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A LINEAR-MOTION BENT-CRYSTAL
GAMMA-RAY SPECTROMETER

O. H. Otteson, W. F. Edwards, and R. G. Helmer

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GAMMA-RAY SPECTROMETER

O. H. Otteson and W. F. Edwards
Utah State University
Logan, Utah

and

R. G. Helmer
National Reactor Testing Station
Idaho Nuclear Corporation
Idaho Falls, Idaho

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A LINEAR-MOTION BENT-CRYSTAL
GAMMA-RAY SPECTROMETER

A B S T R A C T

A new design of a bent-crystal spectrometer is described. The diffraction crystal moves only in translation (i.e., without rotation) as a means of changing the Bragg angle. Details of the design and construction of the spectrometer are presented including a discussion of the diffraction angle measuring system. The testing and calibration of the spectrometer is also described. The line broadening that results from the source being off the focal circle is discussed. For the special case of scanning the energy range of 88 to 620 keV without moving the source, the maximum increase in the line width is about 5% of the optimum width. Results are presented for the measurement of the gamma-ray energies in W^{182} and W^{183} . These energies, which were obtained with a quartz crystal, are generally within 0.02 keV of the quoted uncertainties on the previous measurements which were obtained with germanium crystals.

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INTRODUCTION

The bent-crystal or diffraction spectrometer designed and constructed in this study utilizes the DuMond transmission geometry with fixed detector. It has, however, four major features which distinguish it from previous designs. (1) As a means of changing the Bragg angle the diffraction crystal moves only in translation (i.e., without rotation). (2) The geometry employed requires only a small linear motion of the source to maintain it on the focal circle. (3) An aperture system consisting of a shield and stops is used to prevent the direct beam radiation from reaching the detector. (4) The radius of the focal circle is not a fixed property of the spectrometer.

After a brief summary of the development of bent-crystal spectrometers and the concepts involved, the design and construction of this spectrometer is described (Chapter II). The testing and calibration methods and results are discussed in Chapter III. In Chapter IV are given the results of the measurements of the energies of the gamma rays observed in the decay of Ta^{182} and Ta^{183} with a quartz crystal. These results are compared with previously reported values.

This work was performed at Utah State University and the National Reactor Testing Station as part of the cooperative program of the Associated Rocky Mountain Universities. The University Research Council at Utah State University and the National Science Foundation provided additional funds for the project. This material has been submitted by O. H. Otteson as a portion of the thesis requirements for the Ph.D. degree at Utah State University, Logan, Utah.

CHAPTER I
HISTORICAL DEVELOPMENT OF BENT CRYSTAL
SPECTROMETERS

The diffraction of gamma rays by a crystalline lattice began with the work of Rutherford and Andrade¹ in 1914. Frilley² succeeded in extending the range of flat crystal diffraction down to about 16 milliangstroms. By present standards all of the instruments used were characterized by low efficiency, low resolution and poor wavelength determination. In addition, separating the diffracted spectra from the radiation transmitted directly through or past the crystal was a severe limitation.

In the two decades following the discovery of x-ray diffraction by crystals various investigators came close to the idea of a focusing curved-crystal spectrometer. Reviews of some of the early attempts to focus a diffracted beam are found in References 3, 4, and 5. Two seemingly incompatible conditions were necessary for focusing the Bragg reflected beam: (1) at all points on the surface the angles of incidence and angles of reflection must be equal, (2) at all points on the surface the angles of deviation of the reflected beam must be constant in order to satisfy the Bragg criteria. It was not until 1930 that this problem was resolved. DuMond and Kirkpatric⁶ described in that year a multicrystal spectrograph. It was pointed out⁶ that condition (1) dictates the direction of the reflecting planes while (2) applies to the position of every point on the boundary surface but places no requirements on the direction of the reflecting planes. In the instrument of DuMond and Kirkpatric fifty small crystal elements, each a Siemens "wedge type" spectrograph, were used, however, the geometry for accomplishing exact focusing with a single bent crystal was clearly described and illustrated.

Significant discoveries concerning curved-crystal spectrometers followed rapidly. Johann⁷ constructed a reflection type curved-crystal spectrometer and Cauchois⁸ developed a transmission type. With these

instruments it was recognized that the orientation of the reflecting planes, condition (1), was more critical than fixing the boundaries of the crystal, condition (2). Johannson⁹ was the first to develop an exact focusing bent-crystal spectrometer. The crystal was profiled to a radius $2R$ and then bent to the radius R of the focal circle. The findings of Johann⁷ and Cauchois⁸ indicated that this profiling of the surfaces of the crystal to radius $2R$ was frequently unnecessary and that condition (1) could be satisfied if the flat crystal were bent to a radius of $2R$. Thus, if the length of the crystal were small compared to the diameter of the focal circle this simplifying approximate solution resulted in negligible aberration in focusing.

It has also been shown⁴ that a set of atomic planes normal (before bending) to the initially flat face of an elastically bent crystal and parallel to its axis of cylindrical bending, will experience an increase in grating constant on the convex side and a decrease on the concave side. Thus, for the transmission case, there is a focusing effect through the thickness of the curved crystal as well as from side to side.

DuMond⁴ points out that "an interesting result of the type of reflection taking place in the transmission-type bent-crystal spectrometer is that no correction whatever for x-ray refractive index different from unity need be made to the observed Bragg angle ... provided the internal atomic reflecting planes are normal to the crystal slab." This is not true of the reflection-type bent-crystal spectrometer.

It is the transmission-type bent-crystal spectrometer that is of concern in the present study. The three essential components of a bent-crystal spectrometer are the source, the crystal and the detector. Two distinct arrangements of these components have been used previously. (1) The Cauchois arrangement, Figure 1a, uses an extended source on the convex side of the crystal and gives a focused spectrum on the focal circle, while (2) the DuMond geometry, Figure 1b, utilizes a line source which moves on the focal circle and an electronic detector on the convex side of the crystal.

In Figures 1a and 1b it should be noted that only the Cauchois geometry has a real image necessary for the use of photographic

Fig. 1a. The Cauchois extended source transmission geometry utilizing a collimator and electronic detection.

PPCo-B-8132

Fig. 1b. The original DuMond line source transmission geometry utilizing a collimator. The source moves through an angle 2θ along the focal circle as the diffraction crystal and the focal circle are rotated through an angle θ relative to the stationary collimator-detector system.

detection. However, difficulties in preventing the undiffracted beam from masking the high-energy lines restricts photographic detection to low-energy work. The energy range of the Cauchois spectrometer has been extended to 2 MeV and above by the use of baffles^{10,11} or collimators and electronic detection^{12,13}.

The DuMond geometry, Figure 1b, employs a very concentrated line source of gamma rays located on the focal circle. Electronic detection

is used on the convex side of the crystal. The response of the detector is plotted as a function of the source position on the focal circle relative to the point on said circle where the reflecting atomic planes (produced) of the crystal would converge. This point is designated as the " β -point". With this arrangement every nucleus in the sample may radiate into a solid angle subtended by the entire working aperture of the crystal. When the conditions are met for the reflection of an emission line, the absolute efficiency for reflection of that line is greater by a factor of about 200 than that of the spectrometers using the Cauchois arrangement. This instrument is essentially a monochromator with comparatively high efficiency for small sources.

Referring to Figure 1b (1a) it is seen that a zero diffraction angle is obtained when the source (detector) is at the β -point. Thus, with most bent-crystal spectrometers it is possible to observe each gamma-ray line on either side of the β -point. The two positions of the components of the spectrometer for which the same gamma-ray line is observed are referred to hereafter as the conjugate positions.

In order to record a gamma-ray spectrum and to maintain the Bragg reflection condition,

$$N\lambda = 2d \sin\theta, \quad N = 1, 2, 3, \dots, \quad (1)$$

it is necessary to move a minimum of two of the three main components of the system. The three possible choices are to fix the position of (1) the detector, (2) the crystal or (3) the source. Arrangements (1) and (3) have conventionally used a rotational motion of the crystal to change the Bragg angle.

Arrangement (1) typically requires precision movement of the source in steps of 1 second of arc or even less. At the same time an angular accuracy of 0.05 seconds of arc or better must be maintained while moving the source and rotating the crystal through several degrees. Some of the instruments of this type, illustrated in Figure 1b, use a heavy movable, source shield. Only a few of the precision spectrometers of the present day are of this type.

Arrangement (2) has most of the disadvantages of both (1) and (3) and has not been widely used (see Table 1).

Recently a number of spectrometers have been built using arrangement (3). The requirements for alignment of the collimator-detector system with the diffracted beam are must less stringent than those relating the source position to the crystal β -point. Thus, the mechanical problems are somewhat reduced since only one precision motion is required, namely that of the crystal relative to the stationary source.

A listing of crystal diffraction spectrometers for gamma rays presently in operation is found in Table 1. The listings are arranged according to the geometry employed.

The spectrometer developed in this study is basically a modified fixed-detector type which offers the following advantages: (1) The simplicity of the design significantly reduces the construction cost. (2) For a Bragg angle change of from 0° to 6° on a two meter focal circle, this geometry requires a motion of the source in a direction normal to the translatory motion of the crystal of only 2.2 cm to maintain the source on the focal circle. The source can, therefore, execute all of its motion inside of a simple shield which does not need to be moved. Furthermore, the source can remain fixed when scanning a given line in the conjugate positions of the diffraction crystal. In many cases it is even possible to leave the source fixed when scanning a fairly large energy range since the line broadening introduced by doing so will be small. (3) The absence of the fan-shaped Sollar slit collimator and of the coupled motion of the components reduces the difficulty in changing the radius of the system. (4) The spectrometer consists of three separate sections. These are so designed that they can readily be moved to change radii or the spectrometer location. (5) Since a collimator is not used the luminosity is increased (by about a factor of three at low energies compared with the Caltech Mark 1). (6) The system of stops and shield used in the place of the usual collimator provides an improved diffracted to direct beam ratio.

An inconvenience of this arrangement is that the sine of the diffraction angle is not a linear function of the displacement of the crystal from the zero angle position.

Table 1. Bert-crystal gamma-ray spectrometers currently in use

Location	Radius in Meters	Designers and/or Experimenters	Reference and Date
<u>Cauchois Mounting - Photographic Detection</u>			
1. Univ. of Calif., Livermore	2	Chupp, DuMond, Gordon, Jopson and Mark	10 1957
2. Mass. Inst. of Tech.	6	Kazi, Rasmussen and Mark	11 1960
3. Mol, Belgium	2	Van Assche	14 1964
<u>Cauchois Mounting - Electronic Detection</u>			
4. Uppsala, Sweden	2.5	Beckman	12 1955
5. Leningrad, Russia	4	Sumbayev and Smirnov	13 1963
<u>DuMond Mounting - Fixed Detector</u>			
6. Calif. Inst. of Tech.	2	DuMond	15 1947
7. Stockholm, Sweden	1	Ryde and Anderson	16 1955
8. Leningrad, Russia	2	Lukerskii and Sumbayev	17 1956
9. Chalk River, Canada	2	Bartholomew, Knowles and Lee-Whiting	18 1960
10. Univ. of Manitoba, Canada	1	Douglas	19
<u>DuMond Mounting - Fixed Detector - Fixed Source Option</u>			
11. NRTS - Utah State University	2	Otteson and Edwards	this 1966 thesis

Table 1. Continued

Location	Radius in Meters	Designers and/or Experimenters	Reference and Date
<u>DuMond Mounting - Fixed Source</u>			
12. Argonne National Labs	7.7	Snither, Rose, Ostrander and Hammermesh	20 1957
13. Uppsala, Sweden	2	Bechman, Bergvall and Axelsson	21 1959
14. Tech. Hochs., Munich, Ger.	4.6	Schult	22 1960
15. Calif. Inst. of Tech.	2	Seppi, Henrikson, Boehm and DuMond	23 1962
16. Univ. of Michigan	2	Reidy, Miller and Wiedenbeck	24 1964
17. Univ. of Colorado	2	Henning and Lind	25 1964
18. Iowa State University	2	Hatch and Brown	26 1964
19. Chalmers Univ. of Tech. Göteborg, Sweden	4	Lundqvist, Rohlin, Nilsson and Hardell	27 1964
20. Risø, Denmark	6	Schult, Gruber, Maier and Kock	28 1964
21. Univ. of Calif. Rad. Lab., Berkeley, California	7.7	Astbury, Berks, Crowe, Shafer and Taylor	29 1964

Table 1. Continued

Location	Radius in Meters	Designers and/or Experimenters	Reference and Date
<u>DuMond Mounting - Fixed Crystal</u>			
22. Univ. of Calif., Berkeley	0.125	Barton, Robinson and Perlman	30 1951
23. Argonne National Labs.	0.25	Day	31 1955

CHAPTER II

THE DESIGN AND CONSTRUCTION OF THE SPECTROMETER

2.1 The Spectrometer Geometry

The basic geometry is shown in Figure 2. Photographs of the instrument are shown in Figures 3 and 4. The detector position remains fixed. The source and detector are each located on the line X-X at a distance twice the radius of the focal circle from the line Y-Y and on opposite sides of this line. The diffraction crystal is rigidly attached to the carriage. The carriage is driven along the line Y-Y by a precision lead screw which is turned by a stepping motor. The source moves along the line X-X in order to remain on the focal circle. Since this source motion is small, the angles maintained by the source and by the detector relative to the crystal diffracting planes are sufficiently close to the same value to insure that the entire face of the detector is exposed to the diffracted beam for all energies. The conjugate positions of the crystal are obtained by moving the carriage the same distance each side of the line X-X. The "zero angle" position is taken to be halfway between the two conjugate positions.

Fig. 2. The geometry of the linear-motion bent-crystal spectrometer. The crystal moves along the line Y-Y. When necessary the source moves along the line X-X to remain on the focal circle.

Fig. 3. A photograph of the spectrometer from the detector end.

Fig. 4. A photograph of the spectrometer from the source end.

The source and source holder are on a carriage which is similar in design to the crystal carriage. The direction of travel of the source carriage is adjusted to insure that when the source is moved it will maintain its position on the line X-X.

If a Sollard slit collimator were used with this arrangement it would require a mechanical connection between the crystal carriage and the detector or the source carriage. Although a method for doing this was conceived it limited (1) the ability to use crystals bent to various radii, (2) the luminosity and (3) the portability of the instrument. Instead, two sets of stops and a block shield were used to prevent the direct beam from reaching the detector. The procedure for aligning the shield and stops is given in Appendix A. This simplification provided two of the advantages of this design already mentioned (i.e., increased luminosity and improved diffracted-to-direct beam ratio).

The width of a gamma-ray line profile is usually taken as the full width of the peak at half the maximum peak height (FWHM). The FWHM of line profiles obtained using a bent-crystal spectrometer are nearly constant in wavelength units. The diffracted wavelength is in turn proportional to the sine of the diffraction angle. In Figure 5, when the Bragg angle is changed by a linear translation of the diffraction crystal the sine of the diffraction angle is not a linear function of the displacement. This means that the line widths (in wavelength units) will not be strictly constant in terms of the crystal displacement. The change, $\Delta\lambda$ in the diffracted wavelength produced by a small translation, ΔY , of the diffraction crystal is given by

$$\Delta\lambda = \frac{2d \cos^3\theta \Delta Y}{N R (1+\cos 2\theta)} + \frac{4d \sin^2\theta \cos^2\theta \Delta Y}{N R (1+\cos 2\theta) \cos 2\theta} , \quad (2)$$

where d is the crystal interplaner spacing, θ is the diffraction angle, R is the radius of the focal circle, N is the order of the reflection and ΔY is a small translation of the crystal. Equation (2) is for the case where the source is moved to maintain its position on the focal circle. If the source is fixed at some position $2R - q$ from the Y-Y plane this equation becomes

Fig. 5. The focal circle of the linear-motion spectrometer. The relationship of the diffracting angle to the source and crystal positions is shown. When the source is not on the focal circle $\theta_1 \neq \theta$.

$$\Delta\lambda = \frac{2d \cos^3\theta \Delta Y}{N (2R - q)} \quad (3)$$

The change in wavelength produced by a translation of $\sim 9.159 \times 10^{-3}$ cm of the diffraction crystal (i.e., 100 steps of the motor, $\Delta\theta \approx 4.58 \times 10^{-5}$ radians) is given in Table 2 for both fixed and moving source using the 310 planes of a quartz crystal bent to a 200 cm diameter focal circle.

Table 2. The change in diffracted wavelength produced by a translation of $\sim 9.159 \times 10^{-3}$ cm of the diffraction crystal (100 steps of the motor).

θ	Source		
	Moving	Fixed with $2R - q =$ 199 cm	198 cm
0°	0.1077 xu	0.1084 xu	0.1091 xu
3.5°	0.1079	0.1076	0.1082
7.0°	0.1088	0.1060	0.1065

The line widths in step units (i.e., steps of the motor) will, therefore, not vary greatly (about $2\frac{1}{2}\%$) over the entire motion of the diffraction crystal for these cases.

2.2 Precision Requirements

The precision requirements imposed on the mechanical motion depend upon the accuracy of the wavelength measurement desired. A gamma-ray profile as measured with a bent-crystal spectrometer is shown in Figure 6. To utilize fully the dispersive power of crystals available today

Fig. 6. The log-linear plot of a gamma-ray profile as measured with a bent-crystal spectrometer. The position of the peak is λ_0 and W is the full-width-at-half-the-maximum peak height (FWHM).

it is necessary to determine the center of the spectral line with an uncertainty of no more than about $\pm 0.005 \text{ xu}$ (i.e., $\pm 0.004 \text{ keV}$ at 100 keV and $\pm 0.4 \text{ keV}$ at 1 MeV). With planes in germanium diffraction crystals, resolutions of about 0.10 xu FWHM or better may be achieved. With a minimum of about ten points over a peak it is usually possible to establish the position of the peak to within one twentieth of the FWHM. The uncertainty in the position of the peak is then

$$\delta\lambda_0 = \frac{\pm W}{20} = \pm 0.005 \text{ xu} \quad (4)$$

as desired. This uncertainty can be reduced at lower energies or higher orders where the resolution is improved. Since λ_0 is determined from the points making up the peak the allowable uncertainty $\delta\lambda$ for each of these points can be

larger than $\delta\lambda_0$. However, to allow for future improvement in precision

the $\delta\lambda$ are required to be smaller than $\delta\lambda_0$ by a factor of four or five so that

$$\delta\lambda = \frac{1}{5} \delta\lambda_0 = 0.001 \text{ xu} \quad (5)$$

From Figure 5 of section 2.1 it can readily be seen that Equation (1) can be written as

$$\lambda = \frac{2d Y}{N\sqrt{X^2 + Y^2}} \quad , \quad (6)$$

where Y is the position of the crystal as measured from the zero angle position, X is the position of the source from the line of motion of the crystal, d is the interplanar spacing and N is the order of the reflection. Since X and Y are determined by independent measurements the standard deviation (S_λ) in λ , is given by³²

$$S_\lambda = \sqrt{\left(\frac{\partial \lambda}{\partial X}\right)^2 S_x^2 + \left(\frac{\partial \lambda}{\partial Y}\right)^2 S_y^2} \quad , \quad (7)$$

where S_x and S_y are the standard deviations in the measurement of X and Y respectively. From the partial derivatives of λ with respect to X and Y it can be seen that the greatest uncertainty is introduced at the largest angle. When the partial derivatives in Equation (7) are evaluated at the largest diffraction angle possible (7.5°) with this instrument, the uncertainty S_λ becomes

$$S_\lambda = d\sqrt{25 \times 10^{-8} S_x^2 + 10^{-4} S_y^2} \quad . \quad (8)$$

From Equation (8) it can be seen that for any desired S_λ the allowed deviation S_y will be much smaller than that for S_x .

By setting $\left(\frac{\partial \lambda}{\partial X}\right)^2 S_x^2 = a^2 \left(\frac{\partial \lambda}{\partial Y}\right)^2$ in Equation (7) the deviations S_y and S_x are expressed separately as

$$S_y = \frac{S_\lambda}{\sqrt{a^2+1} \left(\frac{\partial \lambda}{\partial Y}\right)} \quad \text{and} \quad S_x = \frac{a S_\lambda}{\sqrt{a^2+1} \left(\frac{\partial \lambda}{\partial X}\right)} \quad (9)$$

where $\mathcal{A}$ represents a measure of the relative precision required of the X and the Y motions. Since it is desirable to have the accuracy of a measurement determined entirely by the crystal motion, $Y, \mathcal{A}^2$ is set equal to 0.10. If the allowed uncertainty, λ , in Equation (5) is designated as the allowed standard deviation then

$$\delta\lambda = S_\lambda = \pm 0.001 \text{ xu} \quad .$$

The resulting precision requirements on X and Y are

$$S_x = \pm 5.1 \times 10^{-4} \text{ cm}, \quad (10a)$$

and

$$S_y = \pm 8.1 \times 10^{-5} \text{ cm}, \quad (10b)$$

using $d = 2 \times 10^{-8} \text{ cm}$ for the 022 planes of germanium.

Two additional precision requirements are needed to insure the desired accuracy. First, the source must not move perpendicular to the line X-X of Figure 2 more than about $1 \times 10^{-5} \text{ cm}$ so that the uncertainty S_y of Equation (8) is not increased. Second, as the crystal is translated, a very slight but non-repeatable rotational motion may result. The allowed uncertainty, $\delta\theta$, in θ in terms of the allowed uncertainty, $\delta\lambda$, in λ is given by

$$\delta\theta = \frac{\delta\lambda}{2d \cos\theta} \quad . \quad (11)$$

For the 022 planes of germanium with $\delta\lambda = 10^{-3} \text{ xu}$ this uncertainty would be

$$\delta\theta = \pm 2.5 \times 10^{-7} \text{ radians} = \pm 0.05 \text{ sec}. \quad (12)$$

In Equation (5) allowance was made for possible future improvement in precision. Thus, to guarantee the present precision requirements (i.e., Equation (4)) the allowable uncertainties of Equations (10a), (10b) and (12) can be at least a factor of five larger.

2.3 The Crystal Motion Platform

The repeatability of the crystal motion is the critical element in this spectrometer. Every effort was, therefore, made to produce at a reasonable cost a crystal motion platform which would meet the precision requirements discussed in Section 2.2.

The base for the crystal motion platform is a black granite surface plate 14 in. x 6 in. x 36 in. The plate has a 1.5-in. deep vee groove running the entire 36-in. length parallel to the center line and 4 inches from it. The top surface is flat to ± 0.000080 inches and the sides of the vee groove are flat to ± 0.000025 inches.

Centuries of ageing have left granite relieved of the internal stresses and strains found in cast or fabricated materials. A comparison of some of the physical properties of black granite and cast iron is found in Table 3. The motor and bearing mounts of the platform are

Table 3. A comparison of the physical properties of black granite and cast iron.

Physical Property	Black Granite ^a	Cast Iron ^b
Compressive Strength (lbs/in ²)	34,000 to 54,000	13,000 to 33,000
Weight (lbs/ft ³)	180 to 187	473 to 493
Youngs Modulus (psi x 10 ⁶)	8.45 to 13.6	12 to 14
Modulus of Rigidity (psi x 10 ⁶)	4.5 to 5.2	4.6 to 7.9
Heat Capacity (joules/gm)	0.72	0.12
Thermal Expansion Coefficient (per degree C x 10 ⁻⁶)	5.4	8.5
Hardness (Mohs Scale)	6 to 6.5	4 to 5
Coefficient of Friction (steel on) Static	$\sim 0.20^b$	0.15 to 0.20
Vibrational damping characteristics favor granite	15:1	
Cost favors granite	$\sim 3:1$	

^a

Reference 34.

^b

Reference 35.

rigidly attached to the granite base by means of tapped inserts which have been permanently fastened into the granite with epoxy cement.

The precision lead screw was made in the machine shop of Technical Services at Utah State University. It is $1\frac{1}{4}$ inches in diameter, 23 inches long and has 32 threads per inch. The screw, bearing, and thrust assembly is shown in Figure 7. The screw was mounted parallel to the

Fig. 7. The screw, bearing, and thrust assembly.

vee groove by adjusting the positions of the bearing and motor mounts. A traveling microscope was attached to the carriage; by focusing on the edge of the screw and translating the carriage the angle between the screw and the vee was measured. Successive readings of the microscope at one end of the screw and then at the other indicated that the present angle between the vee and the screw is 5×10^{-4} rad.

The procedure used for calibrating the screw and the correction curve for the nonlinearity of the screw is given in Section 3.2.

A drawing of the carriage and base assembly is shown in Figure 8.

Fig. 8. The crystal carriage and base assembly.

A photograph of the entire crystal platform is shown in Figure 9. The components of the platform are so arranged that the carriage has 19 to 20 inches of travel. The "I" beams are aluminum as are the cross pieces. All other parts of the carriage are steel. The carriage is supported in the vee by four hardened steel buttons, two at each end of the long "I" beam. The horizontal contact of the carriage with the granite block is a button which rides on the horizontal flat surface of the base directly under the short "I" beam.

The contact between the screw and the carriage is made by means of a gimble drive assembly shown in Figure 10. The nut is made in two pieces which screw together. By adjusting the relative positions of the two halves the backlash between the screw and the nut can be reduced to a minimum. The gimble ring "floats" between the screw and the

Fig. 9. A photograph of the crystal platform.

Fig. 10. The screw and gimble drive assembly.

carriage. The ring has vee grooves on opposite sides at right angles with each other. The contacts between the gimble ring and the carriage and between the gimble ring and the nut clamp are steel balls which ride in the appropriate vees. This allows the carriage to translate horizontally and vertically a small amount and to rotate through a small angle about both a horizontal and a vertical axis while being pushed by the screw. The carriage is, therefore, constrained to follow the vee only and is not influenced by slight irregularities in the screw.

The crystal and crystal block ride on top of the carriage as shown in Figure 9. The crystal block is held in place by a mount which allows about $\pm 10^\circ$ adjustment in the horizontal plane. A differential screw provides a fine adjustment of this rotation. In this manner the β -point can be positioned.

As mentioned in Section 2.2 non-repeatable rotational motions of the carriage of more than $\pm 2.5 \times 10^{-7}$ radians cannot be tolerated. Work with a prototype model³⁹ indicated that a linear-motion platform of this design could be built without this intolerable rotational motion. To check this aspect of the motion on this spectrometer, a Twyman-Green interferometer was set up as shown in Figure 11. When the carriage moves

Fig. 11. A Twyman-Green Interferometer used to check the rotational motion of the carriage. A and B are front surface mirrors rigidly attached to the carriage. C is a front surface mirror rigidly attached to the base as is the beam splitter F.

without rotating mirrors A and B move the same distance. The fringes observed at the photosensitive diode are, therefore, stationary. If, however, the carriage rotates through an angle $\delta\theta$ so that one mirror travels a distance d farther than the other the fringes will shift. The relationship between d and $\delta\theta$ is

$$D \delta\theta = d \quad (13)$$

where D is the distance between the points where the light strikes the mirrors A and B. If α is the amount of fringe shift observed and λ is the wavelength of the light used then $\alpha = 2d/\lambda$. Equation (13) can then

be written as

$$\delta\theta = \frac{a\lambda}{2D} \quad (14)$$

Observation of the fringes as the carriage moved the entire length of the screw revealed that $a < 1$. For angle measurements it was assumed that the light intensity over the fringes varied sinusoidally. By measuring the resistance of the photosensitive diode, a was determined with an error of about $\pm 1/20$ of a fringe. This uncertainty in a introduced an uncertainty in $\delta\theta$ of about $\pm 0.5 \times 10^{-7}$ radians. Measurements taken on three successive trials produced the values of $\delta\theta$ shown in Figure 12.

Fig. 12. The rotational motion of the crystal carriage as it moves in translation. The maximum allowable rotation is $\pm 2.5 \times 10^{-7}$ radians. A screw division is one revolution of the screw and is equal to 866.667 steps of the motor.

2.4 The Source Motion Platform

The precision requirements imposed on the source motion in Section 2.2 can readily be satisfied with a linear motion platform similar in design to the crystal motion platform.

The base of the source motion platform is a 7 in. x 3 in. x 10 in. piece of Meehanite. A vee groove $1\frac{1}{4}$ inches deep was milled the 10-inch length of the base $2\frac{1}{4}$ inches from one side.

The precision lead screw for this platform is $\frac{1}{2}$ inch in diameter and 10 inches long with 44 threads per inch. Like the crystal motion platform, the nut is in two pieces to provide a backlash adjustment.

The source carriage is 4 inches long and 5 inches wide. The carriage and base assembly are shown in Figure 13. The carriage is supported in the vee by a steel cylinder the length of the carriage. This support provides the necessary rotational stability. The horizontal contact with the base is a hardened steel button which rides on the flat surface of the base.

Fig. 13. The source carriage and base assembly.

The contact between the screw and the carriage is by means of a gimble drive assembly similar to that used in the crystal motion platform. The carriage is, therefore, constrained to follow the vee. Any motion perpendicular to the vee is less than $\pm 10^{-5}$ cm.

The procedure for aligning the platform so that the motion of the source is perpendicular to the crystal motion is given in Appendix B.

2.5 The Diffraction Angle Measuring System

The diffraction angle is determined by measuring the source position X and the crystal position Y . To determine X it is first necessary to establish a reference source position, X_{ref} . After this has been done the value of X for any other position of the source is determined by measuring the change in X on the source motion screw. Since this screw has 44 threads per inch sufficient precision is obtained by dividing each revolution of the screw into one hundred parts.

One means of establishing a reference source position is by observing a strong gamma ray in first and in second order reflection with the source remaining fixed. If from the two resulting equations, Equation 6 with $N = 1$ and 2 respectively, the wavelength is eliminated the unknown dimension is found to be

$$X_{\text{ref}} = \frac{Y_1 Y_2 \sqrt{3}}{\sqrt{Y_2^2 - 4 Y_1^2}} \quad (15)$$

where X_{ref} is the effective distance from the source to the line of motion of the crystal and Y_1 and Y_2 are the distances of the crystal from the zero-angle position for the first and second orders, respectively.

Alternately a source reference position can be established to sufficient accuracy by observing a well known x-ray in the conjugate positions of the diffraction crystal. The desired dimension is then given by

$$X_{\text{ref}} = Y_r \sqrt{\frac{4 d^2}{\lambda_r^2} - 1} \quad , \quad (16)$$

where Y_r is one-half of the distance between the conjugate positions of the diffraction crystal, d is the crystal interplanar spacing and λ_r is the wavelength of the reference x-ray observed.

- Two different means of measuring the crystal position are available:
- (1) a Twyman-Green interferometer with a laser³⁶ as a light source and
 - (2) a precision lead screw with a stepping motor and a preset indexer.

The interferometer components and the laser are arranged as shown in Figure 14. The components of the interferometer are standard. The

Fig. 14. A Twyman-Green interferometer with a laser light source for the measurement of the crystal position.

small size of the laser spot made it necessary to enlarge the fringes for counting. To do this a short focal length lens was placed between the photo diode and the beam splitter.

A major problem in the use of an interferometer measuring system is the need for a bi-directional scaler to count the fringes for both

forward and reverse motions of the crystal carriage. Scalers capable of this task were not available commercially at reasonable prices. However, a bi-directional scaler had been developed³⁷ and was adapted to meet the requirements of a fringe counter.

Another difficulty with counting the fringes was converting the output of the photosensitive diode to pulses which can be accurately counted. This problem was complicated by the fact that small vibrations in the room result in vibrations of the fringes. Logic circuitry was necessary to standardize the pulses and to differentiate between the noise and the signal. A block diagram of the entire system including the logic and the bi-directional scaler is shown in Figure 15.

The output of the photosensitive diode is fed into a high input impedance field effect transistor (FET) amplifier. This high impedance is required because of the high impedance of the photo diode in the "off" or "dark" state. A potentiometer provides DC level adjustment of the input signal. The output of the FET amplifier drives two amplifiers. Each amplifier consists of three sections. (1) A differential amplifier which amplifies the difference between the input signal and a reference level. A potentiometer varies this reference or trigger level. (2) A Schmitt Trigger circuit to improve the shape of the output of the differential amplifier. (3) A level control circuit to invert the signal and to set the proper level for the output.

The outputs of the amplifiers are fed into an AC coupled flip-flop gate. Amplifier A feeds the 'set' and amplifier B the 'reset' of the flip flop. Pulses from both A and B are required before the gate will give an output. A window potentiometer varies the difference between the triggering levels of the two amplifiers. With the window set wider than the noise, but less than the signal, the noise can only trigger one amplifier and is consequently blocked by the gate while each fringe gives an output pulse.

The gate circuit has two outputs of opposite phase. Each output feeds into a one shot multivibrator. One of the one shots is set to be triggered by a positive going signal (i.e., dark to light at the photo-cell) while the other is set to be triggered by a negative going signal

Fig. 15. A block diagram of the logic and bi-directional scaler for fringe counting.

(i.e., light to dark at the photo diode). A switch selects which multivibrator signal is counted by the scaler.

The bi-directional decade scaler is described in reference 37. Each decade consists of three boards: (1) a carry logic board, (2) a uni-directional board and (3) a read out board. The scaler built for this spectrometer has seven decades as the carriage motion is 1.5×10^6 fringes long for the laser used.

As noted above, the second means of measuring the crystal position is the precision lead screw of the crystal platform with a stepping motor³⁸ and a preset indexer³⁹. This motor steps $1.8^\circ \pm 0.06^\circ$ per step or 200 steps per revolution of the motor shaft. A $\frac{1}{3}$ planetary gear system increases the number of steps per revolution of the lead screw to 866.667. The lead screw has 32 threads per inch so that each step of the motor advances the carriage approximately 3.606×10^{-5} inches (9.159×10^{-5} cm). The error due to the uncertainty in the step size due to the motor only is $\pm 1.3 \times 10^{-6}$ inches (3.3×10^{-6} cm). Since the error in the motor step size is random, this uncertainty is non-accumulative. A larger error is the non-linearity of the screw. It is necessary then to calibrate the screw so that corrections can be made for the non-linearity. A description of the screw calibration and the correction curve is given in section 3.2.

Instead of counting fringes the bi-directional scaler can be used to count the accumulated steps of the motor. Once the system is calibrated the position of the crystal is determined without the use of the laser.

2.6 Detection of the Diffracted Beam

The monochromatic diffracted beam is detected by a scintillation crystal. A 3 in. diameter x 3 in. long NaI(Tl) crystal is presently used although the spectrometer is designed to use up to a 5-in. diameter detector.

A block diagram of the detection system is shown in Figure 16. The diffraction crystal selects the energy of the beam being detected. The baseline of the single channel pulse-height analyzer can be varied

PPCo-B-8137

Fig. 16. The detection system.

as the position of the diffraction crystal changes. In this manner only pulses in the energy range of those being diffracted by the bent crystal and of the desired order are accepted. The counts per time interval as determined by the scaler are plotted as a function of the crystal position to give the gamma-ray profile. The baseline of the single-channel pulse-height analyzer could be coupled electronically to the motion of the diffraction crystal so as to follow it automatically.

The multichannel analyzer can also be used when there is a question as to the order of the reflection being observed. The energies of the gamma rays observed will be the order of the reflection times the energy of the photons from first order reflection. The multichannel analyzer is also used when one desires to use the method of Hatch⁴⁰ to measure gamma-ray intensities with a bent-crystal spectrometer.

2.7 The Crystal Clamping Blocks

With the transmission types of bent-crystal spectrometers two methods of bending the crystal have been used. The crystal can be bent by applying a bending moment which can be varied until the desired radius of bending is achieved^{41,42}. In this study the crystal was bent by clamping it between the convex and concave surfaces of two metal

blocks which have matched surfaces the shape of right circular cylinders⁴. An approximate method described by DuMond⁴³ of cutting short-cylindrical arcs on a milling machine was used. This method uses a "fly cutter" of radius a . By tilting the head of the milling machine the cutting tool of the fly cutter is observed to execute an ellipse when viewed from the horizontal. If one writes the equation for the ellipse which has the same radius ($2 R_{fc}$) of curvature at the center of the arc to be cut as the desired right circular cylinder, then the angle at which the milling head must be tilted to generate this ellipse is found to be

$$\theta = \arcsin \frac{a}{2 R_{fc}} \quad . \quad (17)$$

As one moves away from the center of the generated arc the ellipse and the desired focal circle are found to differ in slope by an amount δ given by⁴³

$$\delta = \frac{8}{r\sqrt{1-q^2}} \frac{1 - \sqrt{1-q^2}}{1 + (r^2-1)\sqrt{1-q^2}} \quad (18)$$

where $r = a/b$ the axial ratio of the ellipse, $q = x/a$ and x is the distance out along the major axis of the ellipse. Thus, to cut a surface with 2 meters radius of curvature using a fly cutter of 15.2 cm radius the error of inclination of the surface at the edge of the aperture ($x = 2.5$ cm) will not exceed 1.07×10^{-6} radians. The line broadening introduced by this error is of the order of a few thousandths of an x_u , or less than 1% of the expected line width.

When a flat crystal is bent to a radius $2 R_{fc}$ there is an aberration introduced which comes from the fact that the center line of the crystal deviates at its edges from exact coincidence with the focal circle of radius R_{fc} . The line broadening which results from this aberration is⁴

$$\frac{\Delta\lambda}{\lambda} = \cos\theta(1-\cos\alpha) \sec(\alpha+\theta) \quad , \quad (19)$$

where α is the half angle width of the crystal aperture and θ is the diffraction angle. For small α and θ

$$\frac{\Delta\lambda}{\lambda} \approx \frac{\alpha^2}{2} = 8.0 \times 10^{-5}$$

for this instrument.

The error of inclination of the edges of the aperture resulting from approximating a right circular arc with an elliptical arc is in such a direction as to decrease this latter aberration.

Drawings of the clamping blocks used in this study are shown in Figure 17a and 17b. These blocks were made from Air Die 150 Tool Steel. The resolution, FWHM, achieved with these clamping blocks is given in section 3.3.

2.8 Shielding

Figures 2, 3, 4 and 9 show all of the material used to shield the detector from the undiffracted beam and from scattered radiation.

The source shield has lead walls 4 inches thick. The exit aperture was machined so as to define the beam size and direction. For low-energy photons the radiation level two to three inches outside the desired beam path is no different from the background anywhere in the room.

Mounted on the same stand as the crystal carriage is a lead wall 24 inches long, 15 inches high, and 2 inches thick. An opening is provided in this wall along the path of the diffraction crystal to allow the direct beam to pass to the crystal. The center portion of this opening is filled with a 4-in. thick beam shield. This shield has been machined and positioned so as to block that portion of the direct beam which would otherwise strike the detector.

The detector is also located in a shield with 4-in. thick lead walls. A portion of the shield with 2-in. thick walls extends 20 inches in front of the detector. This portion of the detector shield contains two sets of 4-in. thick lead stops. The set nearest the detector, shown in Figure 2, is aligned parallel to the edges of the beam shield to protect the detector from the direct beam. The stops farthest from the detector are set to allow the diffracted beam to pass but limit as much

PPCo-B-8139

(a)

PPCo-B-8140

(b)

Fig. 17. The crystal clamping blocks, (a) is the concave block and (b) the convex block.

as possible the field of view of the detector to scattered radiation. To minimize the scattering, the leading surfaces of the stops and the beam shield have been machined to be parallel to the direction of the direct beam at their respective positions.

Two 3/4-in. thick lead pieces are mounted on the carriage as shown in Figure 9. These significantly reduce the background due to scattered radiation.

By observing the output of the linear amplifier with a multichannel analyzer the majority of the background was found to be Sb^{124} activity. This activity comes from the quartz capillary tube in which the wire source was encapsulated to keep the wire straight. The O.D. of the quartz is about 0.070 inches. It is, therefore, not possible to entirely shield this radiation from the detector.

CHAPTER III

TESTING AND CALIBRATION

3.1 Test of Crystal Focus

In analogy to the well-known Hartmann method of testing the aberrations of focus of large astronomical mirrors a "Hartmann" test⁴ has been previously developed for determining the aberrations in focus of a bent crystal by use of the diffraction of x-rays or gamma rays from the atomic planes of the crystal.

A tantalum wire, 0.003-in. diameter x 1-in. long, was activated for 16 days in a flux of $\sim 4 \times 10^{14}$ neutrons $\text{cm}^{-2}\text{-sec}^{-1}$ in the Materials Testing Reactor at the National Reactor Testing Station. The tantalum isotopes Ta^{182} and Ta^{183} , which decay by β^- emission to W^{182} and W^{183} , are produced. In addition to the numerous gamma rays of these isotopes tungsten and tantalum K-series x-ray lines are observed. The most intense of these is the $\text{W K}_{\alpha 1}$ which was used for the test.

The source wire was encapsulated in a quartz capillary tube. This capsule was held with its long axis vertical in an aluminum source holder. The small diameter of the wire allowed it to serve as the resolving "slit" for the test.

To perform the test the crystal aperture was divided into 21 sections. A lead shield was designed to cover all of the aperture except the section being tested. The test consists of measuring the line profile for each of these sections of the crystal. The crystal position corresponding to the center of the line profile was found to vary by a few tenths of a millimeter from one crystal section to another. A diagram analogous to a ray diagram in optics was plotted as follows:

1. The relative crystal positions representing the center of the line profile for each of the sections tested were located on a horizontal line.
2. The tangents of the angles of obliquity, ϕ_1 , for each of the sections was determined. Figure 18 shows to an exaggerated

scale the angles of obliquity for several of the sections of the crystal.

Fig. 18. The angles of obliquity, ϕ_i , for several of the sections of the crystal. For clarity these are drawn to an exaggerated scale. The numbered sections of the crystal are the same as the top row in Figure 19.

3. A scale factor of 100 to 1 was chosen to represent the lateral displacement of the line profiles versus the tangents of the angles of obliquity.
4. The tangents of the angles of obliquity determined in step 2 were multiplied by the scale factor of step 3 so that the expanded angle of obliquity, ϕ'_i , was obtained by
$$\phi'_i = \tan^{-1}(100 \tan \phi_i) \text{ for each section.}$$
5. The ray associated with each of the regions of the crystal was then plotted. This was done by drawing a straight line from each of the points on the line of step 1 at an angle corresponding to the expanded angle of obliquity for that section.

This procedure produced the set of intersecting lines shown in Figure 19. The region where these lines intersect to give the best focus is

Fig. 19. A test of the aberrations of focus of a bent crystal. At the left are shown the positions of the centers of the sections of the crystal aperture tested. The "rays" are plotted as described in the text.

also shown. From this is learned the width of the pattern formed by the aberrational errors of focus of the curved crystal. It is easily seen which sections of the diffraction crystal (quartz 310 in this study) need to be blocked out with lead to improve the focusing. It is also learned from this diagram how far the source must be moved to be "on" the focal circle.

A 5 in. x 5 in. NaI detector was used so that the diffracted beam from all sections of the crystal could be observed. It was found that several sections on one edge of the crystal had large aberrations with respect to the remainder of the crystal. In Figure 19 these sections are excluded. The useful area remaining is about 20 cm². The width of the diffraction pattern at best focus for this area is 0.10 mm. This

is only 0.024 mm (30%) wider than the source used and about 10% larger than expected.

It is not possible to tell with this test whether the aberrations are a result of improper bending of the crystal, misalignment of the long axis of the source with the crystal planes, or a result of imperfections in the crystal. The quartz (310) plate used in this study had a deep scratch on one edge which was removed by lapping before bending was attempted. It is this same edge which shows the aberrations in focusing. This aberration may be a result of the lapping.

3.2 Linearity of the Crystal Platform Lead Screw

The interferometer measuring system described in section 2.5 provided the most direct means of measuring the linearity of the screw. The preset indexer was used to preselect the number of steps taken (1 to 99,999) each time the motor is actuated. As mentioned earlier the error in the step size due to uncertainty in the motor step size is random and negligibly small. A plot of the accumulated steps versus the measured position of the carriage would be a straight line for a linear screw. The deviations of the plot from a straight line are, therefore, the corrections for the non-linearity.

The correction curve is most useful when the position of the carriage and the corrections are measured in the same units (i.e., steps of the motor or cm). It was, therefore, desirable to determine the average size of the steps. This was done by measuring with the interferometer the distance the carriage advanced for a fixed number of steps of the motor. Several measurements of 50,000 steps each were made for all portions of the screw. From these measurements the average step size was determined to be 9.15721×10^{-5} cm.

The data for the correction curve were taken every 5000 steps of the motor. The accumulated steps and position of the carriage as measured by the interferometer were recorded for each of these positions. From these data the correction curve shown in Figure 20 was determined. The accuracy of this curve is suitable for a wavelength precision of ± 0.005 xu. However, if greater precision is desired, this curve may

Fig. 20. The screw linearity correction. Step units are steps of the motor. Each step is equal to 9.15721×10^{-5} cm.

introduce more error than can be tolerated. A more accurate curve can be obtained by the same procedure outlined above, but with a more stable laser than was used to obtain Figure 20.

3.3 Resolution and Line Broadening

A desirable feature of a spectrometer is its ability to produce separate line profiles for two gamma rays which are very close together in energy. The full width of the peak at half the maximum peak height (FWHM) is a measure of this ability. With a bent-crystal spectrometer this width, measured in wavelength units, is nearly constant over the range of the instrument. Several factors contribute to the observed width of the line profile. These are: (1) the natural width of the gamma ray or x-ray measured, (2) the effective geometrical width of the emitting source, (3) crystal structure effects such as the Darwin or Ewald diffraction pattern width and mosaic effects, (4) aberrations of focus from imperfections in the crystal and in the crystal bending, and (5) defocusing resulting from the source not being on the focal circle. The observed width of the line profile is the convolution of these effects. When using a quartz (310) crystal bent to a two-meter focal circle with a source less than 0.2 mm wide, which is located on the focal circle, the first four contributions generally result in a FWHM of about 0.30 xu.

If the source remains at a fixed position while making measurements over a range of energies it will not be on the focal circle at all angles. This defocusing, (5) above, will result in additional broadening of the observed line profile. This broadening will not be prohibitive if it is a small fraction of the line width when the source is on the focal circle. When the source is fixed at the position $2 R-q$ the contribution, $\Delta\lambda_d$, to the line width due to defocusing is given by³³

$$\Delta\lambda_d = \frac{\ell \lambda^2}{4 d R} - \frac{q \ell d}{2 R^2} \quad (20)$$

where ℓ is the width of the window in the crystal clamping blocks, d is the crystal interplanar spacing, λ is the wavelength and R the radius of the focal circle. Figure 21 shows a plot of Equation (20) for the 310 planes of quartz bent to a 200 cm focal circle with a window 5 cm wide.

It is assumed that the contributions to the observed line width sum according to the square root of the sum of the squares. A source position can thus be selected for which the observed line is broadened only a few percent for a relatively large portion of the spectrum. For example, if the spectrum is divided into the following three regions with the specified source position for each, the observed line width is broadened less than 5% from the width at proper focus.

	Wavelength xu	Energy keV	Source position q cm
1.	0 - 140	above 90	0.35
2.	140 - 190	90 - 65	1.05
3.	190 - 240	65 - 50	1.70

In Figure 22 the line profiles for the 90.080-keV and 100.12-keV gamma rays are shown. These were obtained with a 2 mm thick quartz plate bent to a focal circle of 192.30 cm by the clamping blocks described in section 2.7. The source was on the focal circle so that the observed FWHM of 0.28 xu is a result of the first four factors above. In Figure 23 are shown the profiles of the 160.568-, 161.320-

Fig. 21. The line broadening resulting from the source being off the focal circle. The line broadening, $\Delta\lambda_q$, is shown as a function of q for several different wavelengths covering the range of the spectrometer. The quantity q is related to the source position by $q = 2R - X$, where X is the source position as measured from the line of motion of the crystal.

and 162.327-keV gamma rays. In Figure 24 the profiles for the 244.230- and 246.028-keV gamma rays are shown. These were obtained with the source fixed at $q = 0.10$ cm. Measurements were made with the source at this position up to 354 keV. The FWHM for each of these lines was found to be 0.28 ± 0.01 xu. The line broadening due to defocusing is, therefore, not difficult to control.

Experimentally it was found that the effective source width is more difficult to control and may contribute significantly to the width of the lines. The source used to obtain the profile shown in Figure 22

Fig. 22. The line profile of 99.080-keV and 100.12-keV gamma rays with the source on the focal circle.

was a 3 mil wire. Later a 5 mil wire was used in a different source holder. The FWHM of the 99.028-keV gamma ray was 0.36 xu with this source. Apparently, the axis of this wire was not parallel to the diffracting planes of the crystal. Consequently, the effective source width was greater than 5 mils.

Fig. 23. The line profile of the 160.568-, 161.320-, and 162.327-keV gamma rays with the source fixed at $q = 0.10$ cm.

Fig. 24. The line profile of the 244.230- and 246.028-keV gamma rays with the source fixed at $q = 0.10$ cm.

CHAPTER IV

RESULTS

4.1 Transition Energies in W^{182} and W^{183}

The numerous well-known transitions in W^{182} and W^{183} resulting from the beta decay of Ta^{182} and Ta^{183} provide an excellent test of many of the properties of the spectrometer. Foremost of these is the precision with which x-ray or gamma-ray energies can be measured. The accuracy of wavelength or energy measurements is directly dependent upon how well the crystal interplaner spacing is known. Several of the tantalum and tungsten x-ray wavelengths are known to a few parts per million⁴⁰. By dividing the values of these known wavelengths by the corresponding measured sines of the diffraction angles the crystal interplaner spacing was determined to be

$$d = 1175.59 \pm 0.08 \text{ xu} \quad , \quad (21)$$

for the quartz crystal used. By use of this value of d and the relationship

$$E = \frac{12372.42 \text{ keV xu}}{\lambda} \quad (22)$$

to obtain the energies from the measured wavelength, the energies in Tables 4, 5, and 6 were determined. As a comparison the x-ray energies reported by Bearden⁴⁰ and the gamma-ray energies measured by Seppi¹⁹, Henning²¹, and Murray⁴¹ are listed. The uncertainties assigned to the measured energies listed in Table 4 are estimated standard deviations. The uncertainties in Tables 5 and 6 are taken to be about one tenth of the FWHM for the weak lines and about one thirtieth of the FWHM for the most intense transitions. The errors in X (Equation 16) and d (Equation 21) contribute a negligible amount.

The resolution of germanium diffraction crystals is greater than that of quartz by a factor of three or four. The precision of the energy

Table 4. Tantalum and tungsten x-ray energies.

X-Ray	Energy in keV and Error ^a			
	Present Value		Bearden ^b	
Ta K _{α2}	56.270	8	56.277	2
Ta K _{α1}	57.531	4	57.532 ^c	1
W K _{α2}	57.977	4	57.9817 ^c	5
W K _{α1}	59.318 ^d		59.31824	25
Ta K _{β3}	64.950	4	64.9488 ^c	6
Ta K _{β1}	65.218	4	65.223 ^c	1
W K _{β3}	66.959	8	66.9514	6
W K _{β1}	67.243	4	67.2443 ^c	6
W K _{β2} ^I	69.08	2	69.101	2
W K _{β2} ^{II}	-----		69.031	3
W (K-O)	69.484	8	69.479	1

^a The errors listed above are in the last digit or digits.

^b Reference 40 (errors are "probable errors").

^c The wavelengths from Reference 40 were assumed to determine the crystal interplaner spacing (see text).

^d The value from Reference 40 assumed to establish the reference source position (i.e., the value of X in Equation 16).

Table 5. Tungsten 182 gamma-ray energies.

Energy in keV and Error ^a							
Present Value		Murray et al. ^b		Seppi et al. ^c		Henning ^d	
65.711	8	65.71	1	65.723	1	65.716	1
67.753	4	67.74	1	67.751	1	67.751	1
84.674	10	84.67	2	84.693	1	84.679	3
100.092	10	100.09	2	100.107	1	100.099	2
113.654	15	113.66	2	113.674	2	113.673	3
152.429	15	152.41	3	152.441	3	152.426	8
156.381	15	156.37	4	156.386	3	156.387	8
179.392	25	179.36	5	179.394	4	179.404	6
222.11	5	222.05	7	222.114	5	222.092	20
229.34	5	229.27	8	229.327	13	229.353	25
264.06	5	264.09	10	264.075	9	264.075	50

^a The errors listed are in the last digit or digits.

^b Reference 41 (errors correspond to 90% confidence limits).

^c Reference 19 (errors are standard deviations).

^d Reference 21 (errors are standard deviations).

measurements made with these detectors should, therefore, be improved by a factor of three or four. Both Seppi¹⁹ and Henning²¹ used germanium crystals. It is encouraging that the agreement between the energies measured in this study, using the 310 planes of quartz, and those of the groups using germanium crystals is very good.

Table 6. Tungsten 183 gamma-ray energies.

Present Value		Energy in keV and Error ^a					
		Murray et al. ^b		Seppi et al. ^c		Henning ^d	
46.473	6	46.48	1	-----		-----	
52.590	8	52.59	1	52.598	1	52.596	1
82.922	10	82.92	1	-----		82.908	2
84.722	10	84.70	2	-----		-----	
99.080	8	99.07	2	-----		99.070	5
101.952	10	101.94	2	-----		101.944	3
102.512	20	102.49	2	-----		102.494	8
103.159	20	103.14	2	-----		103.131	5
107.939	10	107.93	2	107.933	1	107.916	4
109.733	10	109.73	2	-----		109.723	3
142.279	20	142.25	3	-----		142.312	7
144.130	10	144.12	3	-----		144.118	7
160.568	20	160.53	4	-----		-----	
161.320	15	161.36	4	-----		161.335	25
162.327	15	162.33	4	162.323	2	162.358	80
192.678	30	192.64	6	-----		192.664	10
203.335	30	203.27	6	-----		203.402	10
205.055	20	205.06	6	-----		205.076	10
208.84	5	208.81	7	208.814	7	-----	
209.854	20	209.87	7	209.860	5	209.849	15
244.23	6	244.26	9	244.264	6	-----	
246.03	5	246.05	9	246.056	2	245.99	4
291.70	7	291.71	13	-----		291.756	50
313.12	8	313.03	15	-----		313.20	7
354.00	8	354.04	20	354.004	10	354.28	9

- ^a The errors listed are in the last digit or digits.
^b Reference 41 (errors correspond to 90% confidence limits).
^c Reference 19 (errors are standard deviations).
^d Reference 21 (errors are standard deviations).

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