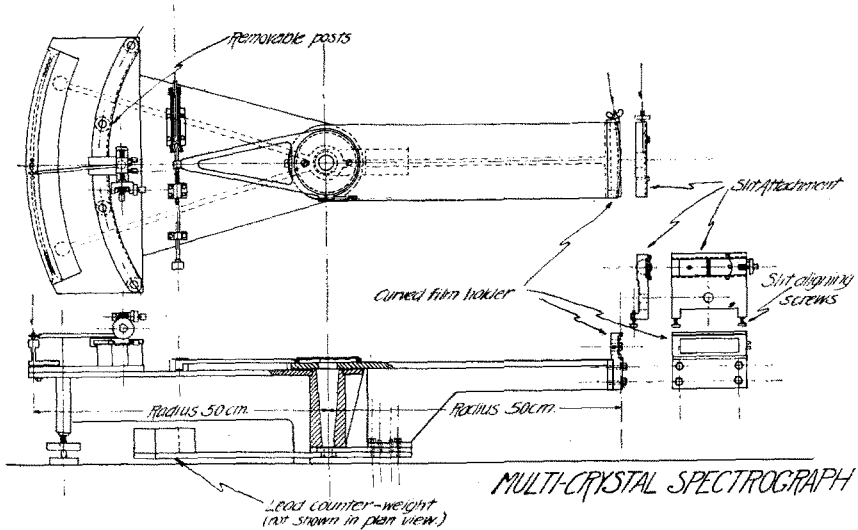mains between two adjacent holes provides an arc of contact of nearly

FIG. 7. *Plan and elevation.*

90° on two opposite sides of each crystal holder. This is amply sufficient
to prevent x-radiation from leaking between the crystal holders.

The crystal holders are very accurately oriented by means described
in the latter part of this paper so that each crystal shall reflect the
$K\alpha_1$ line of molybdenum to exactly the same point on a film mounted in
a curved cassette and coinciding with an arc of the major circle of the
instrument. It is sufficient to orient the crystals accurately for one
wave length and one order. Their focus for all wave lengths and all
orders at various points on the major circle then follows theoretically
as a geometrical consequence. The film cassette is mounted on a coun-
terbalanced arm pivoted at the center of the major circle of the instru-
ment. This permits of swinging the film into a wide variety of positions
so as to explore the spectrum through several orders. The film cassette

can be removed and replaced with a slit to be used in conjunction with an ionization chamber and an electrometer.

It is possible to orient the crystals in their holders so accurately that the lines from different crystals overlap better than 90% of their breadth. These lines have a breadth of about 0.2 mm and are a meter distant from the crystal and wedge. The adjustment is accomplished entirely by photography as the fluoroscope was found to be inadequate. We have often succeeded in completely adjusting several crystals in a single day.
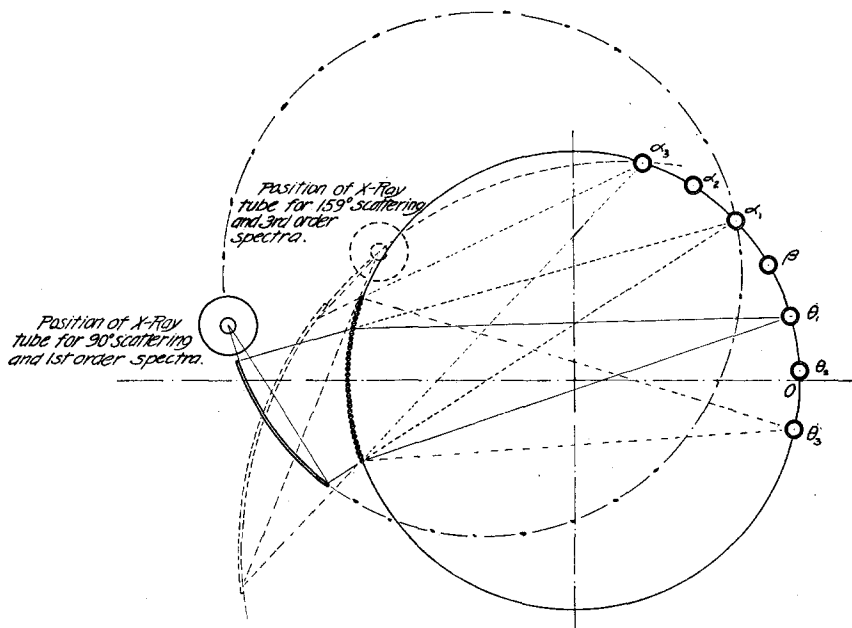
FIG. 8. *Tube in position for scattering, and positions of α, β, and θ.*

A special type of "parallel plate comparator" for measuring the separation of two similar spectral lines on the same negative has been found useful. Its design is described in a separate article in this issue.

It is easy at any time to check whether all crystals are in adjustment by making a relatively short exposure with an x-ray tube in a protecting lead box situated in the proper position in front of each crystal. The tube is mounted on a radius arm centered below the table at the first order virtual source α_1 (see Fig. 8). It is then swung into the proper position for each crystal by means of a graduated circle roughly calibrated by setting on the first and last crystals and dividing the resultant

arc into 49 equal parts. Another method of checking the adjustment of the crystals is to use a curved strip of sheet molybdenum excited to fluorescence by a powerful x-ray tube and placed in front of the instrument.

APPLICATION OF THE INSTRUMENT TO THE COMPTON EFFECT

Fig. 8 shows diagramatically the position of the focal spot of the x-ray tube, the scattering body and the multiple crystal spectrograph for the study of the Compton Effect at 90° scattering angle. It should be noted that for this type of work, in which the x-radiation comes from a scattering body that can be made to have considerable extension, the spectrograph with *virtual* point source is just as well adapted as the spectrograph with *real* point source. The advantages of the "transmission type" of multiple crystal spectrograph with virtual source are: first, with the most common grazing angles of selective x-ray reflection this type permits of much more nearly normal incidence of the radiation on the photographic film. Second, it permits the use of Seeman wedges in front of each crystal. These could not be used in the "reflection type" spectrograph as the wedge of one crystal would cut off radiation from adjacent crystals. In the reflection type the breadth of spectral lines could only be limited by the width of the reflecting face of the crystal.

From the diagram it is easy to see that the angle of scattering can be made extremely homogeneous without much sacrifice of intensity. The inhomogeneity is due to four causes: the finite size of the primary x-ray source; the finite thickness of the effective portion of the scattering body; the fact that the virtual source in the spectrograph occupies slightly different geometrical positions for the slightly different wave lengths involved in the study of the Compton line structure; and, finally, the fact that not all of the x-rays are parallel to the common plane of the major circle of the spectrograph and the circle of the scattering body. The last mentioned item is completely negligible compared to the other three. The scattering angle inhomogeneity can easily be arranged so as not to exceed one degree and is in any case a perfectly definite quantity easily calculable from the geometry of the set-up.

It is to be noted that the fifty small Seeman-type spectrographs receive radiation from an *extended* source. This places rigid requirements on the crystals used as to their perfection and freedom trom strain, for if we consider one point on the photographic film it is evident that this point receives x-rays from *all* parts of the crystal from

its top to its bottom. One very annoying source of trouble described in the latter part of this article came from a slight elastic warping of the individual crystal reflecting surfaces due to various causes, making the surface very slightly helicoidal instead of plane. With a point source such warped crystals gave perfectly sharp spectral lines which were, however, not quite parallel to the wedge and crystal face. An *extended* source, however, would give a *broadened* line with such warped crystals at considerable sacrifice of resolution.

The instrument as now adjusted can easily be used with angles of scattering up to about 160° by a change in the shape and position of the scatterer and a change in the position of the primary x-ray source. The authors also contemplate the use of secondary fluorescent x-rays from a molybdenum radiator taking the place of the primary x-ray source shown in Fig. 8 and excited by a powerful high voltage tube thoroughly screened from everything but the radiator. This would necessitate longer though not prohibitive exposures and would greatly increase the contrast of the Compton Effect by suppressing the objectionable background of continuous radiation.

In Fig. 8 the positions chosen on the major circle for the spectral images and sources in three different orders are shown. θ refers to the images, α to the virtual sources, β is the point where the reflecting crystal planes would converge if produced. The geometry of the instrument permits a certain freedom in the choice of these positions. A number of practical considerations entered into the final choice made. These are:

(1) None of the geometrical limits imposed by the construction of the machine must be violated. The opening of the rectangular windows in the bronze casting requires

$$-90° < \alpha < +90°.$$

All angles are measured positively to the right from a point O diametrically opposite the center of the arc containing the 50 crystals. The design of the enclosing lead box limits the swing of the arm holding the cassette so that

$$-12° < \theta < +45°.$$

The glancing crystal angles cannot exceed 30° because of the angle of the wedges used. This limits the instrument to the fourth and lower orders.

(2) α must be as large as possible to permit working advantageously at large scattering angles.

(3) ψ must be as large as possible to keep the incidence on the film as nearly normal as possible.

For molybdenum k-radiation and calcite a glancing angle of about 7° may be assumed to represent roughly the center of the small spectral region to be studied. We therefore decided to use the following values:

$$\theta_1 = 16° \qquad \theta_2 = 2° \qquad \theta_3 = -12°$$
$$\alpha_1 = 44° \qquad \alpha_2 = 58° \qquad \alpha_3 = 72°$$
$$\psi_1 = 72° \qquad \psi_2 = 79° \qquad \psi_3 = 80°$$

ADJUSTMENTS

The task of adjusting the multi-crystal spectrograph has been one requiring time and patience, but it is believed that the experience gained has indicated changes in the design which will not only shorten materially the time required for the first adjustment but will make any subsequent readjustments comparatively simple.

In the first place, it was found necessary to test each crystal individually after it had been ground and mounted in the instrument, since, as has been stated above, in many cases crystals proved to be useless because the reflecting "planes" were not accurately plane throughout the length of the crystals. In many instances, this would have resulted in approximately doubling the widths of the lines with the consequent loss of intensity and resolution. In a few cases, the widths would have been more than tripled. In some crystals this defect was found to be a strain, probably torsional, imposed by the crystal holder and was corrected by loosening slightly the screws which held the wedge and crystal in place. In other cases, the defect was apparently inherent in the crystals themselves and they were replaced by others. The method of testing was quite similar to that used for orienting, and is described later in this paper. The best method of mounting the crystals in the holders so that they will be immovable and yet under no mechanical stresses is yet to be determined. Cement and beeswax have been tried but success with either seems to be uncertain. At present, it is hoped that a slightly different design of the holders will take care of the problem mechanically, or that pitch may be used successfully as a cement. We have succeeded, however, in obtaining so far, twenty-eight undistorted crystals, seventeen of which are in adjustment and have served successfully for several preliminary spectrographic exposures. These were cemented into their holders with DuPont cement. The number of failures with this cement, however, was rather discouraging.

The orientation of the crystals was accomplished photographically using the $K\alpha$ lines from a molybdenum target tube. The tube was mounted as described above, so that it could be rotated about the point α_1 as center, and positions were marked on an arc on the moving frame supporting it, so that the focal spot could be set at will on the extension of the radius through any desired crystal (see Fig. 9). One of the middle
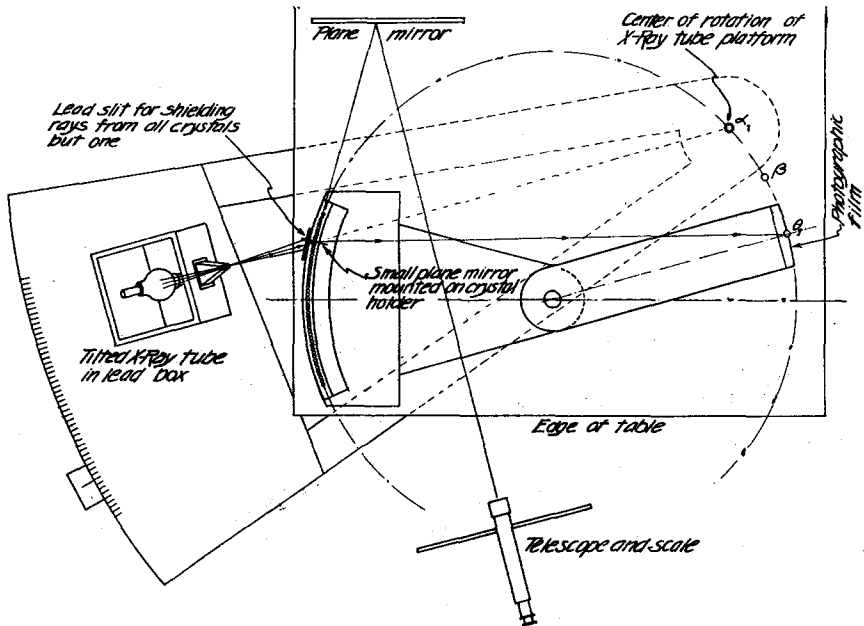

FIG. 9. *Tube mounted for orientation of crystals.*

crystals was selected as a standard reference crystal, rotated by means of the slow motion tangent screw and arm shown in position in Fig. 6 and 6A, until the $K\alpha$ lines appeared in a fluorescope at about the center of the film holder set at θ_1 (16°) for first order spectrum, and was locked in position by means of a set screw. Then each of the other crystals in turn was oriented so that the lines reflected from it coincided on the film with those from the reference crystal. The first rough setting was made with the fluoroscope and usually put the spectral lines within a few millimeters of their proper positions at the film holder. To test this, a photographic film in its black paper envelope was put into the film holder and an exposure made as follows. The x-ray tube was swung into position in front of the reference crystal. A small movable lead plate to shield the neighboring crystals not yet oriented, but with a

slit to permit the radiation to reach the reference crystal, was put in position as shown in Fig. 9. A central longitudinal zone of the film, about one third the width of the 1×4-inch opening in the front of the film holder, was shielded from the radiation by a strip of 1/8-inch brass, and a one minute exposure was taken. Thus only the extremities of the reference spectral lines show on the film, the central third being shielded off. The tube was then moved into position in front of the crystal to be oriented; a similar lead slit was placed in front of it; the film was shielded this time in such a way as to expose only the central third of the spectral lines; and a second exposure was made. A sample negative is shown in Fig. 10. Here, as was usual, the adjustments of three differ-
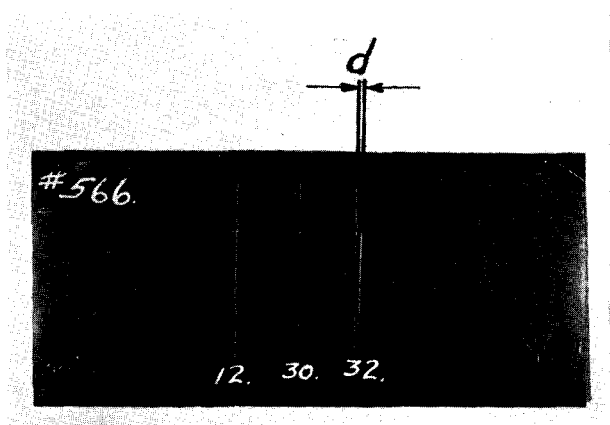

Fig. 10. *Test of orientation of three different crystals.*

ent crystals were tested on the same film by sliding the film envelope in the cassette instead of putting in a new film for each one. The segments of the lines at the top and bottom are in each case those from the reference crystal. Crystal No. 30 was satisfactorily oriented as is shown by the lines so numbered, while 12 and 32 were not. As a basis for calculating the angle through which it was then necessary to rotate crystal No. 32 to bring the lines into coincidence, the distance d was measured on the negative with the parallel plate comparator. A small mirror had been previously mounted on the holder of the crystal being adjusted, and by using a telescope and scale at a distance of about 2 meters (see Fig. 9) a very small rotation could be observed and measured. Since the x-ray beam moves through the same angle as the crystal while the reflected light ray from the mirror moves through

twice that angle, we have for s, the change of scale reading in the telescope required to bring the crystal into the proper orientation, the relation

$$s = 2dr_2 / r_1$$

where r_1 is the distance from the crystal to the film and r_2 is the distance from the scale and telescope to the small mirror. This correction having been made as carefully as possible, a second photographic test was made and, if necessary, the whole process repeated until a satisfactory correspondence of the lines on the negative was obtained.

Several difficulties were encountered in this process. The first attempt met with complete success in only a few instances. Usually from three to ten trials were required, and once or twice, as many as twenty negatives proved disappointing before one finally showed an acceptable coincidence. In fact, for reasons given below, the uncertainty in the setting was of the order of magnitude of the width of the lines, and after the first attempt or two the process became largely one of trial and error, and accordingly the distance d was no longer measured but merely estimated by eye. In the first place, tightening up the set screw designed to lock the crystal holder in place invariably rotated the crystal in spite of the fact that it bears on a split sleeve (shown in Fig. 4) and not on the crystal holder directly. Thus, it was not possible to simply make a careful setting with the telescope and scale and then lock the crystal in place. It was necessary to make a few tentative trials to see just what effect tightening the screw would have, and then make the proper allowance beforehand. This rotation by the set screw did not prove to be an unmitigated evil, however, as it was found possible in most cases to use it as a method of making the final delicate adjustment without recourse to the slow motion screw and arm. Several attempts might be required before this method could be used however, since at first, it was usually found that the screw was already so tight that it could not be turned up enough to produce the required rotation, or, if it was necessary to loosen it, that it became too loose for safety. The final adjustment of most of the crystals was eventually made this way however.

In the second place, it was found impossible to remove the rotating arm from its hole in the crystal holder without disturbing the orientation, so this also had to be done before locking the crystal, which added another element of guess work to the preliminary telescope and scale setting. Then it was usually found necessary to use the arm again on

the next trial and the crystal was disturbed by the reinsertion, so the value of a careful measurement of d on the previous film was lost because the crystal was usually disturbed so much that even when brought back to the same scale reading before making the calculated correction, its actual position was rarely the same to the degree of accuracy required. It was usually possible to remove the mirror from the top of the crystal holder after the final adjustment without disastrous results, but another photographic check was always made to make sure. However, experience has shown that the crystals do not always stay in adjustment and it has been necessary to test them all occasionally and reset the ones found out of position. Usually the required correction is less than the width of a line on the film and if it were not for the necessity of resetting the small mirror on top of the crystal holder, with its face in the proper plane and reinserting the rotating arm, it would be a much simpler matter, but it is usually found that the crystal is still farther out of position after this has been done.

Thus the indicated improvements in the design of the instrument seem to be (1) a mirror permanently mounted on each crystal holder and facing in such a direction that it would never have to be moved relative to the crystal holder, (2) a separate slow motion mechanism permanently attached to each crystal holder, and (3) a means of locking the holder in position after adjustment without disturbing it. Perhaps the last two can be combined in a single device.

The preliminary testing of each crystal for planeness was done in much the same way as was the orientation described above. But in this case spectral lines were obtained on the film from different parts of the same crystal instead of from different crystals. Since the source of radiation, the focal spot of the tube, was small and close to the crystal while the film was much farther away, only a small fraction of the length of the crystal contributed radiation to the lines on the film. Consequently, it was possible to explore it throughout its length by simply raising and lowering the x-ray tube and determining whether the lines reflected selectively from the various parts coincided on the film. Usually, four different parts were checked against the middle. The tube was placed so that the focal spot was at the level of the middle of the crystal and the central zone on the film was shielded while an exposure was made. Then the tube was raised until in line with the upper part of the surface of the crystal, and an exposure made on the central zone of the film only. The film was then moved a few millimeters laterally in the cassette and a similar comparison was made

between the surface at the middle and one fourth of the way down, and so on to the bottom. Lastly, as a check, the top was compared with the bottom. Fig. 11a shows a sample negative revealing one of the worst crystals found. The last exposure, on the right, shows a difference between the top and bottom nearly equal to the separation of the lines of the $K\alpha$ doublet. Fig. 11b shows an investigation of another crystal at intervals of one sixth of its length but with no comparison directly
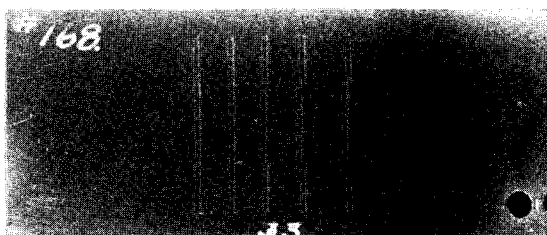
(a)
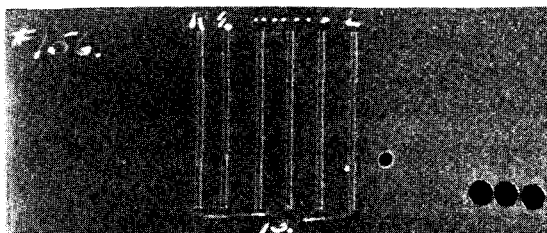
(b)

FIG. 11a and 11b. *Tests of planeness of crystals.*

between top and bottom. Here, there is apparently a uniformly helicoidal surface throughout the length, while in (a) practically all the distortion occurs in the lower half. On both negatives the central segments of the lines are from the central part of the crystal, with the exception mentioned above of the right hand pair in (a).

The reasons for the failure of crystals to stay in adjustment have not been fully determined. It is suspected that slight strains produced by the locking set screw may result in "creeping." There is also reason to suspect a series of mild earth tremors which occurred on the morning of July 8, 1929 and were of sufficient amplitude to be quite noticeable

inside the laboratory. On July 20, a check was made on the fourteen crystals then adjusted and it was found that seven were again out of position from half to the full width of a line. Of the eight which had been adjusted before July 8, only two were still correct, while of the six which had been adjusted after the earthquake, only one was out of position. With the exception of this instance, it has been only an occasional crystal that has been found to require resetting, and with
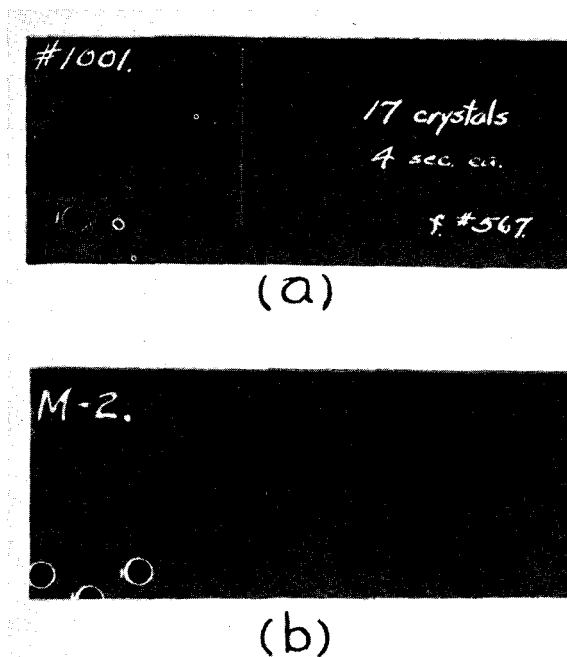

(a)

(b)

Fig. 12a and 12b. *Tests of resolution obtained with seventeen crystals.*

the improvements suggested above, this should not be a serious defect in the instrument.

It should be said that considerable care has been taken to insure that the position of the film is always the same. The containing envelopes are of uniform thickness of black paper, folded only once, so that there is nowhere more than one layer in front of or behind the film, and the ends are closed by a thin layer of cement between the two thicknesses of paper. The upper edge is left open and the loading is done in the dark. The film is held in place against the circular arc of the frame of the cassette by the tension of a flexible brass strip, and

this has vertical reinforcing ribs on the back to prevent bowing in and forcing the film too far forward in the middle. The importance of these precautions is evident, as the beams from the crystals located at the extreme ends of their arc are converging at an angle of about 23°.

Fig. 12 gives an indication of the accuracy with which it has been possible to orient seventeen of the crystals, which are now being used in preliminary tests with scattered radiation. The negative marked (a) is a composite photograph made by placing the tube in front of each of the seventeen crystals in turn and using each for a 4-second exposure. Negative (b) is a 48-hour exposure of the film to fluorescence from a strip of sheet molybdenum placed in front of the crystals and exposed to x-rays. It will be seen that the resolution obtained with the multi-crystal spectrograph is comparable with that given by a single crystal Seeman spectrograph as shown in Figs. 10 and 11.

Seventeen crystals were carefully aligned in a preliminary test and successive exposures of equal duration made on the same film with each. One crystal alone was then exposed seventeen times as long, the film having been slightly displaced in its holder. The blackening of the two lines was identical from which the conclusion is drawn that the superposition of the seventeen crystals was practically perfect and that one can expect the full theoretical multiplication of intensity in practice.

NORMAN BRIDGE LABORATORY OF PHYSICS,
  CALIFORNIA INSTITUTE OF TECHNOLOGY,
    PASADENA, CALIFORNIA,
      NOVEMBER 1st, 1929.