

## A High Resolving Power, CurvedCrystal Focusing Spectrometer for Short WaveLength X Rays and Gamma Rays

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Citation: [Review of Scientific Instruments](#) **18**, 626 (1947); doi: 10.1063/1.1741017

View online: <http://dx.doi.org/10.1063/1.1741017>

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(written in the same order as in Eq. 3) the following values:

$$E_A = E_B = \pm 0.003 - 0.0000225 \text{ cm.}$$

Clearly, vertical displacements of the grinding wheel axis of the order of two millimeters from coincidence with the height of the axis of the dividing head, are tolerable. Longitudinal displacements of the grinding wheel axis produce somewhat more serious errors. Actually however even these errors vanish if, instead of comparing the generated profile with a reference circle whose center is exactly in the perpendicular bisector of the block, we compare it with another true circle whose center is displaced in the  $x$  direction by an amount  $\epsilon/2$  in the sense  $PP'$  of Fig. 8, i.e., in the direction of positive  $\epsilon$ . In fact, the errors intro-

duced by the first term in Eq. 3 are a linear function of  $x$ ; the whole profile is tilted through an angle  $\epsilon/(2R)$  counterclockwise. This is the same as though the center of the circle were displaced to the right a distance  $\epsilon/2$ . Thus a horizontal error in the location of the center of the grinding wheel of two millimeters merely throws the profile of the generated arc off center on the block by 0.5 mm. As far as the *circularity* of the profile is concerned, the term in  $\epsilon$  introduces no error whatever to the high order of approximation calculated here. We have found these predictions verified in practice. Actually the ordinary errors of a grinding machine from variable oil-film thicknesses, vibration, and elastic deflections are larger than those above computed.

## A High Resolving Power, Curved-Crystal Focusing Spectrometer for Short Wave-Length X-Rays and Gamma-Rays\*

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(Received May 21, 1947)

Description is given of a transmission-type, curved-crystal focusing spectrometer for short wave-length x-rays, and gamma-rays having a dispersion of 1.186 x.u. per mm at short wave-lengths. The spectrometer utilizes the (310) planes of quartz in a crystalline plate of dimensions  $80 \times 70 \times 1.0$  mm curved cylindrically to a radius of two meters. High luminosity is obtained since the useful aperture in the crystal holder has an area of 10 cm<sup>2</sup> and subtends 0.00025 steradians at the focus. It also affords high resolution since by photographic tests with x-rays the curved plate has been shown to focus a specified x-ray wave-length to within 0.06 mm of the same position on the focal circle for all parts of its useful aperture and over the entire operating wave-length range. The geometry of the mechanism permits absolute measurements with a precision screw of the sine of the Bragg angle on both sides of the reflecting planes, affording a wave-length range which includes at longest wave-lengths the  $K$ -spectrum of silver and goes down to zero wave-lengths. For short wave-length gamma-rays the

source is placed at the focus. A multiple-slit collimator of tapering die-cast lead partitions spaced apart with tapering separators, is used at short wave-lengths to transmit the monochromatic diffracted beam and absorb the directly transmitted and scattered heterogeneous beam. The present collimator limits the spectrum that can be studied to a shortest wave-length of 7. x.u. corresponding to 1.75 Mev. The intensity of the diffracted beam is to be measured with a special multi-cellular G. M. counting tube of high efficiency, provided with a number of thin lead partitions through which the beam passes successively. In photographic spectra made with this instrument the tungsten and also the silver  $K\beta_1\beta_3$  doublet is completely and clearly resolved. Reproductions of such photographic x-ray spectra are shown in which the line breadths have substantially the natural breadth. Fluorescence spectra of silver have been made in 10-minute exposures. A companion paper gives the all-important precision technique of generating the curved cylindrical stainless steel clamping blocks for the crystal.

### I. THE GEOMETRICAL OPTICS OF THE CURVED-CRYSTAL FOCUSING SPECTROMETER

TWO types of curved-crystal focusing spectrometer may conveniently be distinguished: the transmission and the reflection types. The exact solution of this problem for both these cases was conceived by the author in 1927,

and it was first stated in the literature<sup>1</sup> with explicit diagrams showing the exact geometrical solution for both cases in a paper describing a multiple crystal x-ray spectrograph, an instrument constructed for the study of the structure of the Compton line which utilized the same geometry applied, however, to many little crystals

\* This research is now being conducted under Navy Contract N6onr-244 Task Order IV, dated March 1, 1947.

<sup>1</sup> J. W. DuMond and H. A. Kirkpatrick, "Multiple crystal x-ray spectrograph," *Rev. Sci. Inst.* 1, 88 (1930), see Fig. 2.

rather than to a single, curved crystal. At the time the author thought that bending a large single crystal, with the requisite precision for the high resolving power then needed, presented a more difficult problem than the multi-crystal solution. The sequel, however, has proven this to be untrue. The multi-crystal solution, although it succeeded after roughly a year of very arduous and painstaking adjustments, proved in fact to be a far more difficult instrument to build and to adjust than the curved-crystal solution.

The first curved-crystal spectrometer of reflection type was built by H. H. Johann<sup>2</sup> and the first transmission type was built by Y. Cauchois.<sup>3</sup> Cauchois refers to DuMond's original proposal in her first papers.

One may well ask why the principle of the Rowland concave grating was not immediately extended to x-ray crystal spectroscopy after the discoveries of Laue and Bragg. The answer to this, the author believes, is to be found in the following supposed obstacle which greatly delayed the solution.

We must first recall that the conditions for selective x-ray reflection by crystal lattice planes are a little more complicated than the conditions for diffraction by a ruled grating. Consider the two-dimensional case shown in Fig. 1 in which  $A$  is a point source of composite x-rays and  $B$  a point image of one narrow wave-length band  $\Delta\lambda$  of wave-length  $\lambda$  in the spectrum of source  $A$ . If we set ourselves the geometrical problem of finding a curve (say  $y=f(x)$ ) such that the cleavage surface of a flexible crystal (mica for example) conforming thereto would, by Bragg reflection over an extended area, take x-radiation from  $A$  and focus it selectively at  $B$ , we find the problem is in the strict sense insoluble because Bragg reflection imposes *two* conditions at every point of the surface  $PQ$  which cannot be met by any single equation  $y=f(x)$ . These two conditions are (1) at all points on the surface the angles of incidence and reflection referred to the reflecting atomic planes must be equal, and (2) at all points on the surface the angle of deviation  $\varphi$  of the

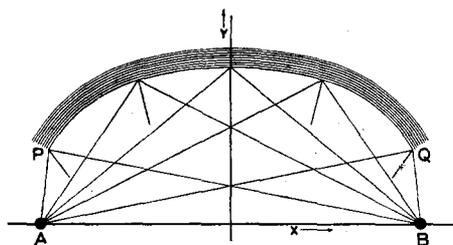


FIG. 1. To illustrate the impossibility of satisfying both conditions for Bragg reflection with a bent crystal over an extended surface if the atomic reflecting planes coincide with the reflecting boundary of the crystal, and if focusing at two conjugate foci is required.

reflected beam must be constant and equal to

$$\varphi = 2 \sin^{-1}(n\lambda/2d).$$

Condition (1) dictates the *direction* of the curve at every point while condition (2) dictates the *position* of each point on the curve. It is easy to see that they are incompatible by noting that condition (2) is satisfied if, and only if, the curve is a circular arc through  $A$  and  $B$ , of radius  $R$ , where

$$R = \langle \overline{AB} \rangle_{AV} / 2 \sin \varphi,$$

whereas condition (1) is not satisfied by this solution.

The author believes that he was the first<sup>4</sup> to see the way out of this apparent impasse. After much

<sup>4</sup> Spectrometers using bent crystals such as mica had been built and used prior to 1927. These were not focusing spectrometers, however, with two conjugate foci (real or virtual). One of these, for example, consisted of a sheet of mica rolled around a cylinder upon which an x-ray beam, propagating at right angles to the axis of the cylinder fell in nearly tangential incidence so as to be reflected from the convex mica surface. The advantage gained was the elimination of the necessity for rocking the crystal or the source. No gain in luminosity was attained.

Another early suggestion was to bend a mica sheet about a cylindrical surface having as its base profile a logarithmic spiral. The origin of the spiral would then certainly give *one* required focal point, but there is no corresponding conjugate focal point. Instead there is a caustic. This fact affords another way of perceiving the incompatibility of the two conditions imposed by Bragg reflection when applied to the cleavage surface of a bent mica crystal.

A third type of bent-crystal spectrometer which does have two conjugate foci and which affords considerable luminosity consists in a crystal such as mica rolled into a hollow cylinder which reflects the x-rays from its internal concave surface. If the source of x-rays is placed on the axis of this cylinder, a monochromatic point image will be formed elsewhere on the same axis. The mica surface may also conform to a hollow conical frustum. The geometry of the focusing is rather disadvantageous for photographic spectroscopy. P. Kirkpatrick has developed a very luminous monochromator in which this kind of focusing is combined with the Johann-type of focusing (our case  $R$  of Fig. 2). Rocksalt crystals are deformed to a barrel-shaped surface to obtain this result.

<sup>2</sup> H. H. Johann, *Zeits. f. Physik* **69**, 185 (1931).

<sup>3</sup> Y. Cauchois, *Comptes rendus* **194**, 1479 (1932); *ibid.* **194**, 362 (1932); *ibid.* **199**, 857 (1934); *J. de phys. et rad.* **3**, 320 (1932); *ibid.* **4**, 61 (1933); *Ann. de Physique* **1**, 215 (1934).

reflection he realized that the two conditions above mentioned *are not in fact imposed on the same surface provided we do not insist on having the atomic reflecting planes parallel to the boundary surface of the crystal*. Condition (1) dictates the *direction* of the atomic reflecting planes but imposes no condition on the *boundary surface*, while condition (2) dictates the position of every point on the boundary surface (at least in the reflection case) but demands nothing of the atomic reflecting planes. If we arrange matters as in Fig. 2 *R* or *V*, it is evident that our ideal problem is completely solved. At *R* (the reflection case) 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 of the surface, condition (1) is 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 *SPI* 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*.

The transmission case, Fig. 2 *V*, is really an analytical continuation of the reflection case. The

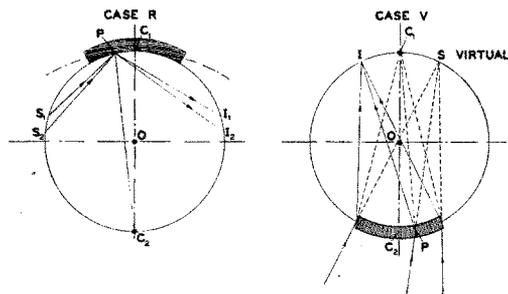


FIG. 2. Case *R* shows the exact solution for the reflection-type, curved-crystal, focusing spectrometer in which there are two real conjugate foci *S* and *I*. The reflecting boundary surface of the crystal coincides with the focal circle (center at *O*), while the atomic reflecting planes are curved so as to be concentric about the center *C*<sub>2</sub> on the circumference of the focal circle.

Case *V* shows the exact solution for the transmission-type, curved-crystal focusing spectrometer. In this type there is one real focus *I* and one virtual focus *S*. The atomic reflecting planes converge to a point *C*<sub>1</sub> on the focal circle (center at *O*), while the neutral axis of the bent lamina coincides with the focal circle.

short reflecting planes traversing the thin crystal sheet may either be thought of as normal to a radius through *C*<sub>2</sub> (just as are the atomic planes in case *R*) or as planes which, if produced, would intersect in *C*<sub>1</sub> diametrically opposite to *C*<sub>2</sub>. It is clear from the figure that the transmission case (Fig. 2 *V*) has one virtual and one real focus, while the reflection case (Fig. 2 *R*) has two real conjugate foci. For obvious reasons the reflection case is usually better adapted to long wave-lengths and large Bragg angles, while the transmission case is better adapted to short wave-lengths and small Bragg angles.

Mlle. Yvette Cauchois has added several extremely valuable contributions to this primary idea. Firstly, she realized that condition (2), fixing the *position* of the boundary or boundaries of the crystal, was less stringent than condition (1), fixing the *direction* of the atomic planes so that, if the arc of the focal circle covered by the crystal is not too large, the aberrations of focusing can be kept sufficiently small for practical purposes without requiring the difficult curved profiling of the boundary surface.<sup>5</sup> Secondly, Cauchois pointed out the important new observation that in the transmission case *there is a focusing effect through the thickness of the curved sheet* as well as from side to side. When the crystal lamina is curved, the strain near the outside (convex) surface of the plate results in a *larger* grating constant than the strain-free value, and hence a *smaller* Bragg angle than the one that obtains for reflection by regions of the crystal on its elastic neutral axis. The opposite effect occurs for reflection by regions near the inner (concave) surface. It is easy to show that this results in exactly the required convergence of all the reflected beams over the entire thickness of the slab to give perfect focusing from front to back. This leads to the conclusion that in the transmission spectrograph it is the neutral axis of the crystalline slab which must be in contact with the focal circle. Cauchois has also made a careful quantitative study of the geometrical aberrations of her

<sup>5</sup> Others, however, have succeeded in building curved-crystal spectrometers of the exact focusing type by suitably profiling the crystal lamina in its unstressed state to the required curvature, twice the radius of the focal circle, and then bending it until the spectra focus on the focal circle. See A. Guinier, *Ann. de Physique* 12, 161 (1939), and R. Bozorth and F. E. Haworth, *Phys. Rev.* 53, 538 (1938).

instrument. The chief geometrical aberration in the Cauchois approximate-transmission type spectrograph comes from the fact that the neutral axis of the curved lamina deviates at its extremities from exact coincidence with the focal circle. Figure 3 shows the geometry of the relative line broadening,  $\Delta\lambda/\lambda$ , which results from this aberration. Geometrical considerations yield the result

$$\Delta\lambda/\lambda \cong \cos\theta(1 - \cos\alpha)/\cos(\alpha + \theta), \quad (1)$$

wherein  $\theta$  is the Bragg angle and  $\alpha$  the half-angle of aperture. Clearly for small Bragg angles,  $\theta$ , and small aperture angles,  $\alpha$ ,  $\Delta\lambda/\lambda$  rapidly becomes negligible. For  $\theta < \alpha \ll 1$  the relative broadening is given by

$$\Delta\lambda/\lambda \cong \frac{1}{2}\alpha^2. \quad (2)$$

There is also a slight geometrical aberration, which can be neglected in our present case, coming from the obliquity of some of the x-rays relative to the base plane of the focal cylinder.

Cauchois and Hulubei have done extensive work in the study of different crystals and crystal planes for this application and, among others,<sup>6</sup> have recommended the use of the (310) planes in quartz, a recommendation which the author has followed in the present instrument.

An interesting result of the type of reflection taking place in the transmission-type curved-crystal spectrometer is that there is no correction whatever to the Bragg angle for the refractive index of the x-rays in the crystal used, provided the internal planes of reflection are normal to the crystal slab. This is not true of the reflection type. Referring to Fig. 4 we see that the ratio of the wave-lengths outside and inside the crystalline medium,  $\lambda_1$  and  $\lambda_2$ , respectively, will be equal to  $\mu$ , the refractive index of the crystal

$$\lambda_1/\lambda_2 = \mu \quad (\mu < 1), \quad (3)$$

while the ratio of the sines of the angles,  $\theta_1$  and  $\theta_2$ , of incidence and refraction at both entrance and exit boundaries of the crystal will also be equal to

$$\sin\theta_1/\sin\theta_2 = \mu. \quad (4)$$

<sup>6</sup> Others who have worked with curved-crystal spectrometers are J. W. M. DuMond and B. B. Watson, *Phys. Rev.* **46**, 316 (1934); *Rev. Sci. Inst.* **8**, 480 (1937); I. Johansson, *Zeits. f. Physik* **82**, 507 (1933); P. Abelson, *Phys. Rev.* **56**, 753 (1939); E. Ingelstam, *Rev. Sci. Inst.* **11**, 160 (1940); J. E. Edwards, M. L. Pool, and F. C. Blake, *Phys. Rev.* **67**, 150 (1945).

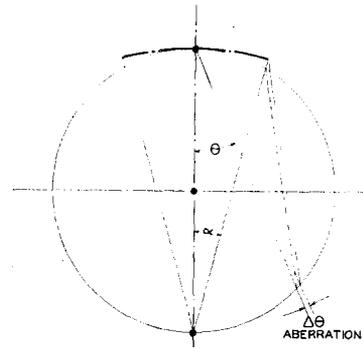


FIG. 3. Geometry determining the line broadening or aberration in the Cauchois approximate type of transmission spectrograph which results from the fact that near its extremities the neutral axis of the lamina fails to coincide with the focal circle. The aberration  $\Delta\theta$  results in a corresponding aberration  $\Delta\lambda$  given in formulae (1) and (2) of the text. For small  $\theta$  and  $\alpha$  this aberration is extremely small.

If the reflecting planes are normal to the boundary surface, the Bragg equation inside the crystal is

$$n\lambda_2 = 2d \sin\theta_2, \quad (5)$$

and it follows from (3) and (4) that outside the crystal we shall also have

$$n\lambda_1 = 2d \sin\theta_1. \quad (6)$$

As the planes of reflection incline away from the normal to the boundary surfaces, the correction for refractive index at first increases very slowly.

## II. DESIGN OF PRESENT FOCUSING SPECTROMETER FOR SHORT WAVE-LENGTH X-RAYS AND GAMMA-RAYS

The design of the present short wave-length spectrometer was started in 1938, and its con-

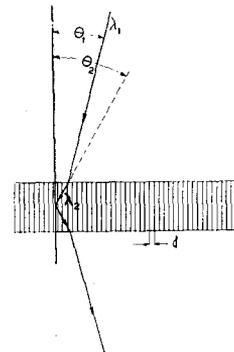


FIG. 4. Geometry demonstrating the absence of correction for refractive index when the atomic reflecting planes are normal to the exit and entry faces of the lamina in the transmission-type spectrograph.

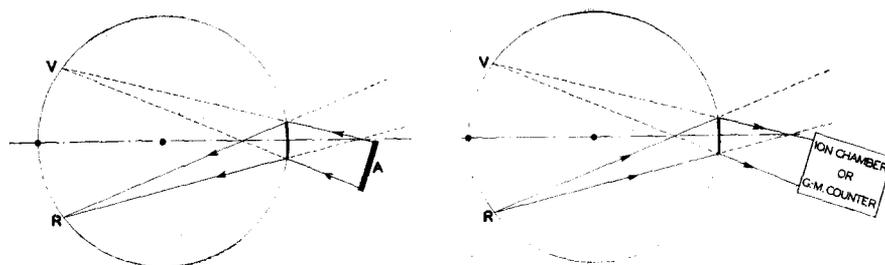


FIG. 5. Two ways of using the transmission-type, curved-crystal spectrometer. An extended source may be placed at  $A$ , in which case spectral lines will be focused as at  $R$ . This case is appropriate for the study of fluorescence excited in a screen placed at  $A$ , but is uneconomical if the total intensity from the source is a limiting factor. For gamma-ray spectra the source may be placed at  $R$ , and the intensity, measured in an ion chamber or counter, is thus plotted as a function of the position of the source  $R$  on the focal circle.

struction and assembly were practically completed save for the all-important crystal clamping blocks in 1940. The work was interrupted by the necessities of World War II research and was not resumed until the spring of 1946.

#### Source Positions for Gamma-Ray and for X-Ray Work

The transmission-type of curved-crystal focusing spectrometer is the one definitely indicated for short wave-lengths. As we have pointed out (Fig. 2), this type has one real and one virtual focus, and hence it is not immaterial in which direction the radiation propagates. Referring to Fig. 5 we may either place an extended source at  $A$  or a very concentrated source at the real focus  $R$ . Now, if we are to work with direct radiation from radioactive substances, it is clear that in order to obtain as much gamma-ray intensity as

possible of some specified wave-length from a limited amount of the radioactive sample, the real focus,  $R$ , is the best place to put the source since in this location every atom can radiate the specified wave-length into a solid angle subtended by the entire working aperture of the curved crystal. The spectrum is explored by moving the sample along the focal circle and plotting the monochromatic intensity observed in the diffracted beam at  $A$  as a function of the Bragg angle  $\theta$ . If the same radioactive source were extended over a surface and placed at  $A$ , on the other hand, the monochromatic intensity observed at a specified wave-length, position  $R$  on the focal circle, would be very much smaller than in the previous case because the solid angle, into which each atom in the source  $A$  could radiate a sharp monochromatic line, would be excessively limited in the horizontal plane. The horizontal dimension,  $\Delta\theta$ , of this solid angle would, in fact, be determined by the width of the diffraction pattern characteristic of the focusing curved-crystal plate, and because of the extreme demands imposed by the problem of resolving the spectra of short wave-length gamma-rays, crystals giving the very narrowest diffraction patterns available must be used. For such perfect crystals, diffraction patterns of the order of a few seconds of arc, or less, in width  $\Delta\theta$  are possible. When this is compared with the available horizontal angular opening of 1.5 degrees, if the source is placed at the focus of the present spectrometer, we see that the latter position (source at  $R$ ) should yield of the order of five thousand times as much intensity at a specified wave-length as the former position (source at  $A$ ). When the source is at position

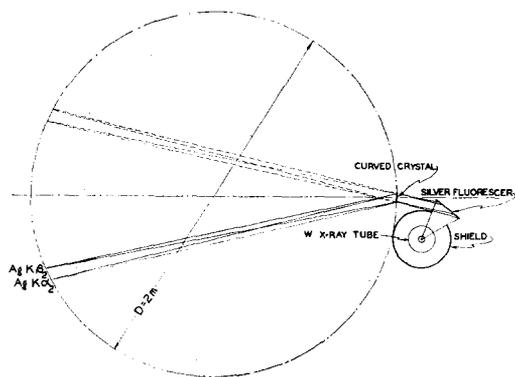


FIG. 6. Showing to scale the geometry of the arrangement used to give the fluorescent spectrum of Ag  $K$ -radiation shown in Fig. 12. The fluorescer is so situated that the entire aperture of the curved crystal is used in forming the spectrum, thus furnishing a test of the quality of focusing.

A, Fig. 5, an entire spectrum over a considerable range of wave-lengths can be formed at one and the same time on a photographic emulsion placed on the focal circle. This arrangement is advantageous for x-ray spectra where a group of different lines over a considerable wave-length range is the object of study and where the radiation is soft enough so that photographic spectra can be profitably used. This is particularly true if fluorescence spectra are to be studied because then the extended source placed at *A* becomes the fluorescent substance. A sheet of the material of sufficient size to supply fluorescent x-rays to all parts of the curved crystal can be excited by primary x-rays from an x-ray tube placed at a short distance. In this case, if the fluorescer is cheap, the extended nature of the source may imply no increased expense. A fluorescent source of doubled area emits twice as much x-radiation with exactly the same power supply to the exciting tube, because such a fluorescer subtends twice as great a solid angle of the primary exciting radiation. Figure 6 shows to scale the geometrical disposition of a tungsten x-ray tube, a silver fluorescing sheet, and our present focusing, curved-crystal spectrometer as it was set up for making the Ag *K*-fluorescence spectra shown in Fig. 12. Clearly defined fluorescence *K*-spectra of silver could be obtained in exposures of ten minutes with a primary tungsten tube operating at 10 ma and about 70-kv peak self-rectified.

The present spectrometer was designed so that it could be used either photographically as an x-ray spectrometer with the source at *A* or as a gamma-ray monochromator with the source at the real focus *R*. This was done to permit easy study of the quality of focus of the curved crystal by means of x-rays before the more difficult study of very hard radiation was attacked. To facilitate the photographic x-ray work, the spectrometer was designed to permit Bragg angles sufficiently large to include the *K*-spectrum of silver. The thought was also present during the design that it would be very valuable to bridge the gap between the gamma-ray and x-ray regions by precision measurements of wave-lengths made in both regions with one and the same instrument. For this reason the design provides means of measuring the sine of the Bragg angle on a precision screw whose revolutions are strictly proportional

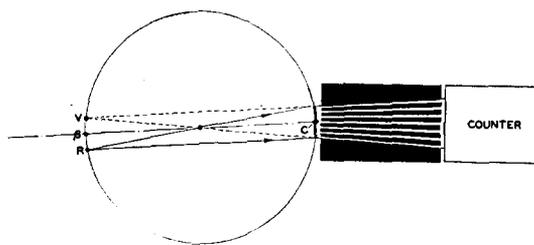


FIG. 7. To illustrate how the tapering lead collimator is used to suppress the beam directly transmitted through the crystal from *R*, and to permit free passage of the monochromatic diffracted beam whose virtual source is *V*. The drawing is not to scale. Dimensions transverse to the beams are greatly exaggerated.

to the wave-length because of the form of the Bragg equation and because of the absence in this case of any correction for refractive index in the crystal.

#### The Lead Collimator for Arresting the Heterogeneous Transmitted Beam

When the spectrometer is in use as a gamma-ray monochromator (see Fig. 7), the Bragg angle,  $\theta$ , and the angle of deviation,  $2\theta$ , of the monochromatized diffracted beam relative to the heterogeneous incident beam are extremely small. For any given position of the source *R* on the focal circle, one, and only one, very small band of wave-lengths is selectively diffracted by the curved crystal and thus diverted out of the original direction from source point at *R* into a new direction from a virtual source point at *V*. All the rest of the spectrum from the source passes directly through the crystal plate with very little absorption indeed. This directly transmitted beam may be many times as intense as the monochromatic diffracted beam, and the former must be prevented from reaching the device which is being used to measure the intensity of the latter. In the present spectrometer the geometry is such that the two beams never cease to overlap if the entire crystal aperture is being used for wave-lengths in the first order shorter than about 27 x.u. Auxiliary means must, therefore, be provided to arrest the transmitted beam and transmit the diffracted beam. For this purpose a lead-antimony-tin alloy baffle system was constructed with six tapering lead partitions, 31.5 inches long, separated by tapering spacers. Both partitions and intervening spacers are each 0.125

inch wide at the end nearer the crystal, and 0.173 inch wide at the other end. The seven slots so formed between partitions are 2 inches high. This system of long tapering slots is surrounded on the top, bottom, and sides with one or more inches of solid lead, and the entire mass is tightly clamped in a heavy steel case to hold it rigid. We shall refer to this baffle system as the lead collimator, but it should be clearly understood that it plays only the part of a baffle for the transmitted beam and in no way determines the resolving power of the instrument. The resolving power is determined solely by the excellence of focus of the crystal. The geometry of this collimator does, however, place a lower limit of 7 x.u. on the shortest wave-lengths that can be studied. Its partitions obstruct half the useful aperture of the crystal. This minimum wave-length could probably be made considerably shorter by the design of a second collimator with narrower slots and partitions.

#### Kinematic Requirements Imposed upon the Design

It is important to provide means that will maintain the lead collimator and the diffracted monochromatic gamma-ray beam strictly aligned while the spectrum is being explored. The surfaces of the partitions in the collimator must at all times point accurately to the virtual source point,  $V$ , because any obliquity of the collimator will introduce a spurious reduction in the spectral intensity observed with the G. M. counter. To avoid the necessity of moving the heavy collimator and the heavily shielded G. M. counter as the

spectrum is explored, the present instrument has been designed so that both the curved crystal and the source and focal circle are simultaneously given the correct motions. It is also desirable to be able to exchange the positions  $R$  and  $V$  of Fig. 7 so that spectra resulting from reflection on both sides of the (310) planes of the quartz crystal can be studied. By measuring with precision the distance between the spectra reflected from both sides of the planes the " $\beta$ -point" or "zero" of the wave-length scale can be determined accurately.

Referring to Fig. 7 we see that the  $\beta$ -point (the point where the (310) planes of the curved crystal would, if produced, converge) is situated on the focal circle diametrically opposite the curved crystal. Thus the focal circle, the crystal, and the  $\beta$ -point constitute one rigid system which must be allowed to rotate about the point  $C$  as the spectrum is explored. In order that the lead collimator need not move, the line  $CV$  must remain fixed in space, and the line  $CR$  must rotate about  $C$  with twice the angular velocity of the line  $C\beta$ . The angles  $RC\beta$  and  $VC\beta$  are each equal to the Bragg angle. Furthermore, the mechanism must be designed to permit the lines  $C\beta$  and  $CR$  to cross over to the other side of the line  $CV$  without interference. Because of the large dimensions of the instrument, the focal circle does not exist physically in its entirety. Instead it is swept out by a radius bar pivoted on the line  $C\beta$  so as to keep  $R$ , the radioactive source, accurately on the circle. To do this  $R$  must slide along the line  $CR$  through a certain small range of displacements. The kinematics of this entire motion is depicted in Fig. 8 which shows the

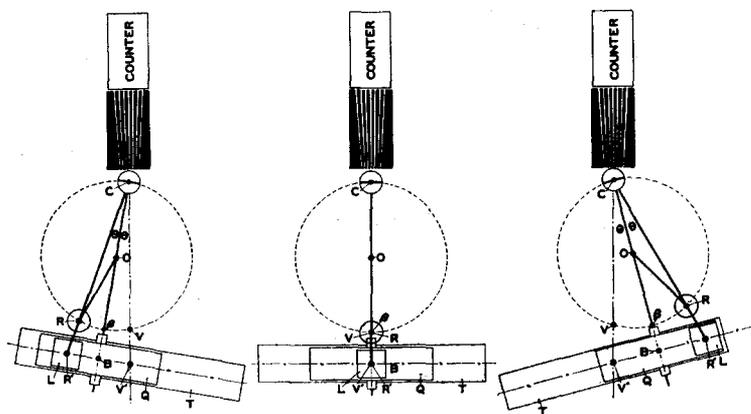


FIG. 8. To illustrate schematically the geometry of the gamma-ray spectrometer. The view at center shows the instrument at the zero wave-length position, while the views to left and right show different wave-length settings for reflections to left and to right of the atomic reflecting planes. The constant distances  $CR'$  and  $CV'$  are made rigorously equal. Displacements of the carriages  $L$  and  $Q$ , effected by means of precision screws, are proportional to the sine of the Bragg angle,  $\theta$ , and, hence, proportional to wave-lengths. The drawing is not to scale. The aperture of the crystal at  $C$  and the width of the collimator are exaggerated.

instrument schematically in several different wave-length settings.

Referring to Fig. 8,  $Q$  is a carriage mounted on ball-bearing rollers so that it can be displaced along a track  $T$ . The track,  $T$ , is pivoted so that it can swing about a fixed pivot,  $V'$ , on the base of the machine. The carriage,  $Q$ , is provided inside with two horizontal longitudinal precision right-hand screws, one situated vertically above the other, which are geared together with equal gears so that they rotate at equal rates in opposite senses. The upper screw, by means of a nut, drives a smaller carriage,  $L$ , along a track on the top of carriage  $Q$ . The lower screw drives the carriage  $Q$  along the track  $T$  by means of a nut provided with a vertical pin at the point  $V'$  which is coaxial with the pivot for the track  $T$ . The points  $V'$  and  $R'$  are thus made to remain at all times equidistant on either side of the line  $C\beta$ . Two radial steel beams are provided on the instrument, each pivoted so as to swing about  $C$  at different heights above the base. The higher of these furnishes the physical realization of the line  $CRR'$  in Fig. 8. It constitutes a link of fixed length between the pivot  $C$  and a pivot  $R'$  on the small carriage  $L$ . This beam is provided with a sliding carriage for the source,  $R$ , which in turn is linked by a radius bar,  $OR$ , to a pivot,  $O$ , on the lower radial beam. The upper radial beam pivots at  $C$  freely and independently of the crystal holder and lower beam. The crystal holder, although it is above the upper beam, is supported on a vertical shaft which passes down through the bearing for the upper beam and is rigidly clamped to the lower beam. The lower beam furnishes the physical realization of the line  $C\beta$  in Fig. 8. It terminates beyond the point  $\beta$  in a projecting cylindrical shaft which can slide longitudinally in bearings passing transversely through the long carriage  $Q$ . These bearings are provided with ball-bearing rollers so that the shaft slides very easily but without play. The displacement of the pivot,  $R'$ , on carriage  $L$  relative to point  $B$  on the carriage  $Q$ , thus measures the sine of the Bragg angle  $\theta$  for the incident beam  $RC$  relative to the crystal planes  $CB$ . The distance from the pivot  $V'$  to the point  $B$  on carriage  $Q$  is maintained rigorously equal to  $BR'$ , and thus the reflected beam is maintained always in strict alignment with the lead collimator.

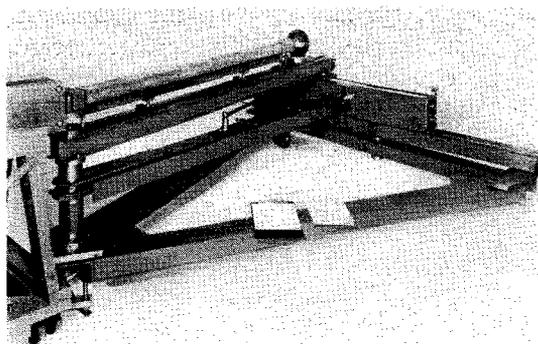


FIG. 9. Photographic view of transmission-type focusing spectrometer arranged for taking gamma-ray spectra. The lead collimator on its stand is seen at the extreme left. No counter or other device for measuring intensities is shown in this view. The crystal holder can be seen adjacent to the right-hand end of the collimator. At the far end of the upper radius beam of the spectrometer is the spherical lead holder for the radioactive sources at the real focus of the instrument. A heavy-walled, lead-shielding conduit stands between the crystal holder and the source holder. On the extreme right the sine screw carriage and swivel track appear. The radius arm which defines the focal circle can be seen just under the upper beam. For photographic x-ray spectra a film cassette replaces the spherical source holder.

The equal interpivot distances  $CV'$  and  $CR'$  together with the pitch of the two master driving screws in the carriage  $Q$  have been so chosen that one revolution of the screws is almost exactly equivalent to one x.u., and, by means of a divided drum and vernier on the upper screw, motions corresponding to 0.001 x.u. can easily be measured.

Figure 9 is a photograph of the spectrometer structure with the lead collimator and spherical lead source holder installed. A long tubular lead shield of rectangular cross section is carried on the upper beam and serves as a conduit for the gamma-radiation. The pivot and radius arm which define the focal circle can be seen just under the upper beam. For photographic x-ray work, when the Bragg angles permit dispensing with the collimator, the x-ray tube stands in its place. The spherical source holder is then replaced with a film cassette for holding the photographic film on the focal circle.

All carriages, slides, pivots, etc. in the instrument are designed with ball-bearing rollers and ball-thrust bearings wherever heavy loads of lead shielding must be supported, but the design is such that kinematic accuracy is maintained, wherever necessary, by lapped pivots which accu-

rately define the motion while the ball bearings merely support the loads. To the greatest possible extent the principles of "kinematic design" have been adhered to throughout, i.e., geometrical over-determination of positions and motions of parts is held to a minimum consistent with wear and strength.

### Adjustments for Obliquity of Crystal-Reflecting Planes and for Radius of Focal Circle

The design admits of a completely rational procedure for measuring and adjusting all of the essential geometry of the instrument to insure its accuracy. Space limitations preclude description of many of these details and adjustments. One important adjustment worthy of mention consists in provision to compensate for any slight departure of the (310) reflecting planes in the curved quartz plate from the desired orientation normal to its polished surfaces. A slight obliquity of these planes results in a position of the  $\beta$ -point on the focal circle not quite diametrically oppo-

site to the point of tangency of the neutral axis of the bent crystal with the focal circle. This then requires that the pivot  $O$  for the radius bar  $OR$ , Fig. 8, should be slightly offset from the line  $C\beta$  in the correct direction to compensate for the obliquity of the crystal planes. A subsidiary lever arm visible in Fig. 9 on top of the lower radius beam is, therefore, provided. This lever can be swung through a small angle by means of tangent screws relative to the lower beam, and the pivot  $O$  mounted on this lever can thus be adjusted to suit the obliquity of the crystal planes. The distance  $OC$  from this pivot to the main pivot under the crystal holder and also the length of the radius bar  $OR$  are adjustable to suit the required diameter of the focal circle; the latter must be determined experimentally after mounting the crystal in its holder.

### The Quartz Crystal and Its Clamping Blocks

The quartz crystal slab is compressed between two hardened blocks of stainless steel, one with a concave, the other with a convex circular cylindrical profile, to hold the slab at the correct curvature. Only the convex steel block actually determines the curvature of the quartz since a rubber gasket is placed between the concave steel surface and the quartz plate. The pressure is not applied directly by the screws which pull the two blocks together. Instead helical compression springs are used between the screws and the blocks to lessen the danger of too great a pressure which might break the crystal in the event of small dimensional variations from thermal expansion or accidents in adjustment. Figure 10 is a working drawing of the two stainless steel blocks showing the ports or windows provided for passage of the radiation. There is a deep horizontal rib across the center of the window which helps to support the plate at the correct curvature. The two smaller vertical ribs joining the horizontal rib with the top of the block are probably superfluous.

The use of a special stainless steel<sup>7</sup> together with the procedure for hardening and tempering it was kindly recommended to us by C. G. Peters

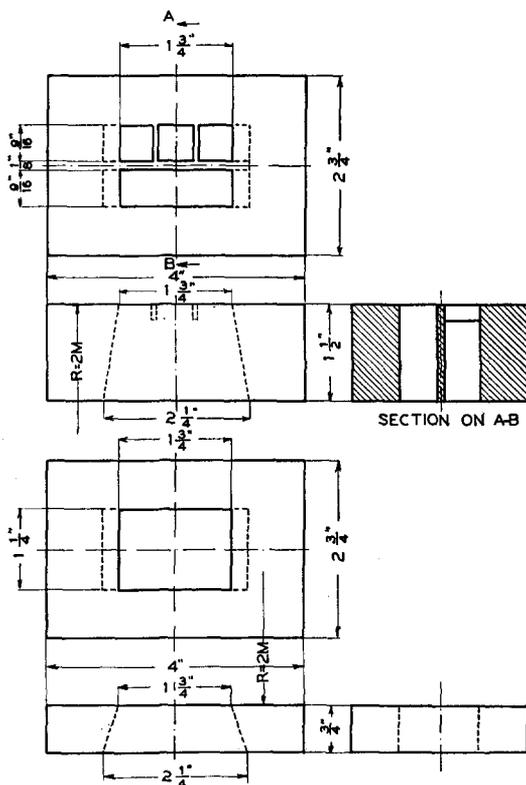


FIG. 10. Working drawing of the convex and concave stainless-steel clamping blocks showing the windows for the radiation. The upper drawing is the convex block.

<sup>7</sup> The material is a heat-treatable stainless steel having the composition Cr 13.5 percent, C 0.35 percent, Mn 0.40 percent, Si 0.50 percent. It is obtainable from either Firth-Sterling or Allegheny Ludlum Steel Companies.

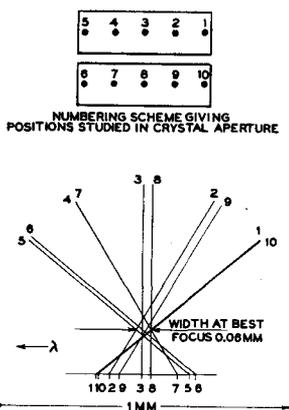


FIG. 11. Ray diagram used for determining, by successive x-ray exposures, the quality of focusing in the curved-crystal transmission spectrometer. The transverse or horizontal scale of this diagram is 100 times the vertical scale. The ten positions in the crystal aperture are shown above.

of the National Bureau of Standards. This is the same material and procedure used for many precision length standards. It was especially recommended for its stability and freedom from warp.

The quartz crystal slabs were obtained from the Monitor Piezo Products Company which procured the original samples of crystalline quartz and sawed them to the correct angles with the prism faces according to our specifications.

The original slabs which were about 5 mm thick were polished optically plane on one side, and the other side was then milled down with a diamond cutter till the slabs were 1 mm thick. The polished faces were now found to be bowed concave by 20 or 30 fringes, probably from strains introduced in the milling of the opposite faces. This bowing was readily removed by etching the milled faces with HF. The polished faces were then contacted against an optical flat, and the milled faces were polished optically flat. This milling and finishing

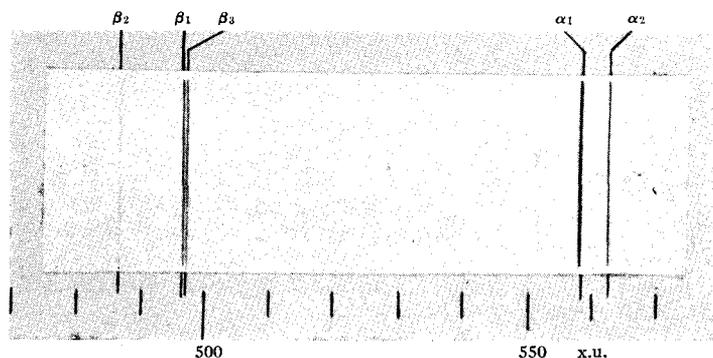
work was done by the Penn Optical Company of Pasadena.

The all-important procedure for the precision profiling to 2-meters radius of curvature of the convex cylindrical stainless-steel block upon which the high resolving power of this instrument is entirely dependent, is described in a companion article to the present one. There is ample evidence that the highest degree of precision is required in this profiled surface. Several schemes were tried with unsatisfactory results before the method of generation with a surface grinder, and subsequent light lapping, was proved adequate.

### Tests of the Accuracy of Focus and Resolving Power to be Expected

Tests of the accuracy of focus were made by means of x-rays using both tungsten and silver characteristic *K*-radiation. A water-cooled tungsten target x-ray tube was placed near the curved crystal of the spectrometer in the position *A* of Fig. 5. Since the focal spot of this tube was much smaller than the aperture in the crystal supporting blocks, only a small portion of the useful aperture was used to form the *K*-spectrum of tungsten at *R*. By shifting the position of the focal spot, it is possible to explore the entire useful aperture of the focusing crystal and to determine how well the positions of the *K*-lines at *R* agree when they are formed from different regions of the crystal. Ten uniformly spaced positions were studied, five above the rib in the crystal window and five below it. In this procedure one position is adopted as a standard of comparison, and the other nine are successively compared with it by making exposures with suitable lead shields over the film, so that one end of the lines from each position on the crystal appear on the

FIG. 12. Fluorescent *K*-spectrum of silver using entire crystal aperture as a test of quality of focusing. (See Fig. 6 for geometry of arrangement.) The silver fluorescer was exposed to radiation from a tungsten target tube excited by unrectified a.c. at 68 kv-r.m.s. and 20 ma for one hour. Save for  $\beta_2$ , clearly visible lines have been obtained with this same arrangement in 10 minutes. Scale of reproduction 1:1. The reproduction is decidedly inferior to the original both as to contrast and resolution.



film adjacent to one end of the comparison line. By such means it is possible to measure shifts away from the comparison line much smaller than the line widths themselves. A scale drawing of the rays from each point on the crystal to points on the film is then plotted, the scale on this plot being 100 times natural in the direction normal to the rays, but natural scale in the direction of propagation. An example of such a ray plot is shown in Fig. 11. Such a diagram clearly indicates not only the quality of focus but also the best distance from the crystal at which to set the film to obtain the narrowest lines when the full aperture is in use. The ray diagram of Fig. 11 indicates an agreement of focus from all ten positions in the crystal aperture to within 0.06 mm on the film when this is placed in the position for best focus. This is about one-quarter of the natural breadth of most x-ray lines in the  $K$ -spectra of the heavier elements. It corresponds to a wave-length range of about 0.07 x.u. At the shortest wave-length permitted by the present lead collimator (7 x.u.), which corresponds to a quantum energy of 1.75 Mev, the resolving power is, therefore, 100. At 0.5 Mev the resolving power is 350. In the *measurement* of wave-lengths somewhat higher precision than this resolving power may be expected since the center of a line can be located rather readily to within less than one percent of its width. These figures represent theoretical limits, and the actual results may be less satisfactory. The resolving power may be reduced (1) by the natural breadths of the gamma-ray lines themselves, (2) by the difficulty of constructing concentrated gamma-ray sources combining sufficient source strength with suffi-

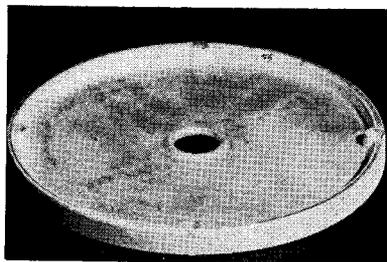


FIG. 13. Die-cast lead disks 0.015 inch thick with reinforced peripheral rim and toroidal bead around central hole, used as partitions in multi-cellular gamma-ray counter.

ciently restricted geometrical dimensions to take complete advantage of the high resolution of the present quartz crystal.

### Focal Volume

The maximum volume available for the radioactive material at the focus of the spectrometer, without sacrifice of resolving power, is about  $0.0075 \text{ cm}^3$ . The shape of this volume is that of a four-sided prism, about 3 cm high, whose cross section is a rhombus. The major and minor diagonals of this rhombus are approximately 5 mm and 0.1 mm, respectively.

### Photographic Tests of Resolution and Focus by Fluorescence Spectra of Silver $K$ -Radiation

Figure 6 shows to scale the geometry of the primary x-ray tube, the radiator and the spectrometer when used for taking fluorescence spectra with a silver radiator. In this case considerable attention must be paid to careful shielding with lead to prevent stray primary radiation from fogging the film. Figure 12 is a full-size reproduction of the fluorescent  $K$ -spectrum from the silver radiator. Because of the extended nature of the latter, such a spectrum utilizes the entire useful aperture of the curved crystal and, hence, furnishes a test of the excellence of focus insofar as the natural widths of the x-ray lines themselves permit. These natural widths, which have been measured with the two-crystal spectrometer,<sup>8</sup> are in this instance about four times wider than the best resolution of the spectrometer as estimated above from Fig. 11. A second silver fluorescence spectrum was also made with all but one-eighth of the total crystal aperture shielded with lead, and no appreciable reduction in the line widths was observed. By visual estimate these line widths are of the same order as the natural widths given by Allison. The spectrum of Fig. 12 is over-exposed as regards the alpha-lines in order to bring out the  $\beta_1$ ,  $\beta_2$ , and  $\beta_3$  lines clearly, and hence the ratio of intensities is somewhat falsified.

<sup>8</sup> Compton and Allison, *X-Rays in Theory and Experiment* (D. Van Nostrand Company, Inc., New York, 1935), p. 746.

### Detection and Measurement of the Intensity of the Diffracted Monochromatic Gamma-Ray Beam

The multi-cellular counter for measuring the intensities of the diffracted monochromatic beam of gamma-rays will be described here only briefly because it is still in a developmental stage, subject to possible modifications. It consists of a brass tube, 3.25 inches I.D., which contains a series of die-cast lead alloy disks, each disk having a round hole at the center 0.375 inch I.D. The disks in the present design are 0.015 inch thick, and are reinforced at the edges with a rim about  $\frac{1}{8}$  inch in radial thickness. The thin wall of the disk terminates in a toroidal bead surrounding the central hole to avoid a sharp edge there. Figure 13 shows one of these disks. These disks are silver-plated (.001-inch thickness) to hold back alpha-particles. They are threaded over four rods passing through holes in their rims with spacer rings between each pair of disks so that the spaces between the lead partitions are each 0.5 inch wide. An axial steel rod of 0.040-inch diameter passes through the central holes in the entire assembly of disks. On this rod are threaded short, thin-walled tubes to each of which are hard-soldered four radially projecting, fine tungsten wires, 0.010-inch diameter and 1.3 inches long. Each wire has a glass bead at its outer end. These spider assemblies are cleaned by a.c. electrolysis in sodium hydroxide, and are assembled on the central steel rod with the radial wires half-way between each pair of lead disks. They form the anode-collecting wires for each cell of the counter. The monochromatized gamma-ray beam from the spectrometer, after passing through the lead collimator, enters the end of the multi-cellular counter and passes axially through all the lead disks ejecting photo-electrons, Compton recoil electrons, and in the case of the hardest radiation some "pairs" of positive and negative electrons into the spaces between the lead partitions. The only gas filling used to date has been a mixture of argon and alcohol vapor. It is planned to try lead tetramethyl and also xenon as a filling gas.

Considerable empirical study has been given to the best geometrical dimensions, and the design described above is the result. These studies were made with a small model (Fig. 14) consisting first

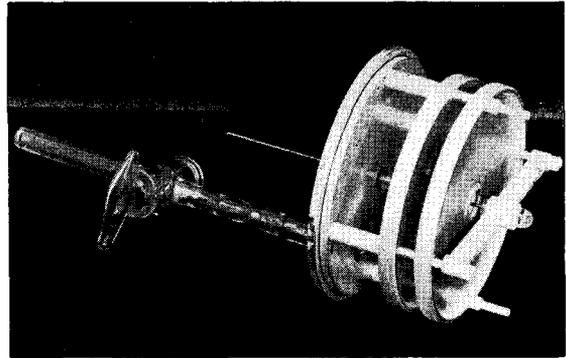


FIG. 14. Small, one-cell model counter with cover removed. The two lead partitions mounted on rods supported on the removable end cover of the counter are visible. A glass bead, terminating one of the four prongs of the collecting spider, can be seen between the two lead partitions.

of one collector between two partitions, then two collectors between three partitions. The two-cell counter with a 2-mc radium source gave just twice the counting rate of the single cell. The sensitivity has also been explored over the area of the lead disks, by use of a very narrow beam from the radium source, and found to be quite satisfactorily uniform. The threshold of this counter occurs at about 900 volts, and the plateau is about 200 volts wide when the dimensions are as given above. The two-cell counter gave substantially the same result as one cell in this regard. A counter of this type with ten cells is now under construction.

The counting efficiency of the above described counter turns out to be about 0.9 percent per cell, that is to say 0.9 percent of all gamma-ray photons from the radium source passing through the cell are counted. It is not certain how many cells can be made to work successfully together before dimensional variations from cell to cell too greatly reduce the plateau width or other limiting difficulties arise. An efficiency of 10 percent, however, seems not too much to hope for. A paper describing the multi-cellular counter and its characteristics in more detail will be published in due course.

It is planned to protect the above described multi-cellular counter from the cosmic-ray background by means of a number of anticoincidence counters of conventional type placed around the outside on top and sides. Heavy lead shielding

will be provided to eliminate background from local sources of radioactivity.

A Van Heerden silver chloride crystal counter will also be constructed and studied for adaptation to this particular application.

### Choice of Scale in the Gamma Ray-Spectrometer Design

A word should be said about the choice of scale in the design of such a curved-crystal, focusing gamma-ray spectrometer. If the linear dimensions are all multiplied by a factor  $f$ , clearly the volume at  $R$ , the real focus within which radioactive material can be utilized, will be multiplied by  $f^3$ , and so without loss of resolving power the gamma-ray intensities available for measurement will be multiplied by  $f^3$ . Such a change of scale will increase the cross-sectional area of the multicellular counter by a multiplying factor  $f^2$ , but for radiation of the same hardness the axial length need not be increased at all. It seems likely that the limitation as to the minimum gamma-ray intensity detectable from sources of low specific activity per unit volume, will be the irreducible cosmic-ray background in the counter after protection of the latter by external anticoincidence counters. This effect should be proportional to  $f$ , therefore, and the *ratio* of gamma-ray intensities to background, i.e., the contrast, should

increase consequently as  $f^2$ , the square of the scale factor. Actually it may be that the contrast ratio may even increase a little more rapidly than  $f^2$  because the thickness of the quartz crystal slab can be increased without danger of breakage on bending by the multiplying factor  $f$ , and up to a certain point there may be something to gain from higher percent reflection in thicker slabs. This reasoning thus indicates the advantage to be gained by large scale in the design of a gamma-ray spectrometer of this type. The practical limitation is set by the size in which perfect specimens of suitable single crystals can be obtained from which to cut or make the curved-crystal slab. The possibilities in the case of other crystals than quartz have not yet been explored.

### Acknowledgments

The author wishes gratefully to acknowledge the most valuable assistance of J. P. Youtz, W. K. H. Panofsky, Russel Yost, David Lind, and E. R. Cohen in the work of assembly and testing of this instrument. The construction of the parts was accomplished by B. E. Merkel, instrument maker of the California Institute of Technology Physics Department instrument shop, with admirable skill which deserves the writer's highest praise.

### Calendar of Meetings

#### October

- 15-18 American Society of Civil Engineers, New Orleans, Louisiana
- 20-24 American Society for Metals, Chicago, Illinois
- 21-23 American Standards Association, New York, New York
- 21-25 American Chemical Society, California Section, San Francisco, California
- 23-25 Optical Society of America, Cincinnati, Ohio
- 30-31 National Research Corporation and the American Chemical Society (High Vacuum Symposium), Cambridge, Massachusetts

#### November

- 3-5 National Electronics Conference, Chicago, Illinois
- 3-7 American Institute of Electrical Engineers, Chicago, Illinois
- 6-7 Society of Automotive Engineers (Fuels and Lubricants Meeting), Tulsa, Oklahoma

- 7-8 Conference on X-Ray and Electron Diffraction, Mellon Institute of Industrial Research, Pittsburgh, Pennsylvania
- 9-12 American Institute of Chemical Engineers, Detroit, Michigan
- 17-19 Institute of Radio Engineers and the Radio Manufacturers Association, Engineering Department, Rochester, New York
- 28-29 American Physical Society, Houston, Texas

#### December

- 1-3 Society of Automotive Engineers (Air Transport Engineering Meeting), Kansas City, Missouri
- 1-5 American Society of Mechanical Engineers, New York, New York
- 26-31 American Association for the Advancement of Science, Chicago, Illinois
- 29-31 American Physical Society, Chicago, Illinois