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ARGONNE 7.7-METER BENT CRYSTAL
GAMMA-RAY SPECTROMETER*

by

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TABLE OF CONTENTS

	PAGE
Abstract	2
Introduction	3
General Description	4
Design of the Instrument	
General Considerations	11
Specifications on Quality of Quartz and Orientation of Plate	14
The Crystal Clamp Blocks	18
The Crystal Mount	24
Crystal Table and Drive	25
Interferometer	35
Collimator	41
Detector	52
Optical Lever	55
Collimator Drive	60
Bulk Shield Carrier and Drive	64
Conical Motions	70
In-pile Components	72
Assembly and Alignment	78
Operations and Control	95
Calibration and Measurement	101
List of Figures.....	110

ABSTRACT

A bent crystal gamma-ray spectrometer of the transmission type having a focal length of 7.7 meters has been built for studying neutron-capture radiation. The source is placed inside the reactor CP-5 in a horizontal straight-through hole. The instrument is designed to utilize a 30 cm x 30 cm quartz plate cut normal to the 310 planes. Undiffracted radiation is absorbed by a baffle consisting of 108 Pb plates each 40 x 11 x 0.040 inches mounted between tapered spacers so as to focus on the virtual image of the source. The detector is an array of 16 NaI (Tl) crystals comprising a volume 10-1/2 x 10-1/2 x 2 in. The drive system rotates the crystal one second of arc in 20 seconds. The 2:1 motion required between the crystal and the detector is maintained by an optical lever system. The Bragg angle is measured with an interferometer and the gamma-ray energy may be determined relative to the Hg^{198} green line. The instrument now operates with a 10 x 15 x 0.6 cm crystal.

I. Introduction

When a thermal neutron is captured by a nucleus a compound nucleus is formed which has an excitation energy of about 6-9 Mev, on the average. This excess of energy may be emitted by various competing methods. In the case of the lightest atoms, emission of charged particles is possible and (n, α) and (n, p) reactions occur. For the very heavy elements the fission reaction may occur. However, for most elements the excess of energy is emitted in the form of gamma radiation. These gamma rays are called capture gamma rays; they are emitted in times of approximately 10^{-13} - 10^{-14} second. Since there usually are many nuclear states between the initially formed state of the compound nucleus and its ground state, there is a variety of cascade branches available for the loss of the excess of energy. In the course of the cascade a long-lived state may be reached and an isomer will be observed. In addition, the ground state may be beta-unstable and additional gamma rays which follow the beta decay may be observed.

It is evident that complete measurements of the energies and intensities of capture gamma rays would provide important information about nuclear level schemes. It is to be hoped that a knowledge of, perhaps, the first ten excited states of 90 per cent of the elements would possibly show some interesting regularities. It is, therefore, very desirable to have methods

of studying such gamma rays^{1,2} that have high efficiency, high resolution and high accuracy in energy measurement. The method that we have chosen is one that has never before been used for capture gamma-ray studies, namely, the direct crystal diffraction method as developed by DuMond³. This paper contains a description of the design, construction and operation of an instrument based on the above-mentioned method, and gives some preliminary performance data.

II. General Description of the Instrument

In this section we present a general description of the constructional features of the 7.7-meter bent crystal gamma-ray spectrometer (in principle, similar to DuMond's⁴ 2-meter instrument but differing in many mechanical details) as an introduction to the more detailed description of the design and construction of the component parts set forth in the next several sections.

In broad outline the spectrometer consists of a source of gamma rays and a mechanism for sorting and detecting these gamma rays shown schematically in Figure 1. In the Figure the components are out of proportion; in particular the crystal and clamp are exaggerated for emphasis.

1. B. B. Kinsey - Chapter 25 - Beta and Gamma Ray Spectroscopy - edited by Siegbahn, Interscience 1955. This chapter has a complete list of references on the various methods of studying capture gamma radiation with the exception of reference 2.
2. L. V. Groshev, B. P. Adyasevich and A. M. Demidov, Proc. of the Int. Conf. on the Peaceful Uses of Atomic Energy 1955, Vol. 2, p. 39.
3. J. W. M. DuMond - Chapter 4 - Beta and Gamma Ray Spectroscopy - edited by Siegbahn and J. W. M. DuMond, Ergebnisse d. exakt Naturwiss. Bd XXVIII 232 (1955).
4. J. W. M. DuMond, R.S.I. 18, 626 (1947).

Figure 1. Schematic diagram of spectrometer

The source is situated in the Argonne heavy water reactor (CP-5) in the center of a horizontal straight-through hole which passes close by the core of the reactor. The source material may be any element or isotope with a sufficiently high cross section for neutron capture so as to emit capture gamma rays of measurable intensity (in the energy range 20 kev to 7 Mev) and which can be prepared in an appropriate physical form. A collimated beam of gamma rays from the source impinges on the bent quartz crystal. For a given angular setting of the quartz crystal with respect to the incident direction of the gamma-ray beam only those gamma rays with the proper energy (actually with a small spread in energy about this proper value) will be selectively diffracted by the atomic planes of the crystal. The intensity of the diffracted beam is determined by suitable counters which have been shielded against the undiffracted beam by a collimating device.

The quartz crystal is located a distance 7.7 meters from the source in the pile and held in a bent state between a pair of stainless steel clamp blocks whose surfaces have been machined to a 7.7-meter radius of curvature. The convex surface of the front clamp block defines the radius and the figure of curvature to which the crystal is bent. Referring to Figure 2, we see that the clamp blocks are supported on a crystal mount which in turn is supported directly on the crystal table. The crystal mount provides the three degrees of freedom necessary to place the quartz crystal precisely over the axis of rotation on the crystal table. The crystal table and the crystal table drive are in turn mounted on the pintle which is positioned very precisely relative

Figure 2. Cut-away view of central structure and shielding of spectrometer

to its floor location by means of a three-inch steel ball resting on the floor bolster. The Bragg angle through which the quartz crystal is rotated is measured by means of an interferometer (not shown in Figure 2), the movable mirror of which follows the motion of the crystal table. The interferometer may be seen in Figure 3 which shows an overall view of the instrument. The fringe pattern of the interferometer is set for circular fringes and the fringes are counted by a photomultiplier and automatically recorded.

The primary base of the spectrometer is a heavy (7 tons) Meehanite casting shaped roughly like a sector of a circle. The pintle which supports the crystal table and drive as mentioned above also serves as a support for the primary base. In addition the pintle serves to locate the base casting relative to the source in the pile.

Located on the primary base and surrounding the pintle are two support rings designated as the inner and outer support rings. These support rings have hardened and ground track surfaces on their outer periphery on which the wheels supporting two ring structures ride. The inner ring structure supports the front end of the channeled collimator by means of the collimator nose piece. The rear end of the collimator is supported by a pair of wheels which rides on the track running along the rear of the primary base. One of the wheels serves as the drive wheel; both wheels and the collimator drive are attached to the collimator tail piece which in turn is tied to the extended side plates of the collimator box itself. The channeled lead

Figure 3. Overall view of spectrometer

collimator serves to separate the diffracted from the undiffracted gamma ray beam coming through the bent quartz crystal. For the collimator to pass only the diffracted beam through its channels it is necessary that the collimator be rotated about the axis of rotation of the quartz crystal through an angle twice that through which the crystal has been rotated. As the quartz crystal is turned through the range of angles from 0° to 15° each side of zero, this two-to-one ratio of angles is maintained by an optical lever linkage between the collimator and the crystal table. The light source for the optical lever is located at the forward end of the collimator, attached to the collimator nose piece. The optical lever mirror is located above the quartz crystal itself on an adjustable mirror mount attached to the top of the crystal clamp blocks. The sensing components of the optical linkage are located on the optical lever bench about two meters from the optical lever mirror.

An array of detectors is located at the rear of the channeled collimator to record the gamma rays which pass through the open channels. There are sixteen detectors in the array, each consisting of a large NaI (Tl) crystal and photomultiplier tube. These detectors are connected in parallel to a single preamplifier and power supply and feed a single channel analyzer. Because of the large volume of NaI the detectors are surrounded by a large bulk shield consisting of approximately a cubic yard of lead with a $16'' \times 16''$ hole through its center in which the channeled collimator rides. The bulk shield is physically separated from the collimator and rides on its own massive carrier. The back end of this carrier rides on the same track as

the collimator; the front end is supported by the outer ring which rides on the outer ring support.

III. Design of the Instrument

General Considerations

In considering the design of the Argonne Bent Crystal Spectrometer it is best to first point out some features of DuMond's 2-meter spectrometer.³ This instrument utilizes a quartz plate $80 \times 70 \times 2.0$ mm which is curved to a right cylinder of 2-meter radius. The useful aperture of the crystal is 17 cm^2 . The most massive part of this instrument, the channel collimator and shield, is kept stationary. As the crystal mount is rotated, the focal circle rotates and the source of gamma rays is made to move on the focal circle in an appropriate manner.

The Argonne instrument differs from the DuMond instrument in several respects, as follows:

1. The source of gamma rays is at a fixed position inside of the CP-5 reactor. (Capture gamma rays of greatest intensity are to be had only by putting the source at the position of greatest neutron flux.)
2. The focal length is 7.7 meters.
3. The dimensions of the quartz crystal are $300 \times 300 \times 4$ mm with a useful aperture of about 250 cm^2 .

Because it is impractical to attempt to move the source transversely inside the available 6" hole through the pile or, of course, to move the pile itself, the source is kept stationary. Therefore, the heavy channel collimator

and bulk shield must follow the motion of the crystal table rotating at an angular rate twice that of the crystal table. As can be seen from Figure 1, as the crystal rotates the focal circle will rotate with it and the fixed source will not remain on the focal circle. However, for the 310 planes of quartz used, the Bragg angles for gamma radiation are very small. For example, the Bragg angle for annihilation radiation (510 kev) is only 34 minutes of arc. Since the amount that the source will be out of focus is $R(1 - \cos \theta)$, where R is the diameter of the focal circle (7.7 meters) and θ is the Bragg angle, the source will be inside the focal volume unless very low energy radiation is studied. For these reasons the source is kept at 7.7 meters from the crystal when studying gamma radiation of energies above 100 kev. For purposes of studying radiation of lower energy a means of moving the source inside the pile is provided.

In choosing the focal length of the instrument, the main limitations are the size of the building and the sizes of quartz plates that are available. If the linear dimensions of an instrument of this type (except for the thickness of the quartz crystal) are multiplied by σ , the focal volume and proportional strength of the source will increase by σ^3 . The area of the quartz crystal will increase by σ^2 , the solid angle of radiation intercepted by the crystal remaining constant. Similarly the area of the detector required is increased by σ^2 . No increase in the depth of the detector will be needed if the same range of gamma-ray energies is to be studied. However the

thickness of the quartz crystal may be increased by a factor σ and the quartz will not be subjected to any greater stress on bending than in the smaller instrument. This will increase the reflectivity of gamma rays by a factor σ , provided σ is not too large. In the pile room the sources of background will increase by σ^2 and the net improvement will be σ^2 .

From the above discussion it follows that the instrument should be as large as possible. The size of the room in which the CP-5 reactor is located limits the diameter of the focal circle to 7.7 meters, giving a factor of σ of 3.85 in comparison with DuMond's 2-meter instrument.

There is an additional factor in choosing the size that must be considered because the source is located in the reactor inside of a tube of finite size (6" diameter). Whereas in an instrument such as DuMond's which uses a long-lived source in a laboratory there is no limit as to the size of quartz crystal that could be used; this is not the case in the Argonne instrument. Since the walls of the 6" diameter tube are in a region of high thermal neutron flux, the quartz must be prevented from "seeing" this source of high background. This requires placing a tapered collimator between the source and the quartz crystal. This collimator is located inside the reactor and contains an opening which is tapered, as can be seen in Figure 1. It is narrower on the side toward the center of the pile. The size of the aperture is determined by the nearest point on the side wall of the 6" tube that the quartz is permitted to "see". As the crystal size is increased this aperture has to be decreased and with it the size of source that is useful. A graph of crystal size vs. gamma-ray intensity shows a broad maximum. Our crystal size was chosen

so as to be as large as possible but not to be off of the broad maximum of the above-mentioned curve. Of course, the deciding factor in choosing the size of crystal is the availability of raw material.

Specifications on Quality of Quartz and Orientation of Plate^{**}

The quartz plate was prepared by Hilger and Watts, Ltd. The specifications as set forth to them are reproduced here. The quartz from which slab is cut must be monocrystalline, perfectly clear, white, free from inclusions, flaws, optical or electrical twinning. The slab must be large enough to give a finished rectangular piece 12 inches x 12 inches and 4 mm thick. The orientation of the slab should be as follows: the large flat faces should be parallel to the optic or trigonal axis. Two opposite edges should be parallel and two other edges perpendicular to the trigonal axis. The atomic planes with Miller indices (310) are to be normal to the large flat faces and parallel to two slab edges. To accomplish this the large flat face must make an angle $\phi = 13^\circ 53'$ and $53''$ with the normal to any one of the prism faces of the quartz crystal. $\phi = 13^\circ 54' \pm 30''$ is close enough. Figure 4 shows a view of the crystal looking along the optic or trigonal axis with the orientation of the slab as seen on edge. Six completely developed prism faces are shown.

The correctness of the orientation of the (310) planes relative to the faces and edges of the slab are to be checked with an x-ray goniometer by reflection at one of the edges. These planes may be identified by their grating constant $d_{18^\circ} = 1177.6 \text{ x.u.}$ (Siegbahn scale). Two pairs of edges should be made parallel and the two others perpendicular to the (310) planes to within

^{**}Footnote on page 18

Figure 4. Sketch showing orientation of quartz slab relative to optic axis

± 30 seconds of arc. One large flat face of the blank is to be normal to the (310) planes to ± 30 seconds of arc and this face is to be clearly marked as the reference face.

From a slab (at least 3" thick) and large enough to cover a finished piece 12" x 12", oriented as outlined above, the work should proceed as follows:

1. Lap and polish one face sufficiently flat to permit establishment of optical contact between it and a large thick rigid optical glass flat. (Surface should be etched lightly in HF before contacting.)
2. Grind down the quartz plate so that a finished thickness of 4 mm will be obtained.
3. Lap and polish the second face.
4. Remove quartz from glass and etch second surface.

The large face which was originally polished in (1) above should be finished to a flatness of 8 fringes or better. This is to be the reference face and should be clearly indicated. The second face should be finished so that a final parallelism between the two large faces of no more than 20 fringes is obtained.

The specified tests for parallelism and flatness must be passed by the slab after light etching to remove surface strains of polishing. The edges of the finished slab which are parallel to the optic axis are to be clearly indicated for identification by a slight beveling of the corners. All sharp corners are to be rounded off and etched to remove all possibility of incipient cracks. Figure 5 shows a sketch of the finished plate.

LARGE SURFACE POLISHED FIRST TO BE CLEARLY INDICATED

Figure 5. Sketch of finished quartz plate

** The specifications and directions for preparation of the quartz slab were decided upon after our experience in obtaining the original plate for this instrument. The specifications on this plate were drawn too tightly and hence required nearly 2-1/2 years to fulfill.

The new specifications are designed to speed up delivery of a new plate and also to provide an additional safety factor in bending by a 2/3 reduction of thickness.

The first plate (dimensions 12" x 12" x 6 mm in thickness) broke as it was being bent, after it was in contact with the steel clamp block over 1/4 of the desired aperture. A piece of this broken plate was trimmed to make a 6" x 4" rectangle which was bent successfully. This smaller bent crystal has been used for all of the experimental work performed to date.

The Crystal Clamp Blocks

The method of bending the crystal that was used was the method of "imprisonment".³ For this purpose two pairs of clamps were made from type 420 stainless steel. One pair was for the 12" x 12" quartz plate and the other was for the 6" x 4" plate. In each case the over-all dimensions of the openings in the clamps were made equal to 2/3 of the corresponding dimensions of the quartz. In the first case two ribs crossed the aperture and in the second case a single rib was used. In each case the steel was given an appropriate heat treatment³ which results in highly stable components. Figure 6 shows a front view and Figure 7 a rear view of the clamp blocks used for the smaller quartz plate.

Figure 6. Front view of clamp blocks for small quartz plate

Figure 7. Rear view of clamp block for small quartz plate

The cylindrical surfaces were generated by the method described by DuMond.⁵ However, in order to carry out this procedure with the much heavier components that were needed for our instrument, a separate machine had to be built.⁶

After completing the grinding operation the convex clamp blocks (one each for the large and small crystal) were lapped against a concave lapping block that had been machined in the same manner as the clamp block. A pair of cast iron lapping blocks (having no apertures), one concave and one convex, of 7.7 meters radius was prepared and these were lapped together. Figures 8 and 9 show two views of the lapping fixtures being used to prepare the cast iron lap blocks, A and B. A random motion is imparted to the upper lap block, B, by the optical lapping machine. The orientation of the generators of the cylindrical arc is maintained by the parallelogram defined by the arms, C. The parallelogram is able to define the required arc because of the rocking plate, D, and the self-aligning bearings E. The focal length of the concave lapping block was then measured optically. In order to obtain a good image in this test the concave lapping block was polished with a convex pitch lap in which aluminum oxide was embedded. When the focal length was close to the desired value the concave lap was used to lap the convex clamp block. As a result of taking great care in the grinding operation the total time required for lapping was only a few hours.

The concave clamp blocks were not lapped since in this method for

5. DuMond, Lind and Watson, R. S. I. 18, 617 (1947).

6. H. Ostrander, American Machinist, 100, 118 (July 2, 1956).

Figure 8. Side view of lapping fixture

Figure 9. Front view of lapping fixture

clamping the quartz the crystal is only in contact with the convex clamp block around which it is bent whereas a rubber gasket separates the quartz from the concave clamp block. In our case the radius generated on the concave clamp was made equal to 7.7 meters plus the 6-mm thickness of the quartz plate.

The bending of the quartz was carried out on top of a large surface plate, in an air-conditioned, dust-free room. Since the generators of the cylindrical surface had been located so as to be parallel to one pair of edges and perpendicular to the other pair of edges of the clamp block, it was possible to locate the (310) planes of quartz parallel to the generators by using a 0.0001" dial indicator. The bolts that were used for clamping were then "ganged" together so as to avoid non-uniform clamping. A set of four dial indicators, one at each corner, was located on the concave clamp. These were set before the clamping began and readings were taken as the clamping progressed. These served as rough indicators of the progress of the clamping process.

However, the precise advance of the clamping operation was followed by observing the central black Newton's ring located between the quartz and the rib on the convex block. The clamping was continued until the fringe covered more than 90% of the width of the aperture, i. e., along the 6" dimension in the case of the 6" x 4" crystal.

The Crystal Mount

As part of the alignment procedure it was required that the neutral plane of the crystal be placed over the central pivot of the spectrometer.

Furthermore, the (310) planes had to be aligned so as to be exactly vertical (as is the axis of rotation). The method used to accomplish this is shown in Figure 10. The crystal clamp block mounting plate, A, can be moved in either of two perpendicular directions in a given plane by adjusting the four screws B, and then locked in place through the ring C being tied to D, using the bolts E.

The plane of the plate, D, can be made horizontal by adjustment of the 16 levelling screws F which rest on the crystal table G. This adjustment is then maintained by the locking screws H.

Crystal Table and Drive

The primary design requirements of the crystal table on which the crystal mount and crystal clamp blocks ride is that it rotate in a truly horizontal plane about a fixed vertical axis and at a sufficiently low angular velocity. Also, although the angular velocity must be monotonic it is desirable but not essential that it be uniform. The design of the crystal table and crystal table drive evolved to satisfy these requirements may be seen in Figures 11 and 12.

The crystal table A is made of Meehanite cast iron for dimensional stability and is roughly a cylindrical plate 18.5" in diameter and one inch thick. A 3-1/2" diameter hub on its upper surface serves to position the crystal mount as a unit about the vertical axis of the crystal table. A tapered bore in the center of the table is accurately lapped to fit a taper on the inner shaft, B, to which the table is rigidly fastened, and which supports the table.

Figure 10. Drawing of crystal mount ring system

PH 6-1082
8-15 56
B 4

Figure 11. Drawing of crystal table drive

Figure 12. Crystal table drive - blown up view

The inner shaft then rides on a pair of matched, precision class, 7 ball bearings, C, which are retained in the outer shaft, D. The outer shaft is supported directly on the pintle, E, to which it is bolted. The precision bearings are made with an accuracy such that the concentricity of the inner and outer races when rotated relative to one another through 360° does not vary by more than 0.0001". The location of the maximum runout on each bearing race is indicated on each one so that the two bearing races used are oriented in their bearing seats in the outer shaft as a matched pair. That is, the location of maximum runout on each is aligned vertically to minimize the precession of the inner shaft. In addition, the upper and lower bearings are separated by as large a distance as possible, 4.830", so that the runout of the inner shaft and, therefore, of the axis of the crystal table is held to less than 0.0001" in a full revolution. Also the precision bearings may be preloaded by means of the locknut F, so that the load which the crystal table must carry does not introduce any play in the bearings. These design features then provide the fixed axis of rotation for the table perpendicular to the plane of the table and this axis is readily made vertical by adjusting mounting of the outer shaft on the pintle support.

Around the periphery of the crystal table there is machined a dovetail profile which relates to measuring the angular rotation of the crystal table and which is discussed under the description of the interferometer. It is required that those surfaces of the dovetail which define the outside diameter of the crystal table be concentric to within 0.0002" all around the table. This tolerance was met by machining the dovetail with the table mounted on its own

inner and outer shaft and turning on the precision ball bearings. In the use of the instrument the maximum angle of rotation of the table will be 30° corresponding to first order diffraction of 20-kev radiation at a Bragg angle of 15° on both sides of the undiffracted beam. The errors mentioned previously can be further reduced by choosing that 30° range of the table rotation in which they are found to be a minimum.

The searching pattern for the capture gamma-ray energy spectrum from any source in the pile is made by rotating the quartz crystal from a Bragg angle of 15° one side of zero to 15° the other side of zero, zero Bragg angle corresponding to gamma rays of infinite energy. There are two ways in which the searching of the spectrum can be carried out. Either (1) the counting rate can be taken for discrete values of the Bragg angle with the crystal table moving stepwise, or (2) the average counting rate can be taken for a small range of Bragg angles with the crystal table rotating continuously. For this type of spectrometer the gamma-ray line widths, that is, the full-widths at half maximum height, $\Delta \theta$, are constant, depending almost entirely on the mosaic structure of the crystal. In general, $n \lambda = 2d \sin \theta$. For $n = 1$ and for small angles for which $\sin \theta \simeq \theta$ this gives $\lambda = 2d \theta$, or $\Delta \lambda = 2d \Delta \theta$. DuMond has found experimentally in his two-meter curved crystal spectrometer with a 1-mm thick crystal, that $\Delta \lambda \simeq 0.125 \text{ x.u.}$ ⁷ For the (310) planes of quartz $d = 1.175 \text{ \AA}$; hence the line width at half-maximum in terms of the equivalent angular spread of the instrument if the resolution were infinite becomes $\Delta \theta \simeq 5 \times 10^{-5} \text{ radian}$, or $\Delta \theta \simeq 10 \text{ seconds of arc}$. A reasonable

7. DuMond, Lind and Watson, Phys. Rev. 73, 1392 (1948).

number of points required to delineate a peak stepwise might be taken as 10 points, which would require turning the crystal table in steps of one second of arc for case (1).

With the obvious requirement that the crystal table rotate in extremely small steps, it becomes apparent that the mechanical design of such a drive system would be far less difficult if the table were to rotate continuously, even though the rate of rotation required would be extremely small. The rate of rotation required may be determined from an estimate of the counting rates to be expected. DuMond⁴ found his crystal to have a focal volume of 0.0075 cm^3 , which when scaled up to approximately an eight-meter instrument gives $\sim 1/3 \text{ cm}^3$. For most substances one mole equals approximately 10 cm^3 , so that our sources may be taken as about $1/30$ mole. The number of captures per second per unit neutron flux is then $1/30 \times 6.06 \times 10^{23} \times \sigma \cdot 10^{-24} = 0.02\sigma$, where σ is the capture cross section in barns. With a thermal flux of 10^{13} neutrons/ cm^2 sec we have a source strength of 2×10^{11} disintegrations/sec per barn of neutron capture cross section. The corresponding counting rate at the detector, C. R., can be given then as

$$\text{C. R.} = 2 \times 10^{11} \Omega \epsilon_r,$$

where Ω = solid angle subtended by the bent crystal,

ϵ = efficiency of detector and collimator combined,

r = reflection coefficient of the crystal.

The solid angle, Ω , per square cm of quartz crystal, is 2.7×10^{-7} steradian; the NaI detector efficiency $\sim 1/2$, and the collimator efficiency

$\sim 1/6$, giving $\epsilon \simeq 1/12$; $r \simeq 0.018$ for a six-mm thick crystal as scaled (assuming a linear dependence on thickness) from $r = 0.003$ for a one-mm thick crystal⁸ for 412-kev gamma rays. Thus C. R. $\simeq 80$ Cps./cm² of crystal for one barn cross section, at 412 kev gamma ray energy. Now for the full-size quartz crystal of 12 inches square to be used in this spectrometer, there would be about 150 cm² of effective area, and if we consider a lower limit of 0.1 barn for the neutron capture cross section, C. R. $\simeq 1000$ Cps. However, only a fraction of the total disintegrations will be in a given branch. As a lower limit consider a weak branch containing 1% of the transitions which would have a peak C. R. $\simeq 10$ Cps. If we now consider as reasonable an angular velocity of the crystal table of one second of arc per 10 seconds of time, we have for this 1% transition of 412 kev a C. R. $\simeq 100$ counts/second of arc, and for a counting period of 15 seconds a peak height of 150 counts.

The counting period was chosen to be of 15 seconds duration, followed by 5 seconds dead time during which the count rate is transferred to a chart recorder, making a total period of 20 seconds. The above value for the angular velocity is chosen so that the gamma-ray peaks will be adequately delineated with about five points over the upper half of each peak.

In addition to a constant slow speed for surveying the entire range of the energy spectrum it is also required that the crystal table drive be capable of a more rapid motion so as to move quickly from one part of the spectrum to another. The mechanical design of the drive to give the required slow and rapid motions is best described with reference to Figure 12 showing

8. Lind, West and DuMond, Phys. Rev. 7, 475 (1950).

an exploded view

The slow traverse drive is a differential gear system consisting of a worm, J, a pinion carrier, G, the set of 10 pinions, H, and the two spur gears, L and M. The spur gears differ from one another by one tooth; gear L has 361 teeth around its periphery, while gear M has 360 teeth. The ten pinions, H, are the same at each end and have the appropriate number of teeth to mesh with a 360-tooth spur gear. The bottom end of the pinions thus mesh with spur gear M while their upper ends do not quite mesh with spur gear L. Considering first only a single pinion instead of the set of 10, the functioning is as follows: The worm gear J drives the pinion carrier G causing the lower end of the pinion H to roll against the lower spur gear which is attached to still another gear N. The latter gear, N, a part of the rapid traverse drive, is locked against a second worm gear, K, so that the lower spur gear is unable to move. Thus the pinion as it is carried around by G is caused to rotate about its own axis. At the same time the upper end of the pinion is rolling in contact with the upper spur gear. Now if the number of teeth on both L and M were the same, the pinions would be free-wheeling and there would be no advance of the crystal table. However, since there is one tooth more on L than there is on M, the clearance between adjacent teeth on L is smaller than on M, or than that on the pinion itself, by $1/360$ of a tooth width. Thus as each tooth of the pinion bottoms on the spur gear L, the latter is forced to advance by $1/360$ of a tooth. In one complete revolution of the pinion carrier the spur gear and consequently the crystal table to which

it is attached is caused to advance by one tooth and we have here a stepdown ratio of 360:1. An additional stepdown ratio of 360:1 is obtained between the gears J and G and a further reduction of 100:1 between the primary motor drive and the worm J. Thus a total stepdown ratio of 1,296,000 to 1 is obtained, which, with a 27-rpm motor, drives the crystal table at the average rate of about 1 sec of arc in 20 sec of time.

With only a single pinion the advance of the table would come in steps too large for satisfactory delineation of the peaks. To reduce the size of these steps 10 pinions are used, and this then places further requirements on the additional nine pinions. Instead of having the 10 pinions equally distributed around the circle, each succeeding pinion is removed successively further from the preceding one by $1/10$ th of a pinion tooth spacing, i.e., by 6 minutes of arc. Thus the spacing between pinions one and two is $36^{\circ} 6'$, instead of 36° , between pinions two and three it is $36^{\circ} 12'$, etc. Furthermore, the teeth on the upper and lower end of each pinion must now be rotated relative to one another by an amount which is related to this increased spacing. Pinion No. 1 will have the teeth on both ends in line; pinion No. 2 will have the teeth on the upper end offset relative to those on the bottom end by an amount equal to 0.11 of a tooth; pinion No. 3 by 0.22 of a tooth; etc.

The rapid traverse drive operates through the worm gear K rotating the gear N. The worm gear J maintains the pinion carrier stationary while the rotation of the lower spur gear M attached to N causes the pinions to spin

about fixed axes of rotation. The upper half of the pinions in turn drive the upper spur gear L directly causing the crystal table to rotate without the stepdown ratio of 360:1 contained in the differential gear system. The rapid traverse rate is such that the crystal table makes one revolution in about one hour.

Interferometer

In order to be able to measure the Bragg angles precisely and to be able to delineate carefully the line shape of gamma rays an interferometric method was adopted. Such a method can be used for automatic scanning and furthermore can be used for absolute energy measurement as will be shown below.

As shown in Figure 3 the interferometer is arranged next to the crystal table. Figure 13 shows a closeup view of the interferometer and its orientation relative to the crystal table and Figure 14 shows a closeup view of the movable mirror of the interferometer and the pusher unit. As the table turns it pushes (by means of the pusher unit) the movable mirror of the interferometer. The distance that the mirror is moved is equal to $R \sin \theta$ where R is the radial distance from the center of the crystal table to the point at which the mirror is pushed and θ is the angle through which the table has turned. Since the optical path is changed by twice the distance moved we find

$$n \lambda_{gr} = 2 R \sin \theta$$

Figure 13. Interferometer showing location relative to crystal table

Figure 14. Close-up of interferometer pusher unit

where n is the order of the interference and λ_{gr} is the wavelength of the optical spectral line used (the green line from Hg^{198}).

If the interferometer has been set so that $n = 0$ when the spectrometer is set at zero Bragg angle, then when a Bragg maximum is found in the first order,

$$\lambda_{\gamma} = 2 d \sin \theta$$

where λ_{γ} is the wavelength of the gamma ray and d is the grating constant for the (310) planes. Therefore

$$\lambda_{\gamma} = n \left(\frac{\lambda_{gr} d}{R} \right)$$

The quantity in parenthesis is a constant of the instrument and if it is measured precisely one can then use the instrument for absolute energy measurements. Using the green line of mercury and R equal to approximately 10.5 inches one finds

$$E_{\gamma} \approx \frac{5 \times 10^6}{n}$$

where E_{γ} is the energy of the gamma ray in kev.

If one considers the limits of precision of the instrument one sees that in the expression $(\lambda_{gr} d / R)$ the poorest known quantity is d . This is known to 1 part in 25,000 - 30,000. The wavelength of λ_{gr} , 5461 A. U., is known to 8 significant figures. The quantity R need only be measured to 0.0001" in order that R be known to 1 part in 10^5 . If only relative measurements are desired then the constant $(\lambda_{gr} d / R)$ can be determined by using a precision

measurement of some gamma-ray energy.

By choosing R approximately equal to 10.5 inches and using the green line of mercury it is found that a displacement of the crystal table of 1 second of arc causes about a 5-fringe shift of the fringe pattern in the interferometer. This means that by counting only an integral number of fringes one can delineate with great detail lines whose widths at half-maximum are about 15-20 seconds of arc.

The interferometer that is used is of the Twyman-Green type. In such an interferometer it is required that accurately parallel light be used. The components of the interferometer are shown in Figure 13. Since the lowest energy of the γ rays to be studied is 20 kev it is required that nearly 250,000 orders of optical interference be counted. For this purpose a light source that is monochromatic is needed. A Hg^{198} electrodeless discharge tube, A, is used for this purpose. It is excited by a 250-megacycle/sec oscillator, B. The green line passes through a band-pass optical filter, C, made of 4 mm of didymium glass and 2 mm of heat-resistant yellow glass. The light then passes through the condensing lenses, D, and is focussed on an 0.020" hole at the focal point of lens E. The parallel light then strikes the primary beam splitter F. A compensator, G, is placed in the fixed arm so that white light fringes may be obtained. The white light fringes are used to find the position of the zeroth order. The fixed mirror, H, can be moved so as to place the position of the movable mirror, J, near the center of its travel when the crystal is at zero Bragg angle. The front surface mirror,

K, is used to turn the reunited beams 90° into the lens L which then focusses the light on a pin hole in front of the photomultiplier M. A second beam splitter inside the housing, N, is used to send some of the light through the periscope, P, for purposes of monitoring the fringe pattern and fringe counting.

Lenses E and L are achromats of 3" diameter with 16" focal length. The two beam splitters and compensator are $2\frac{1}{2} \times 3\frac{1}{2} \times \frac{1}{2}$ " thick and are flat to $\frac{1}{5}$ of a fringe and parallel to $\frac{1}{4}$ fringe. The splitters have a dichroic coating so as to minimize absorption.

The fixed and movable mirrors are flat to about $\frac{1}{4}$ of a fringe. Two types of mirror mounts were built. In one a pair of mirrors mounted at 90° to each other (dihedrals) is used (A and B, Figure 14). The members of the pair are adjusted individually. In the second type of mount a single plane mirror is used. In all cases where mirrors or optical flats are adjusted, a three-point adjusting system is used. The three points (i. e., C, D, and E, Figure 14) form the vertices of a right triangle. The three points were in all cases located on the jig-borer. The dihedrals were built so that in case the ways, F, on which the movable mirror travels could not be machined precisely then a rocking of the mirror mount about the dihedral axis would not affect the fringe pattern. The ways were machined to be parallel to 0.0001" per foot.

The movable mirror follows the motion of the crystal table through the intermediary of the pusher unit consisting of a dovetailed clamp, G, and precision steel ball, H. The clamp is attached to the dovetail on the crystal

41
table, J. The pusher unit pushes against the two lapped steel blocks, K and L, which are mounted so as to be accurately parallel to each other and perpendicular to the direction of travel of the movable mirror. One of the blocks, L, is spring loaded so as to squeeze the precision steel ball. The pusher unit may be moved so as to fit anywhere along the dovetail on the crystal table. In practice, the combination of interferometer and pusher unit serves as a very precise device for testing the smoothness of the crystal drive system.

Collimator

Since the Bragg angles are very small, the direct beam and the diffracted beam will overlap unless one moves many meters back from the crystal. Instead of so doing a tapered baffle collimator is used. The baffle consists of a set of plates of absorbing material which is arranged with tapered spacers between the plates. The taper is chosen so that the channels between the plates all focus on a line which corresponds to the location of the virtual gamma-ray source.

The plates may be made so as to conform to the necessary taper or they may be flat. In the former case the transmission curve of the baffle is triangular, whereas in the latter case it is trapezoidal. The flat top of the trapezoidal transmission curve permits a little more leeway in the assembly of the collimator.

In designing such a baffle one must first choose the overall length of the channels. In addition, one must consider that the direct beam, which is

to be absorbed as completely as possible by the baffle, is between 10^3 and 10^6 times more intense than the diffracted beam. Furthermore, a maximum value of the energy for which the undiffracted beam will be entirely excluded, i. e., minimum angle of deviation between direct and diffracted beam, must be chosen. This value was chosen to be about 5 Mev.

Figures 15 and 16 show two views of the collimator box and supports. The nose piece A is tied to the box B and supports the front end of the box via the inner ring and the inner support ring (see Figures 2 and 29). The tail section C of the collimator is used to tie to the box the rear support wheels which ride on the track (see Figure 2).

The collimator is designed to have a theoretical transmission of 50%, i. e., equal thicknesses of channels and plates at the forward end. This choice is the optimum for our requirements. Figure 17 shows a cut-away view of the assembly of the collimator and collimator box. The collimator plates are made of lead containing 5% Sb. The plate spacers are tapered steel shims which were machined with the taper uniform to 0.0001" as measured at 10 equally spaced locations. The vertical (magnesium) spacers and spacer (lucite) buttons were used to minimize the free span of lead so as to reduce buckling of the lead. In the central channel the magnesium vertical spacers were replaced by lucite ones so that one can sight through the collimator for alignment. Magnesium was chosen for all but the central vertical spacers instead of other light elements, for example, Be or lucite, so as to avoid materials that would scatter neutrons. This was done so as not to pre-

Figure 15. Front view of collimator assembly

Figure 16. Overall view of collimator assembly

Figure 17. Diagram of method of assembly of collimator plates

clude using the collimator for experiments with neutrons.

The assembly required 108 lead collimator plates each 0.0395" thick x 11" high x one meter long. The thickness must be held very precisely if one wants the collimator to be useful over its full aperture. The collimator plates were rolled flat and to a uniform thickness on a 10-foot planer.⁹ A 2" thick steel plate that had been ground flat was mounted on the planer bed. A pair of 0.0395-inch ground steel shims over a meter long were bolted to the plate parallel to the direction of the bed of the planer. A stainless steel roller was mounted on the planer head. The rolling was done by bringing the head down in small steps and rolling the lead from an original thickness of 0.043" down to a final nominal dimension of 0.0395". By this method and by using great care in handling (using vacuum handlers) the nominal dimension was held to within 0.0001" over the entire area of each plate.

In choosing the appropriate material for the plates consideration was given to the use of some other heavy material having greater rigidity and higher absorption coefficient. For example, an element with a greater density than that of Pb would permit one to use thinner plates with larger spaces, i. e., a greater than 50% geometrical transmission for the collimator design. Among the elements considered in this connection were U, W and Au. Uranium cannot be used because of the background of γ rays from its decay products which would be counted by the NaI crystals. Tungsten is eliminated because tungsten sheets of the size required have not been made as yet and a major research effort would be required. Furthermore, the cost would be prohibitive. The use of gold was considered and while the material could be

9. C. S. Kipfer, Amer. Machinist, 99, 109 (Feb. 28, 1955).

4-1
made available the sheets could not be rolled by precious-metal workers to the precision required for the assembly. The comparatively low cost of the Pb-Sb alloy was also a great advantage.

The method of assembly that was used is shown in Figures 18, 19 and 20. The collimator was assembled in a horizontal position, i.e., with the box (and plates) turned 90° from its normal vertical direction. One collimator side plate and one collimator body plate of the two-inch thick steel collimator box were bolted together and mounted on a large surface table. The above unit was levelled so that when the center channel (the 55th) was reached the assembly would be exactly horizontal.

One serious problem in stacking a large number of plates and spacers is that the overall thickness of the assembled stack will exceed the sum of the dimensions of its components. This is due to the fact that all the air cannot be squeezed out from between adjacent parts, nor would one want to squeeze the lead sheets to such an extent. Even a very small such regular error between each of the lead plates and spacers would very soon eliminate focussing in the remainder of the channels. To avoid this the following stacking procedure was adopted:

The steel plate spacers were made 8" longer than necessary, i.e., they tapered from about 0.039" to 0.050". A subassembly of ten collimator plates, plate spacers and vertical spacers was assembled on the surface table as shown in Figure 18. One of the collimator side plates was set on top of this assembly as a convenient means of providing a reasonable amount of

Figure 18. View of collimator during assembly showing sub-assembly of 10 plates and spacer units

compression and the height of the subassembly was checked at its four corners (see Figure 19). The oversize steel spacers were then adjusted so as to make the heights at the corners conform to the previously calculated build up, using gage blocks and 0.0001" dial indicators to check this, as may be seen in Figures 18 and 19. With this done, the spacers were then cut to size and notched, and the unit of ten was reassembled in the collimator box. This procedure was repeated with the next subassembly of 10, etc. When the central channel was reached it was found to be horizontal to within 0.001". Figure 20 shows an end view of the partially assembled collimator.

After reaching the 108th plate, a 1/2" thick lead spacer was placed on the stack. The other collimator side and body plates then were bolted into place completing the box. In tightening these bolts, they were not drawn up snug since the pressure on the lead collimator plates could be adjusted by using these bolts. The collimator box was then turned so that the channels were vertical. The side plate added last had been provided with several set screws which bottomed against the edge of one of the body plates, and by means of which the side plate could be sprung slightly free along this edge. By this means the lead collimator plates were allowed to hang free at their bottom while held tightly along their upper ends only. After several hours the visibility through the central channel was seen to improve considerably and the box was completely buttoned up.

The collimator transmission was measured by using a Au^{198} source of 411.8-kev gamma rays in the form of a foil 0.001" thick and 1 cm on a side.

Figure 19. Method of checking sub-assembly of 10 plates

Figure 20. Completed assembly of about half of the collimator

The foil was held in a thin aluminum sandwich in which it was irradiated in CP-5. The above unit was held in a large lead cylinder which had an appropriate opening and faced the collimator which was 8.4 meters away. One of the detector units (see Figure 21) was used with a single channel pulse height analyzer to check the transmission. The latter was measured at 9 places over the area of the collimator.

In the first assembly of the collimator the lucite spacer buttons (see Figure 17) were omitted. It was found that that section of the collimator which had been assembled first, i. e. , the lowest set of plates in Figure 20, had a very low transmission and a weighted average transmission of about 12% out of a possible 50% was obtained. The collimator was then re-stacked with the lucite spacer buttons, and the transmission rechecked. By slight adjustments of the pressure on the plates (this was done by using additional shims and tightening the side plates) a final overall transmission of 28.5% was obtained. This value is the geometrical transmission, i. e. , it does not include the attenuation introduced by the 5 Mg vertical spacers which varies with energy.

Detector

The diffracted gamma-ray beam that emerges from the 8" aperture of the large crystal clamp block diverges to over 10" in diameter (1" per meter) by the time it reaches the back end of the baffle collimator. In order to detect the diffracted beam with high efficiency an array of NaI (Tl) crystals is used. Figure 21 shows an individual detector unit and the "egg crate" A containing the array of 16 units. Each unit consists of a crystal, B, $2\frac{3}{8}$ " $\times$ $2\frac{3}{8}$ " in area and 2" thick in the direction in which the gamma rays travel.

Figure 21. Detector-showing individual unit and array of 16 units making complete detector

Each crystal is packaged in a thin-walled aluminum can. Between the can and the crystal is the customary layer of MgO. Each crystal has its own photomultiplier, C, as a detector of scintillations.

The array provides a detector volume of about $10\text{-}1/2 \times 10\text{-}1/2$ inches in area and 2" deep. The photomultipliers are all connected in parallel and feed a single preamplifier, D. The pulses from the latter are analyzed in a single channel pulse height analyzer. Pulse height analysis is used so as to minimize background and to avoid overlap of orders in the diffracted beam. The high voltage is supplied to the photomultipliers from a single power supply. Each photomultiplier has a variable resistance connected in series with its branch of the high voltage supply. By adjusting these resistances the sensitivity of each of the detector units may be adjusted independently.. In carrying this out it is important to keep the high voltage on at all times. Even a short shutdown of the high voltage will produce instabilities in the system.

The detectors were usually adjusted with a Cs^{137} source of 663-kev gamma rays. The resolution of the array of 16 crystals and tubes at 663 kev was found to be 15%. It should be pointed out that the latter figure has no bearing on the resolution of the gamma-ray spectrometer.

The window width of the single channel analyzer can be changed manually and is set at an appropriate value. The center of the window on the analyzer can be varied either automatically or manually as the detector drive system moves.

Optical Lever

In order to avoid any mechanical interaction between the motion of the very massive collimator and shield (14 tons) and the crystal table, the latter was isolated mechanically from the former. The method of accomplishing this isolation is described later. However, as in all diffraction spectrometers, the detector must rotate at twice the angular speed of the diffracting crystal. This condition requires some sort of linkage between the crystal table and the collimator, which carries the detector. The type of linkage chosen is an optical one.¹⁰

The optical lever consists of three main sections as shown in Figures 2 and 3. Part I is attached to the front of the baffle collimator and consists of a light source and condensing lens which focusses the light onto a slit 0.001" wide which is mounted vertically. This slit is at the focal plane of a 3" diameter, 15" focal length lens. The parallel beam of light which emerges from this section strikes a front surface mirror which is the second part of the optical lever system. Figure 22 is a closeup view of the mirror, mirror holder, and mount looking at the back of the mirror. The mirror is 6"x 3-1/2" x 1/2" thick and is flat to 1/2 a fringe. The mirror mount is a ring structure similar to the one used in mounting the crystal and described earlier. It is necessary that the front surface of this mirror be oriented so as to be exactly vertical and also to contain the central axis of the crystal pivot.

10. F. S. Tomkins and M. Fred, Jour. of the Opt. Soc. 41, 641 (1951).

The basic idea for the optical lever evolved from the system described in this paper.

Figure 22. Optical lever mirror and mirror adjusting ring system

The beam of light emerging from this mirror then enters Part III, the sensing unit of the optical lever. This unit is located on a heavy concrete pedestal located to one side of the base of the spectrometer. The beam of light reflected from the mirror enters lens A, Figure 23, which is 3" in diameter and 16" in focal length and is focussed onto the slit B which is 0.004" wide and is in front of a photomultiplier, C. On the pedestal is a reference light system, D, similar to the one just described but of smaller scale. This system focusses a light beam from another 0.001" slit onto a second 0.004" slit in front of a second photomultiplier E. The two beams of light cross at right angles at the center of a 4-sided glass prism F which is mounted so as to rotate about an axis which passes vertically through the point at which the beams cross. The glass prism is rotated at 1675 rpm and 4 pulses of light are detected by each photomultiplier in each revolution. It is clear that only when near normal incidence on the prism will the light be able to enter the slits in front of the photomultipliers. With the dimensions used the angle was limited to 25 minutes of arc on each side of normal incidence. The theoretical pulse shape is trapezoidal and is pictured in Figure 24. In practice the sharp breaks are rounded off.

The beam of light emerging from the light source on the collimator and then reflected from the front surface mirror will be unchanged in direction if the collimator is rotating at exactly twice the speed of the crystal table. The pulses in the two photomultipliers will have a definite phase relation to each other. If the collimator is not following at the correct 2:1 speed then the phase relation between pulses is changed. The two photo-

Figure 23. Optical lever sensing unit

Figure 24. Theoretical pulse shapes from optical lever sensing unit showing phase shifts due to misalignment

multipliers are connected to a coincidence circuit whose output is proportional to the time displacement of the pulses. The latter is related to the changed phase relation mentioned above. This output is fed through a servomechanism system to the collimator drive and causes it to speed up or slow down to re-establish the 2:1 ratio of speeds.

It can easily be shown that if the beam from the mirror deviates by an angle δ from the correct direction then the phase shift of the pulses will be proportional to the time required by the prism to rotate through an angle ω , where

$$\omega \simeq \frac{3 f \delta}{t} - \delta$$

f being the focal length of the lens A, 16", and t is the thickness of the prism, 1 inch. For an angle δ of 5 seconds, ω is equal to about 250 seconds of arc. This corresponds to a time shift of 7 microseconds between the two pulses. Figure 24 shows the way the pulses shift due to a failure of the drive to follow the required 2:1 motion. It should be pointed out that the times between successive pulses to a given photomultiplier are nearly 9,000 microseconds.

With this method of controlling the spectrometer the 2:1 ratio of speeds is easily maintained. The collimator is always within 4 seconds of arc of its proper location. Since the opening angle of the channels in the baffle collimator is nearly 8 minutes of arc, the optical lever is seen to operate in an entirely satisfactory manner.

Collimator Drive

As was indicated, it is necessary to maintain the appropriate 2:1 ratio of the angular speed of the collimator-detector system with respect to

that of the crystal table. To accomplish this the output from the optical lever control system is applied to a Brown servo balancing motor, A, Figures 25 and 26, which controls the output speed of a Vickers hydraulic transmission, B. The hydraulic transmission provides a variable speed output with constant torque and is particularly suited for this application because it can be used for continuous, intermittent, or continuous reversing service (and can be stalled indefinitely under load without damage). There are two such transmissions, B and C, used on the collimator drive, one each for slow and rapid speeds; two 1/4 hp motors, D and E, power the two transmissions. Of the two wheels that support the rear of the collimator box, only one, F, is the drive-wheel.

The average angular speed of the crystal table on slow traverse drive was shown to be 1 sec of arc in 20 sec of time. The corresponding angular speed of the collimator-detector system must then be 2 sec of arc in 20 sec of time. With the collimator wheels 15-3/4" in diameter riding on a track of approximately 102" radius, the required angular speed of the drive wheel is about 6 sec of arc in 20 sec of time. Thus the requirements on this drive system are not very different from those on the crystal table drive. In fact, the gear system used for obtaining the slow and rapid speeds here is exactly the same as that used in the crystal table drive and described on page 26, except that the spur gears L and M, Figure 12, have 201 and 200 teeth, respectively, instead of 361 and 360. One other difference is that the worm gears (J and K, Figure 12) are in this case housed in separate worm blocks.

Figure 25. Collimator drive; direct view

Figure 26. Collimator drive; side view

Only one of these, J, is visible in Figure 25. Each worm gear is driven by its own hydraulic transmission, B and C, respectively.

The servo control mentioned above applies only to the slow speed drive, which is used in the normal survey of a gamma-ray energy spectrum. The rapid speed drive on the other hand may be manually controlled to move the collimator-detector unit relatively quickly from one place to another (distances that might otherwise take several weeks to traverse on slow speed). The manual control is in this case also fed to a Brown servo motor, G, which controls the output speed of hydraulic transmission C.

Bulk Shield Carrier and Drive

Under the description of the detector units it was pointed out that the NaI used amounts to about $10\text{-}1/2 \times 10\text{-}1/2$ inches in area and 2" thick. With this large volume of NaI the general room background would be too large without considerable shielding. The detector unit is therefore enclosed within a large bulk shield of lead whose walls are 12" thick on all sides, except its front face into which the channelled collimator is placed. In Figure 27 can be seen a view looking into the bulk shielding taken during its assembly. Most of the bulk shielding is built up of Radioprotecto shaped lead bricks, A, contained within the steel, box-like structure, B. Access to the detector unit is through the extreme rear when the large lead door, C, is raised. The lead door which is shown partially raised in the figure is lifted by means of a long stroke hydraulic jack, D. Operation of this jack has been made automatic by means of an hydraulic pump (see Figure 3).

In addition to the shielding contained within the box B, a front section of lead, E, is added to prevent background radiation from entering through the relatively thinner side walls of the collimator box. The way in which the shield is built up to completely enclose the collimator-detector unit may be seen in the isometric drawing, Figure 2.

As stated earlier, the collimator-detector unit is completely separate from the bulk shield, being "threaded" through a 16 x 16" hole in the bulk shield which extends up to the lead door at the rear, and having the extended side plates of the collimator continuing on back to the wheels supporting it at the rear (see Figures 2 and 28). The reason for this separation is to simplify the problem of moving the relatively light (3/4 ton) collimator-detector unit in a very precise way without having to do the same with the heavy (12 ton) bulk shield. With a half-inch gap all the way around between the collimator box and the bulk shield there is adequate leeway for moving the bulk shield carrier with much less precision. The gap that results in the bulk shield to provide this clearance is effectively blocked off by means of a 4" thick lead "horse collar", a part, F, of which is shown in Figures 27 and 28, which is attached to the front of the collimator, and by the lead-filled section, G, of the collimator nose piece, H.

The heavy shielding described above required a massive carrier, J, which is built up of a 12" steel-channel framework, made integral with the steel box B, and support plate, Z of Figure 28, for the shield E. The front end of the shield carrier is attached to the outer ring, K, which rides on the

127

Figure 27. Bulk shield and carrier; side view

Figure 28. Bulk shield; front view

outer ring support, L. The outer ring support is L-shaped in cross section (as may be seen in Figure 29) and is bolted to the primary base, M. The outer ring K contains two sets of wheels. One set of wheels, N, consisting of six bearings, maintains a horizontal alignment; another set of two wheels, P, constitutes the vertical support. The back end of the shield carrier is supported on two 15-3/4" diameter wheels, Q, which ride on the same track, T, as the collimator rear wheels, and whose axles carry the load of the shield carrier by means of two large bearing boxes, S.

With the bulk shield carrier, as with the channelled collimator, only one of the rear wheels, Q, is a drive wheel, the other being an idling wheel. On the drive wheel is attached a differential gear system identical to the one used on the collimator. In fact, the entire drive mechanism is identical to that described on page 33, except for the method of servo control of the hydraulic transmission's output speed.

With reference to Figures 25 and 26 we see that for the shield drive the output speed controls of the hydraulic transmissions H and I are physically connected to the collimator-detector unit by means of the mechanical links, K and L, respectively, which cause the shield carrier to follow as a slave system. In practice it turns out that the heavy bulk shield carrier moves very readily, and with the mechanical linkage used to control its speed, it is necessary to limit the rate at which the collimator drive starts up or changes speed so as to maintain the clearance between the collimator and the bulk shield. Should the shield carrier overtake the collimator it is possible for it

Figure 29. Cross-section showing central ring structure and primary supports

to override the collimator drive and affect the alignment of the collimator and crystal. To prevent this, there are stops on the speed control of both the slow and rapid traverse hydraulic transmissions on the collimator drive limiting the angular rotation of the servo motors, and spring loading to return them to their zero setting. In addition there are limit microswitches which cut off the collimator, shield and crystal table drives if the collimator and shield approach too closely, and all data taking is halted until the source of trouble can be corrected.

Conical Motion

The outer surfaces of all the wheels, P, Q, and R, Figure 29, are tapered and ride on tapered surfaces on the inner and outer support rings, L and S, and the track, T. Each of these tapered surfaces is a section of a cone whose apex is located as accurately as possible on the vertical center line of the pintle U. The philosophy here is as follows: if one considers a perfect cone rolling on a perfectly machined, fixed conical surface, the apex of the rolling cone will remain fixed in space without being physically tied down, with no reaction at the center pivot. Here the fixed conical surfaces are the tracks L, S and T and the rolling cones are the respective wheels. Within the accuracy of machining and aligning these components, the reaction of the motion of the collimator shield carriers at the pintle, and therefore on the crystal table axis, is held to a minimum.

As may be seen in Figure 28, the primary base, M, of the spectrometer is shaped roughly like a sector of a circle, and its large size may be estimated from the yardstick included in the photograph (just in front of the pintle). It is made of Meehanite cast iron for dimensional stability and weighs 7 tons. Figure 29, a cross section through the center line of symmetry, shows the important parts of the base and illustrates the ribbed understructure. The inner and outer support rings are bolted to the primary base with the vertical axis of the pintle as center with respect to their machined, outer, vertical surfaces. The track, T, is bolted down to a machined surface along the rear of the base again with the vertical axis of the pintle as center. The load of the collimator and shield is carried by the primary base along this rear track surface and at the central ring system, and is transmitted to the floor along the rear periphery and through the pintle, with approximately two-thirds of the load being carried at the pintle.

The pintle carries the center load without having the base physically tied to it. A split ring, V, is located in a groove around the periphery of the pintle, and a lip on the inner support ring rests on the split ring. The inside diameter of the hole through the inner support ring and the primary base match very closely the outside diameter of the pintle to minimize lateral play. The position of the pintle therefore locates this central position of the primary base. The position of the pintle in turn is located with respect to the floor by means of a 3" steel ball, W, and the two tapered inserts, X, Y, located in the bottom of the pintle and in the floor bolster, Z. This latter positioning is quite positive

since for the center position of the pintle to shift, it is required that a load of about 17 tons must be lifted up on the spherical surface of the large steel ball. The floor bolster itself is locked in its final fixed position by means of adjusting bolts, a, working against a steel box, b, grouted in the concrete floor.

Along the rear of the primary base the load is carried by 50 set screws, d, threaded through the base and resting on steel blocks on the concrete floor. These set screws were used in leveling up the base. The set screws, e, located around the remaining periphery of the base were drawn up just snug without carrying any load, but rather to help the base casting resist deformation as the heavy load is moved from side to side.

In-Pile Components

The in-pile components are shown schematically in Figure 1 to consist of a source located at the center of the reactor in a straight through hole; a source monitor slit and source monitor counter located at the "source" end of the hole; and tapered lead and bismuth collimator located at the "crystal" end. Figure 30 shows in greater detail a cutaway section of the reactor.

The hole through the reactor consists of two 9" dia. tubes, A, for a five-foot section near the two opposite faces of the reactor which neck down to a 6" dia. tube, B, through the central section. Into these fixed reactor tubes it was necessary to insert the spectrometer components with allowances for adjustments to be made during alignment. First, by means of a telescope

Figure 30. Cut-away view of source tube in reactor

and reticule located in each of the 9" dia. tubes at the opposite faces of the reactor, a fiducial center line was established through the hole in the reactor and the future crystal pivot location. With reference to this fiducial line in-pile components were inserted as follows: First the outer lead annulus, C, at the "source" end was inserted into the 9" dia. tube. This lead annulus has attached to each end face a set of three set screws, D. By means of a reticule located at each end and accurately centered in the hole through its center, the outer lead annulus was adjusted to be in line with the fiducial center line. Next a 9" O.D. steel tube, with a 5-1/2" O.D. aluminum tube, E, flanged and attached to it, was inserted from the "crystal" end of the reactor. The 5-1/2" tube is long enough to pass all the way through the reactor and end flush with its opposite face, and is threaded through the outer lead annulus. It formed a very close fit with the inside diameter of the outer annulus so that that end of the 5-1/2" tube was thereby also aligned. The walls of the 9" dia. steel tube contain set screws with which both it and the attached end of the 5-1/2" tube were aligned to the established fiducial center line. The 5-1/2" outside diameter of the aluminum tube provided for adequate clearance between it and the reactor tube B to prevent any future deformation due to thermal stresses in the reactor tank (not shown).

The tapered collimator (see Figure 1), inserted into the reactor from the "crystal" side, is for the purpose of limiting the material other than source material which the quartz crystal "sees" as described on page 13. The outside diameter of the lead section of the tapered collimator is a close

fit with the inside diameter of the 9" steel tube and of about the same length. Attached to the inner face of this lead section is an 18-inch long bismuth section, also with a tapered hole, whose outside diameter is a free fit inside the 5-1/2 " diam. aluminum tube. The machining tolerances are such that with the close fit indicated between the lead and the steel tubes, the alignment of the tapered collimator is as required. In addition there was inserted an additional foot-long bismuth section with a reverse taper to protect the mouth of the other bismuth collimator. Also the reverse taper is such as to further limit the location inside the reactor "seen" by the quartz crystal.

All the above-mentioned components remain fixed in position in the reactor. The only component which is moved in and out is the source tube, F. The source tube has an outside diameter of 5" and rides by means of roller wheels, G, within the tube E with inside diameter 5-1/8". A short detachable section of tube, the source nose piece, H, rides at the front of the tube F and carries the source, I. The source nose piece has graphite shoes, J, as glides. The source itself may consist of any suitable element or isotope which can be prepared as a foil or contained in a sample holder. The source dimensions are 10 cm high, 2 cm deep (the axial direction of the reactor hole) and 1-20 mils wide. The source holder, K, is a double yoke frame; the source is attached to the ends of the inner yoke while it is sprung inward slightly, then the inner yoke is stretched by being drawn tightly to the outer yoke, thereby drawing the source taut and straight. The outer yoke of the source holder is carried by the source nose piece via two pivot pins, L. A source alignment rod, M, which is attached to the outer yoke each time the nose piece and source

tube are assembled, provides a means of rotating the source about a vertical axis from outside the reactor. The nose piece is held fixed to the source tube by means of two tie rods, N, which extend to the far end of the tube, at which point they are held fixed by spring loading. In this way the nose piece with a "hot" source can be dropped off remotely when the source tube has been removed from the reactor. With the source nose piece firmly fixed to the source tube, the two additional adjustments required for the source are made externally on the source tube itself. First it is possible to rotate the whole unit about the axis which is the center line through the reactor hole; and second it is possible to move the source in and out along this axis a total of 10 inches. This latter adjustment is made by means of a lead screw threaded in the adjusting boss, P.

Once the source has been properly positioned within the reactor hole it is necessary to be certain that this position is maintained. To do this a source monitoring system is used which will detect any lateral shift of the source and any change in power level of the reactor. The source monitoring collimator, Q, consists of three sections; an inner section of lead with a 0.003" wide slit, 4" long; an outer stainless steel section with a 0.003" wide slit, 2" long; and a central section of stainless steel with a slit about 0.010" wide, 26" long. The separation of the two 0.003" slits is such that the width of source seen at the source position about 10 feet away is just 0.020", which is equal to the actual maximum width of source to be used. Under these circumstances any lateral shift of the source results in a decrease

in gamma-ray intensity passing through these collimator slits and is detected by the source-monitoring counter. The counter is a NaI (Tl) crystal and photomultiplier which feeds a count rate circuit, which in turn records the count rate on an Esterline-Angus chart recorder.

The source-monitor collimator fits into one of the two inner lead annuli, R. The innermost of these annuli provides some additional shielding preceding the source-monitor collimator, with an oversize slit down its center, and both annuli are necessary to reduce the biological hazards and the background in the neighborhood of the source monitor. These lead annuli are contained within the source tube and move with it, but the source-monitor collimator remains fixed in position. Once it has been aligned with respect to the true vertical, its position is fixed by means of an extended arm, S, at its outermost end, which is fastened to the face of the reactor. The source tube may be moved in and out (within the prescribed adjustment limits) and rotated without affecting the alignment of the source-monitoring collimator.

Alignment of the source tube with respect to the previously established fiducial center line was carried out as follows:- At the source position a narrow slit was attached to the source holder centered just as the source itself would be. A centered reticule was then placed in the end of the source tube at the face of the reactor (with the source-monitor collimator removed). Then with the telescope set up on the established center line it was found that only the source end of the source tube needed any correction. This was done by adjusting the graphite shoes, J, until the slit simulating the source was

aligned both vertically and horizontally. The alignment of the source-monitor collimator within the source tube was then determined by the machining tolerances imposed and held on these components.

The source nose-piece and source holder are made of dowmetal (Mg-Al alloy). The parts of the source holder immediately adjacent to the source are made of beryllium to minimize the background coming from within the focal volume of the quartz crystal. Both the aluminum source tube and the aluminum tube in which it rides are a source of background which is strongest over the region nearest the location of the source. As was mentioned previously the tapered lead and bismuth collimators are for the purpose of limiting the region within the reactor "seen" by the quartz crystal. However, without the bismuth reverse-taper section (see Figure 1) there is a penumbra region in the gamma-ray beam which arises from this region of strong background source. The reverse tapered bismuth section and the concrete shield wall placed between the reactor and the quartz crystal eliminate the penumbra entirely. The concrete shield wall, as shown in Figure 1, has actually been replaced by a beam catcher filled with concrete and with a tapered hole through its center which passes only the umbral portion of the beam. In addition, the mouth of the tapered collimator has been plugged with 2" of paraffin backed up with 0.010" thick cadmium sheet to reduce the intensity of neutrons emerging from the hole.

IV. Assembly and Alignment

The components of the spectrometer and some of the procedures

are listed below in the order in which the assembly took place. Each phase of assembly and alignment which is of importance to the overall accuracy of the instrument is further described in detail.

1. Fiducial center line through the beam hole in the reactor;
the in-pile components
2. Floor bolster and the primary base of the spectrometer
3. Front ring system
4. Rear track
5. Bulk shield carrier
6. Channeled collimator
7. Interferometer
8. Crystal table and drive
9. Crystal mount
10. Mounting of the crystal clamp blocks
11. Optical lever
12. Locking together the crystal table and collimator.

1. The establishment of the fiducial center line through the beam hole in the reactor and insertion of the in-pile components was carried out during the early stages of construction of CP-5. It was thus possible to use optical techniques in aligning these components. The procedure followed has already been described fully in Section III, page 72.

2. The location of the floor bolster, as was indicated on page 71, determines the location of the pintle and the primary base. The pintle, in turn, determines the location of the vertical axis of rotation of the crystal

table which must be located a distance 7.7 meters from the nominal position of the source in the reactor and must intersect the fiducial center line already established through the hole in the reactor. The 7.7-meter distance is not very critical since there is available ample adjustment of the position of the source in the reactor. However, the axis of the crystal table should both be vertical and intersect the fiducial line to the highest degree of accuracy attainable.

The steel box (b of Figure 29), in which the floor bolster sits, was located at the approximately correct position at a depth below the floor level appropriate to the correct beam height, and grouted into place. A subassembly of the floor bolster, 3" dia. steel ball and the pintle was set in place. The pintle was at this stage supported by means of a detachable, cylindrical extension of the floor bolster. Thus, any horizontal adjustments to be made in the position of the pintle were applied through the adjustment screws of the floor bolster. The supporting cylinder also contained four set screws, diametrically opposed in pairs, with spherical ends so that the pintle could be rotated through 360° within its support. Also, by means of these set screws, the axis of rotation of the pintle could be made vertical; this was done next using a precision spirit level on the top surface of the pintle and rotating the pintle. Next, a plumb bob, suspended by a 0.001" dia. wire, was mounted on a suspension and attached to the top of the pintle. (Figure 31 shows the plumb bob suspension in an arrangement used later during alignment of the collimator.) The wire mount is adjustable in the horizontal plane, and by

Figure 31. Method of locating center of rotation of various components

rotating the pintle through 360° while sighting the wire through a short focus telescope, the plumb bob could be located on the axis of rotation of the pintle. With this done, and the pintle vertical, its axis of rotation could be made to intersect the fiducial center line established through the beam hole in the reactor. The position of the floor bolster was adjusted until the telescope sighting through the reactor hole showed the wire to be on the fiducial line. It was necessary to check to be sure that the pintle had remained vertical during the adjustment of the floor bolster, and, indeed, it had done so.

The crystal table (without its drive) mounted on its inner and outer shaft was then placed in position on the pintle, and the plumb bob suspension was attached to the surface of the crystal table. The 0.001" dia. wire was located over the center of rotation of the crystal table just as had been done before, and the alignment of the table axis with the fiducial center line checked. It was found to be exactly in line. Coincident with this the crystal table was found to be rotating in a horizontal plane on checking with the precision spirit level riding on the table top. The crystal table, shafts and pintle were then removed in preparation for placing the primary base in position.

The primary base casting is actually made up of two halves, mirror images of each other, bolted together on their line of symmetry and keyed into position. The base casting was set in position and the center bore into which the pintle fits was centered over the floor bolster to within $\pm 0.001''$. The two halves of the base were then separated temporarily so that the pintle

with its split ring attached could be inserted. The outside diameter of the pintle and the inside diameter of the center bore in the base are a close fit so that with the two halves of the base bolted together, the location of the base determines the position of the pintle. The weight of the base is supported on the pintle via the inner support ring (see Figure 29) which was next put into place. The base was then leveled by adjustment of the set screws along the rear, and, once leveled, the load was also distributed to the support screws along the remaining periphery of the base. Once again the crystal table and shafts were mounted on the pintle and the plumb bob located on the table axis. The crystal table axis was found to be located still on the fiducial center line and the crystal table found to rotate in the horizontal plane.

3. To locate the inner and outer rings coaxial with the crystal table axis a 0.001" dial indicator was mounted on an extension from the crystal table. The inner ring was then located so that its vertical machined surface was centered with a minimum runout. This amounted to 0.005" over 360° and a maximum variation of 0.002" over the full range required for the collimated travel. The inner ring support on which the front end of the collimator is supported was then set into position and the horizontal alignment wheels, f, (Figure 29) adjusted by means of eccentric shafts, g, until the ring support ran coaxially with the inner ring. The tapered wheels, R, of the inner support ring were found to run at the same height, to within 0.001", all the way around.

In the same way the outer ring was located with comparable accuracy and the outer support ring adjusted to run uniformly. In both cases, however, it was found necessary to correct slightly the taper on the wheels to match

that of the tracks on the inner and outer rings so as to obtain contact over the full width of the wheels.

4. The tapered track (T of Figure 29) was put into place next.

The track is actually made up of sections 16" long with the butting ends cut obliquely to the radii at about 45°. The vertical surface just back of the tapered face of the track is an accurately machined cylindrical surface which provides a reference radius for the assembly of the sections. The radius from the crystal table axis to the center of the track is 101.8125"; the radius to the reference cylinder is 103.2075". The actual value of this reference radius is not nearly as important as the uniformity along the entire length of the track. The track sections were machined on the same radius generating fixture used to profile the crystal clamp blocks.^{5,6} In setting up the generating fixture to machine this radius, using reasonable toolroom tolerances, an error in the value of the radius of as much as 0.1" could be made, but the uniformity of the radius could be held to one part in 10,000 or better.

The machined surface of the base on which the track sections were to be set was first made level by setting down 1/4" thick steel shim plates which were individually shimmed to provide a preliminary level surface. The track sections were set down on this level surface in as nearly perfect an arc as possible by the following technique. A length of 3" aluminum I-beam long enough to provide a radius arm for checking the reference radius on the track sections was attached to the inner ring support. Using a 0.001" dial indicator attached to the radius arm the track sections were set so that

the reference radius was the same along their entire length. The bolt holes in the track were then transferred to the primary base and the track sections dowelled in position.

The height of each track section varied from one piece to the next, and this was corrected for by individually shimming each section of track to match heights at the butting ends. In addition the taper of each track section was set correctly at this same time by using an angle plate having a taper matching that on the track. The angle plate was constrained to move circumferentially by means of the reference radius and a precision spirit level mounted on its upper flat surface checked the setting over each track section as well as between adjacent sections.

Later, after the bulk shield and carrier had been set in place, the track sections were again checked. This time a 0.001" dial indicator was attached to the hub of a carrier rear wheel and the pointer of the indicator rode on one surface of a precision parallel 48" long, set level with the precision spirit level. Some slight final corrections were made in some of the track sections at that time.

5. The bulk shield carrier was set in place next. The alignment requirements here are less stringent than on most other components. It is required that the drive wheels be at the appropriate radial distance from the pivot of the crystal table and that the unit ride roughly horizontal and with the height set so as to provide ample clearance for the collimator box and its extensions. The carrier was set for this proper radial position and the

wheels were attached to the bearing boxes at the rear. The rear of the carriage was set to ride horizontally and at the correct height by adjusting the positions of the bearing boxes (S of Figure 27) within their mounts. The front end was shimmed to the correct height and bolted to the outer ring support, as may be seen in Figure 27. The wheels at the rear were then aligned so that the axles were radial to the center of rotation. The wheels were blued and the length of contact along the track checked; one wheel contacted along about one-third its width, the other about two-thirds its width. The taper on each wheel was corrected slightly to match more nearly that of the track, and the contact on both wheels was improved to almost the full width.

With the bulk shield carrier properly positioned, the shaped lead bricks were stacked inside the carrier box. The sides were built up to the height (shown in Figure 27) at which the collimator box needs to be bridged, and the front lead section (E of Figure 27) was set in place. With this additional load in place, the level of the rear track was checked again, as mentioned above.

6. The channeled lead collimator box was set into place next with the front nose piece already attached, and the tail section was then tied on. The alignment requirements on the collimator are: that the center line through the central channel be on the fiducial line already established through the beam hole in the reactor; that the collimator be horizontal and located at the correct focal distance from the source; and that the collimator rotate about the crystal table axis as its center.

In the construction of the collimator box it had been specified that the front face of the box be perpendicular to the center line through the box and therefore to the center line through the central channel, to within 0.001" per ft. Also, the vertical face of the nose piece which is attached to the front face of the box was required to be perpendicular to an imagined extension of the above center line. The extension of this center line must then pass through the center of the circle of bolts used to tie the nose piece ring to the inner support ring. The location of the center of the bolt circle from the face of the collimator box was set to give the required distance from the crystal table axis to the channeled collimator. Figures 15 and 16 show the collimator box with the nose piece and tail piece attached, set up on a large surface table used to check the accuracy with which the tolerances were held, as well as to layout critical dimensions. Once checked out, the nose piece was dowelled in place on the front face of the collimator box. The tail piece was likewise located properly in the assembly on the large surface table and dowelled into place.

By referring to Figures 27 and 28, one sees how the collimator nose piece is attached to the inner support ring. The front end of the collimator box was set at the correct height by shimming between the nose piece ring and the support ring, and at the correct distance, to the required accuracy, by virtue of the location of the bolt holes. The collimator box was then made horizontal by blocking it up at the rear. The central channel of the collimator was then aligned with the crystal table axis. It was not feasible to reassemble

the crystal table on the pintle at the time since it was set up with the interferometer separately to check the crystal table drive. Therefore a duplicate of the outer shaft of the crystal table was made up and attached to the pintle with plumb bob, etc. riding on it. Figure 31 shows this arrangement as used to align the collimator. The plywood table shown here could be rotated and the 0.001" dia. wire located in line with the pintle axis as before and checked to be in line with the same fiducial line through the reactor. A narrow slit was centered in the central channel at the rear of the collimator. Using a telescope with a micrometer eyepiece to locate the center of the central channel at the front of the collimator, all three references were brought into line by making lateral adjustments on the nose piece ring and rear of the box.

With this alignment completed the ring on the nose piece and the inner support ring were dowelled together. The rear wheels and wheel brackets were then attached to the tail piece and the wheel brackets adjusted in height to maintain the collimator box level. At the same time the axles were adjusted to be radial by shimming between the wheel brackets and the tail piece, and then finally these were dowelled together.

The remainder of the shaped lead bricks was then set into the box and the lead door fixed in position. Also the other half of the front lead section E, Figure 27, and the lead horse collar F were added, and the box, G, of the nose piece filled with lead to complete the bulk shield.

7. The interferometer was the next component to be added to the assembly. Before doing so it was necessary to install the support plate R

(see Figure 11 and 12), which provides a support for the interferometer base as well as for the worm block of the crystal table drive. The support plate has a bored hole, S, into which an insert is pressed. The insert has a conical tapered hole in which a 1" dia. precision ball, T, sits. A corresponding insert in the underside of the interferometer base rests on this ball which provides a fixed support point. Two other support points for the interferometer base are provided by two legs which rest on the primary base casting and provide their support under the two arms of the interferometer casting (see Figure 13). For them a 1/2" dia. precision ball rides in between two V-grooves; the one in the bottom of the interferometer base is directed along the length of each arm, while the one in the top of the support leg is set at right angles to its mate.

The support plate had to be placed so that the interferometer would be clear of the arms of the collimator carrier and the bulk shield carrier. The pintle had already been oriented properly so that the bolt holes in the pintle and the support plate determined the latter's position. With the position of this one fixed support point determined, the remaining two support points needed to be located so that the ways (F, Figure 14) of the movable mirror slide would be tangential to the crystal table. Also the height of the supports required adjustment to make these ways horizontal, and, therefore, in the plane of rotation of the crystal table. To make and check these adjustments it was necessary that the crystal table be in position. The crystal table and drive were accordingly installed next, but a description of this procedure will

be deferred. Without the worm block attached the crystal table can be turned freely and could be used to check the alignments indicated.

The two support legs were located so that the ways were approximately tangential to the crystal table when the movable mirror slide was at the middle of its range of travel. A precise adjustment of the tangency requirement is equivalent here to setting the zeroth order of optical interference coincident with the position of the crystal table at which the pusher ball, H, Figure 14, is at its furthest position within the two parallel blocks K and L. This precise setting is being deferred until the absolute energy measurements are to be made, at which time an optical technique will be used to make this adjustment.

The base plates of the two support legs have four set screws (with locknuts) in them, as may be seen in Figure 13, by means of which the interferometer base could be leveled. A 0.0001" dial indicator was mounted on the crystal table and was used to indicate along the direction of the ways. Adjustment of the support legs then made the ways coplanar with the crystal table. It should be mentioned that the interferometer base was installed with all the interferometer components, except for the dihedral mirrors and their mounts, in place. These are readily removed or attached without upsetting the orientation of the mirror significantly.

8. The crystal table and drive and the interferometer had been set up separately to check out the behavior of the drive mechanism. It was thus only necessary to reassemble these crystal table and drive components in

place on the pintle and the support plate. The base of the outer shaft was set into the bore in the top of the pintle before the support plate was set down. A central hole in the support plate provides clearance for the outer shaft. Reference to Figure 12 makes apparent the way in which the gear drive and table are assembled. The crystal table had already been shown to rotate in the horizontal plane. One further check was made at this time. The runout of the crystal table was checked with a 0.0001" dial indicator reading the lapped surface around the edge of the table. Less than 0.0001" runout was detected in a full revolution of the table, which was better than the specifications called for.

9. The crystal mount was next set in place on top of the crystal table without any alignment of the mounting plate for the crystal clamp block, A, Figure 10, being made at this time. The only check necessary was that the fit of the center bore in the leveling plate D on the hub on top of the crystal table G be close enough to eliminate any play between the two, and yet permit tilting the former.

10. The bending of the quartz crystal plate within the crystal clamp blocks was described in detail on page 18. The front clamp block, i. e., the one with the convex profile, was bolted to the mounting plate mentioned above before bending the crystal. Thus, after the bending had been completed, the assembled crystal, clamp blocks and mounting plate were carefully moved to the location of the spectrometer, and moved into position over the crystal mount on rollers on a specially built ramp. Four jack screws threaded through

the mounting plate were used to free the rollers and ramp from beneath the mounting plate and then to lower the unit onto the crystal mount. Obviously, great care was taken not to jolt the crystal clamp blocks and risk cracking the bent crystal.

It is essential to locate the neutral plane of the crystal directly over the axis of rotation of the crystal table, and to align the (310) planes of the quartz parallel to this axis. As was mentioned on page 21, the generators of the cylindrical surface on the front clamp block had been located parallel to the vertical edges, and perpendicular to the horizontal edges of the block. In addition, the front surface of this clamp block is square with all these edges so that the horizontal edge of the front surface is equal and parallel to a chord of the cylindrical arc, and a line which is perpendicular to this front surface and bisects it is a radius of the arc which also bisects the arc. Such a line was engraved on the upper edge of the front clamp block when it was set up on the radius generating fixture. This engraved line served later as a reference for locking together the crystal table and collimator drives to a first approximation. The (310) planes could be readily aligned vertical and parallel to the crystal table axis using a precision spirit level on top of the front clamp block and rotating the table, the required adjustments being made on the crystal mount as indicated on page 24. A special fixture was made up to provide a visible extension of the line of intersection of the neutral plane of the bent crystal and the perpendicular bisector of the arc. This fixture holds a length of 0.004" dia. wire stretched taut and accurately

93
positioned at a distance from the convex face of the front clamp block equal to one-half the thickness of the crystal. The fixture was set up on top of the front clamp block with the wire along the radial bisector of the arc. In this way the wire could be observed through a full revolution of the crystal table with a short focus telescope, and the vertical center line through the crystal which it defines located over the crystal table axis. It was necessary to make several alternate adjustments of the levelling and centering before a satisfactory alignment was obtained.

11. The components of the optical lever had been previously assembled separate from the spectrometer and tested. These were now set in place as shown in Figure 2. The light source was mounted on the front end of the collimator and aligned square with it and level. The sensing unit was mounted on the concrete pedestal and the base casting of this unit (see Figure 23), levelled at the appropriate height to receive the reflected beam from the optical lever mirror. The optical lever mirror mount was bolted to the top of the front clamp block and the mirror set temporarily in the mirror holder (see Figure 22). The shapes of the pulses from each of the two arms, detector and reference arms, were then adjusted to be as nearly trapezoidal as possible. This was done in each arm by adjusting the distance between the light sources and source slit, the source slit and the collimating lens, and the focussing lens and the detection slit.

The most critical requirement for the optical lever is that the reflecting face of the mirror be located exactly on line with the axis of the crystal table. To accomplish this the mirror was replaced by a rectangular

open frame of Meehanite metal carrying a 0.004" dia. wire located at the equivalent position of the reflecting face. It will be noted in Figure 22 that the mirror holder provides a three-point support at the back of the mirror. The thickness of the mirror in the region of these three points was determined to the nearest 0.0005". The frame was set up in a jig borer and the position for the center of the wire in the frame determined on the basis of the previously measured thicknesses from equivalent points on the rear of the frame. This could be done on the jig borer to within 0.0001" by careful work, and 3/8" dia. holes were line-bored and reamed in the upper and lower parts of the frame. The wire itself was then held centered in pins which were press fitted into the larger bored holes. Thus with the frame mounted in place of the mirror the wire could be located exactly over the crystal table pivot by the technique used previously, and once centered, replaced by the mirror. The mirror holder can be rotated, over a small range, with respect to the mirror mount. Also, the reference arm on the sensing unit can be rotated with respect to the detector arm about the rotating prism as center. These two adjustments were later used to set the two arms in coincidence after the crystal table and collimator were zeroed together.

12. Locking together the crystal table and collimator precisely on zero could best be done using a reference gamma-ray line from a source in the reactor. This was done later and is described under a discussion of the calibration and measurements, Section VI. However, in order to be

able to detect such a reference line diffracted by the crystal, the collimator must be at twice the Bragg angle within small limits. Thus a preliminary, approximate setting of both the collimator and crystal table was necessary.

The reference line engraved on the top of the convex clamp block, mentioned previously on page 92, was used to set the crystal clamp blocks perpendicular to the fiducial line through the beam hole in the reactor. Also, the fact that the front face of this clamp block is perpendicular to the engraved reference line was utilized. With the close tolerances specified and held on the machining of the clamp blocks, on the orientation of the crystal in the clamp blocks, and on the orientation of (310) planes in the quartz crystal, this meant that the (310) planes were reasonably well set for zero Bragg angle, i.e., for infinite gamma-ray energy. This much of the setting was done actually before the mount for the mirror of the optical level was set in place and covered the engraved reference line. The collimator was then set at zero Bragg angle also, by utilizing the fact that the front of the collimator box was square with the center of its central channel. Finally, the collimator and crystal table drives were locked together by setting the output of the two arms of the optical lever into coincidence.

V. Operations and Control*

A schematic diagram of the control system is shown in Figure 32. The normal method of searching a spectrum is carried out as follows: The drive control of the crystal table is set for clockwise or counterclockwise operation. The crystal will begin to rotate and the collimator will follow at

Figure 32. Block diagram of control system

the correct 2:1 ratio of speeds by virtue of the action of the optical lever on the collimator drive. The bulk shield will also move with the collimator because of the mechanical linkage between it and the collimator. The detector unit moving with the collimator will have its output fed through a preamplifier to the single channel pulse height analyzer. The energy center of the analyzer window is shifted automatically as the collimator rotates as will be discussed later. The output of the pulse height analyzer is then fed to a counting rate computer and finally to a chart recorder.

At the same time as the above output data are being accumulated, the crystal table is pushing the movable mirror of the interferometer. Motion of the latter gives rise to a set of pulses from the fringe counting system corresponding to the number of fringes that have moved past a fixed pinhole in the field of view of the photomultiplier in the fringe counter. The fringe counting circuit is arranged to feed a signal to one operation pen on the chart recorder for every five pulses and to a second operation pen for every 100 pulses and to both simultaneously for every 1000 pulses. In this manner a continuous fringe count is maintained.

In addition to the above described system there is a set of cutout circuits which prevents faulty operation of the spectrometer. The power will be cut off from the drive motors if:

1. The rear shield door is not closed
2. The shield has moved to either the clockwise or counter-clockwise limiting microswitches on the base (maximum travel)

*

A detailed description of the new features of the electronic systems is to be published.

3. The collimator and shield have not moved in step with each other so that there is a possibility of them colliding (relative travel)

4. The Hg^{198} lamp is not lit

5. The source monitor is not counting above a predetermined level

6. The optical lever is in-operative

7. The pile door is closed

8. The chart recorder is off.

Items 1 through 3 are fixed cutouts whereas items 4 through 8 can be by-passed.

The optical lever linkage is operative only on slow motion. When the table is turned rapidly the collimator and shield can be moved rapidly into coincidence by means of the secondary position monitor described later. The coincidence position is determined by following the output of the coincidence circuit of the optical lever on a fast oscilloscope as the collimator is moved toward the proper location.

Since the single-channel analyzer is used to count pulses arising from gamma rays having energies from 20 kev to 7 Mev, it is necessary to provide a method of automatically shifting the center of the analyzer window as the crystal table turns. For this purpose a gear rack is bolted to the back end of the base, concentric with the rear track. A set of six 15-turn helipots, each with an appropriate gear box and pinion gear which meshes the above-mentioned rack, is attached to the rear of the collimator and each is rotated

as the collimator moves. Figure 33 shows three of the helipots. The rack is just out of view at the bottom of the figure.

The six helipots make up two sets of three each. One set of three helipots is operative clockwise from the zero position whereas the other set is used on the opposite side of zero. Whereas the pinion gears which mesh with the rack are rotating all the while the collimator moves, the helipots only rotate over definite regions of the rack. This is accomplished by appropriately clutching and unclutching the gear boxes. The gear boxes have ratios of 1:1, 5:1 and 27:1. The first is used to cover the energy range from 20 to 135 kev, the second from 135 to 850 kev, and the third from 850 kev to 7 Mev.

The width of the analyzer window is adjusted manually since there are relatively long time intervals during which the same width of the window may be used. In addition, the automatic window level adjustment may be bypassed and manual adjustments made.

The rack is also used to provide a secondary, rough position indicator. A 40-turn helipot, also mounted on the rear of the collimator, is rotated directly by a pinion gear that meshes with the rack. The helipot is set with its 20th turn at the zero Bragg angle position of the spectrometer. The 40-turn helipot is part of a bridge circuit which contains a second 40-turn helipot mounted on the control console. The helipot on the control console may be used either to control or to monitor the setting of the 40-turn helipot on the collimator. In the first case an unbalance in the circuit

Figure 33. Helipot system for adjusting window level of pulse height analyzer

feeds a signal to the Brown motor which adjusts the output of the rapid traverse hydraulic transmission on the collimator. An unbalance remains until the collimator has moved to the proper location. This system is most useful for moving the collimator and shield rapidly from one place to another. When used in the monitoring setting, the console 40-turn helipot rotates so as to always be in balance with the 40-turn helipot on the collimator.

VI. Calibration and Measurement¹¹

Under the description of the interferometer, page 35, the use of the interferometer as a primary means of measuring the angular rotation of the crystal table, either absolutely or relatively, was described. In addition, the spectrometer is provided with an indirect secondary measurement of the Bragg angles. Along the reference circle at the back of the rear track, a metric scale with divisions of 0.5 mm has been located, with a pointer attached to and moving with the rear of the collimator. On this scale readings can be repeated to an accuracy of about 0.2 mm, while successive readings differing by 0.1 mm may be discerned. An angular motion of the collimator of one mm on this scale is equivalent to an angular rotation of 80 sec of arc, which means an angular rotation of 40 sec of arc for the crystal table. Thus this secondary measuring scheme can be used to locate the energies of diffracted gamma rays to an accuracy of about 10 sec of arc, or to one part in 1100 at 100 kev and one part in 110 at one Mev. An accuracy 50 times greater is obtained by counting fringes.

11. A preliminary report on this section was presented at the 1956 Washington meeting of the A.P.S., D. Rose and B. Hamermesh; Bull. of the Amer. Phys. Soc. Series II, Vol. 1, number 4, paper K13.

To calibrate the spectrometer, a pure Au foil 0.001" thick 0.2 cm long and 10 cm high was placed in the source holder and inserted into the beam hole in the reactor. The 411.77-kev gamma-ray line following β decay of Au^{198} provided a relative calibration line whose energy is well known.¹² Also, as was mentioned previously, the line provided a means of exactly zeroing together the collimator and crystal table drives, which it was necessary to do before calibrating.

The Bragg angle corresponding to 411.77 kev may be found from

$$\theta = \frac{18,137}{E},$$

where $\theta \simeq \sin \theta$, is the Bragg angle in minutes, and E is the energy in kev. This gives $\theta = 44.043'$. The corresponding reading on the scale on the reference radius is 6.72 cm, using 103.2" as the radius of the reference circle. The collimator was then positioned at the angle corresponding to this scale reading relative to the approximately determined zero. The crystal table was then rotated approximately to the Bragg angle corresponding to this gamma-ray energy as indicated by the optical lever, and the crystal moved through a small range of angles about the approximately correct value until the first peak was detected. Pulse height analysis showed that this was indeed the 412-kev line with a peak height of about 10,000 cpm above background. With the crystal set at the Bragg angle corresponding to peak intensity, the collimator was rocked about its former position. A trapezoidal transmission curve was obtained with a peak intensity of about 14,000

12, Muller, Hoyt, Klein and DuMond, Phys. Rev. 88, 775 (1952)

cpm above background. The optical lever was then adjusted to coincidence with the crystal table and collimator both set on peak positions for the 411.77-kev line, and the shape of the diffracted peak delineated in both positive and negative first order.

Any asymmetry in the line profile which is not a mirror image in positive and negative order must be due to an instrumental error. These first line profiles obtained of the 411.77-kev line were asymmetric with several distinct bumps appearing in one case on the high energy side, and in the other on the low energy side. This could be caused either by aberrations in the focus of the bent crystal, or to incorrect positioning of the source with respect to the focal volume of the crystal, or both. To determine the cause, a "Hartmann" test was performed on the crystal in which only a small portion of the crystal was used at one time and the line profile determined for each such portion of the crystal. Comparing the Bragg angles for the peak position of each portion then gives an indication of the errors involved. The crystal aperture was divided into six regions and the peak positions were found to vary over a range of 24 sec of arc. A plot of this angular variation versus crystal width then gives an indication of the best focal position for the source, and the aberration in crystal focus. The source was found to be off of the best focal position by three inches. With the source position corrected, the Hartmann test was again repeated. Now five of the six regions of the crystal were found to peak within a variation of 2.4 sec of arc and the sixth region within 4 sec of arc of the mean of the others. The width of

the aberration at the source position was 0.06 mm for the five best regions and 0.18 mm for all six regions. There is no noticeable change in the line profile obtained with and without this one poorer region blocked out.

Figure 34 is a plot of the first order diffraction peak of the 411.8-kev gamma-ray line obtained with a source that was 0.001" thick. The full width at half-maximum height is 13.2 seconds of arc (0.15 milliangstrom), which gives a resolution of 0.5% at this energy. For this instrument, the resolution varies with energy, so that at 4 Mev it will be about 5%, and at 40 kev about 0.05%. The reflectivity, i. e., the ratio of intensity of the diffracted to that of the undiffracted beam, was measured to be 0.015 for the 411.8-kev line⁺. The reflectivity varies as the reciprocal of the square of the energy. The overall efficiency was calculated to be between 10^{-9} and 10^{-10} . The estimated measured value for the 411.8-kev line turns out to be about 3×10^{-10} .

It was not possible to see the second-order diffraction peak with this source whose strength was an estimated 10 curies. Therefore the source was changed to one 0.010" thick, 2.5 cm deep and 10 cm high, to give an estimated source strength of 1000 curies. Figure 35 shows the positive and negative, first and second-order diffraction peaks obtained with this thicker gold source. The full width at half-maximum of both first order peaks is 23.7 seconds of arc. The calculated increase in line width due to the increased source width is 6 seconds of arc; however, about 10 seconds of arc is actually found. The corresponding width of both second-order peaks is also about

⁺ It is of considerable interest to note that the reflectivity scales approximately with the thickness for a bent crystal (See reference 8).

Figure 34. First order diffraction peak from the 411.8 kev gamma ray from Au^{198} from a thin source

Figure 35. First and second order diffraction peaks from the 411.8 kev gamma ray from Au^{198} from a thick source

23.7 seconds of arc. Figure 36 shows the line in the negative second order. The ratio of the peak intensities in first order from the two sources is about 22, rather than 100 as expected from the increase in the volume of the source. This difference is attributed to additional self-absorption in the deeper source whose depth is about 17 e-folding distances for the 411.8-keV gamma ray in gold. However, the extra depth of source will be important for the capture gamma-ray search in the higher energy region to offset the attenuation in the diffracted beam due to the decreased reflectivity.

Returning to the calibration of the scale on the reference circle used in the secondary measurement of Bragg angles, the scale distance equivalent to 411.77 keV and the zero setting may be found from the first and second-order peaks. The zero value obtained from each pair of positive and negative peaks agreed to within 0.01 cm. The scale distance found from the four peaks was 6.69 and 6.70 cm, taking first and second differences. The corresponding scale reading for any other energy can be found from $(411.77/E) \times 6.695$, where E = energy in keV.

Figure 36. Second order diffraction peak from the 411.8 kev gamma ray from Au¹⁹⁸ from a thick source

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LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1	Schematic diagram of spectrometer.	5
2	Cut-away view of central structure and shielding of spectrometer.	7
3	Overall view of spectrometer.	9
4	Sketch showing orientation of quartz slab relative to optic axis	15
5	Sketch of finished quartz plate	17
6	Front view of clamp blocks for small quartz plate	19
7	Rear view of clamp blocks for small quartz plate.	20
8	Side view of lapping fixture	22
9	Front view of lapping fixture	23
10	Drawing of crystal mount ring system	26
11	Drawing of crystal table drive	27
12	Crystal table drive - blown up view.	28
13	Interferometer showing location relative to crystal table. . .	36
14	Close-up of interferometer pusher unit	37
15	Front view of collimator assembly	43
16	Overall view of collimator assembly	44
17	Diagram of method of assembly of collimator plates.	45
18	View of collimator during assembly showing sub-assembly of 10 plates and spacer units	48
19	Method of checking sub-assembly of 10 plates	50
20	Completed assembly of about half of the collimator	51

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
21	Detector-showing individual unit and array of 16 units making up complete detector	53
22	Optical lever mirror and mirror adjusting ring system. . . .	56
23	Optical lever sensing unit	58
24	Theoretical pulse shapes from optical lever sensing unit showing phase shifts due to misalignment.	59
25	Collimator drive; direct view.	62
26	Collimator drive; side view	63
27	Bulk shield and carrier; side view.	66
28	Bulk shield; front view	67
29	Cross-section showing central ring structure and primary supports	69
30	Cut-away view of source tube in reactor.	73
31	Method of locating center of rotation of various components	81
32	Block diagram of control system.	96
33	Helipot system for adjusting window level of pulse height analyzer	100
34	First order diffraction peak from the 411.8 kev gamma ray from Au ¹⁹⁸ from a thin source	105
35	First and second order diffraction peaks from the 411.8 kev gamma ray from Au ¹⁹⁸ from a thick source	106
36	Second order diffraction peak from the 411.8 kev gamma ray from Au ¹⁹⁸ from a thick source	108