GAMMA-RAY WAVELENGTH MEASUREMENTS OF GOLD 198, IODINE 131, COBALT 60, AND TANTALUM 182 USING A CURVED CRYSTAL FOCUSING SPECTROMETER

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A B S T R A C T

A description of the two-meter curved crystal focusing spectrometer, including improvements in several of the component parts, is given. The systematic errors inherent in the measurements and the calibration necessary to determine them are discussed. The construction of a sensitive geiger counter for the detecting system was necessary and was achieved only after many failures. The over-all instrument sensitivity is low, requiring sources of the order of twenty to fifty millicuries. The gamma-ray spectra of four sources, Gold 198, Iodine 131, Cobalt 60, and Tantalum 182, were studied. In the case of Iodine and Tantalum the entire spectrum was not obtained because of the lack of sufficient source strength. The results for all these sources and the method by which they were obtained are given.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I Description of Gamma-Ray Spectrometer.

The spectrometer used in this study of gamma-ray wavelengths has been described in other places[1] but it is felt that a short description is necessary here for completeness.

This is a transmission-type spectrometer which makes use of Bragg reflection* from the (310) atomic planes in a quartz crystal. This quartz crystal which is 2 millimeters thick is curved to a 2 meter radius by clamping it against the convex surface of a stainless steel block which has been accurately profiled to a cylindrical surface of this radius. This crystal and holder will be described in more detail later. If a given spectrometer setting corresponds to the Bragg angle for a wavelength of gamma-ray emitted by the source then these gamma-rays will be diffracted by the crystal and the detecting system will respond. Of course only a small fraction of the gamma-rays with this wavelength will be diffracted. The gamma-rays of other wavelengths will continue on through the crystal. In order that this

*The connection between wavelength and angle of incidence for Bragg reflection is given by (for first order reflection)

$$\lambda = 2d \sin \theta$$

where λ is the wavelength in centimeters, and d is the spacing of the atomic planes being used, in centimeters. θ is the angle between the incident direction of gamma-rays and the atomic planes used. If the beam is incident at an angle θ the diffracted beam will make the same angle θ with the atomic planes so that incident and emergent angles are equal. Thus the deviation of the refracted part of the beam from its initial direction is 2θ.

beam of gamma-rays which is not diffracted by the crystal shall not reach the detecting system, a system of lead baffles called the collimator is placed between the crystal and the detecting system. The construction of this collimator will be discussed later.

Figure 1 illustrates schematically the operation of the spectrometer. It should be kept in mind that this figure is only schematic and dimensions are exaggerated to illustrate the operation. The view on the left shows the spectrometer at a setting which will give reflection from one side of the atomic planes of the quartz crystal and the view on the right shows the setting for reflection from the other side of the same atomic planes. The view in the center shows the zero wavelength setting, in which all wavelength gamma-rays will be detected by the geiger counter. In order that the lead collimator and support (which weigh nearly 1500 pounds) need not be moved as the Bragg angle is changed, the spectrometer operates by rotating both the source and the crystal to maintain the incident and emergent angles the same.

In Figure 1 the focal circle (which has a diameter equal to the radius of curvature of the crystal) is shown although it does not exist as such on the instrument. The source is constrained always to move on the focal circle by the radius bar SR while the focal circle itself (whose center is at R) rotates bodily about the point P of its circumference. The carriage B pivots about the point X which, along

with the pivot point P, is fixed in space. The carriage C rolls along B keeping always perpendicular to the beam PA. This beam can slide thru carriage C as necessary to allow the above motion. The carriage D in turn rolls along the top of carriage C. The distance DP is fixed. Since the distance SR is fixed also, the source S moves on ball-bearing ways on beam DP.

The motion of the two carriages C and D is determined by two long precision screws located in C (one above the other) which are geared together so as to turn in opposite directions and which have the same pitch and same rate of rotation. There are thrust bearings at the ends of these screws. Carriage C is moved by means of a nut fixed to B (at X) running on the lower screw. By means of a nut fixed to D running on the upper screw, carriage D is moved the same distance on C as C is moved on B.

Thus the angle DPA is always equal to the angle APX. Each of these angles is equal to the Bragg angle defined above. Thus the distance of carriage D along carriage C, as measured from the position shown in the central view in Figure 1, is proportional to the sine of the angle DPA. From the Bragg condition, then, this distance is directly proportional to the wavelength being measured in any given spectrometer position.

The pitch of the precision screw is such that one revolution (which can be read to 0.001 of a revolution) moves carriage D 1 millimeter relative to carriage C. With the

spacing of the atomic planes being used in the quartz crystal this one revolution corresponds very nearly (in fact to 3 parts in 10,000) to a wavelength difference of 10^{-11} centimeters which is called a milliangstrom. The name "x-unit" is usually reserved for the Siegbahn scale and is therefore not 10^{-11} centimeters exactly. The actual calibration of this screw will be described later.

Figure 2 shows two ways of using the transmission-type curved crystal spectrometer, of which the arrangement at the right is used for measuring gamma-ray wavelengths.

Figure 3 shows the fundamental geometry of the curved crystal focusing spectrometer used in transmission. Due to the fact that the crystal is bent to a radius which is equal to the diameter of the focal circle there will be a slight aberration due to the failure of the crystal to lie on the focal circle as shown in Figure 4. The relative line broadening from this aberration is given by[1]

$$\frac{\Delta\lambda}{\lambda} \cong \frac{\cos\theta\,(1-\cos\phi)}{\cos(\phi+\theta)}$$

where θ is the Bragg angle and ϕ the half angle of aperture as shown in Figure 4.

II Component Parts of the Spectrometer

A. Source Holder

The source of radiation for the spectrometer is in most cases a thin strip of material of thickness from 0.001 inch to 0.010 inch, about one inch high and varying in depth from 0.10 inch to 0.25 inch depending upon the absorption in the source of radiation being measured. In the case of softer gamma radiation which is strongly absorbed in the source material itself only a much smaller depth of the source on the side facing the crystal and counter will be effective in emitting gamma-rays which can be measured.

The source is placed on the focal circle so that the narrow edge looks at the crystal. Figure 5 shows the source geometry with the shielding necessary. There are at least 4" of lead surrounding the source except in the forward direction. The bottom part of the source shield sits on a metal plate which rolls on another plate fastened to the beam by means of ball bearings in hardened tracks. This is precisely made so that as the spectrometer moves, the motion of the source along beam PD (see Figure 1) is very accurately in a horizontal plane and in the radial direction.

As shown in Figure 6 the source is placed in a holder which holds it accurately vertical. The sloping jaws of this holder (into which lead is molded) merely limit the maximum divergence of the beam of radiation. They do not define a source slit. The entire source width emits radiation into the crystal aperture. This source holder mounts

on a circular disc which fits into a disc shaped hollow in the lower hemisphere of the source shield so that adjustment may be made to insure that the source is looking at the crystal strictly edge on (so as to minimize its effective width on the focal circle and insure optimum resolving power).

The surfaces involved are sufficiently accurately made so that it is possible in the following way to insure that the source stands accurately vertical. The lower hemisphere of the source shield, which has its top and bottom surfaces machined parallel and sits on a plate that moves parallel to itself is made level using a precision level, so that its top surface lies in a horizontal plane. Thus when the source holder is perpendicular to this surface, the slot that the source fits into will be vertical. The necessity for getting the source strictly vertical arises from the fact that the easiest way to have the source parallel to the generators of the cylinder around which the crystal is bent is to have them both vertical. How this is done on the crystal holder will be seen later.

B. Collimator

In order that the diffracted radiation may be detected without interference from the main beam of radiation which goes directly through the crystal, a system of lead baffles is necessary. The angle between the diffracted radiation and the transmitted radiation is twice the Bragg angle for that radiation but is still a small angle. For

example, this angle between main and diffracted beams is about 44 minutes of arc at a wavelength of 25 x 10^{-11} centimeters (500 kev energy). With reference to Figure 1 again, the diffracted radiation always appears to originate at the point called V (virtual source). Thus a system of lead baffles which would pass radiation coming from this point and no other would pass the diffracted beam. In previous work this baffle system, which we shall call the collimator, consisted of 7 tapering lead sheets with 8 tapering open spaces. As the transmission characteristics of this collimator determine how close the instrument can be used to the position shown in the center of Figure 1, (and hence how short a gamma-ray wavelength can be measured) it is desirable to have the acceptance width as small as possible.

The improvement made in this collimator was affected as follows. A set of lead sheets 4 inches high, 31.5 inches long and tapering from 0.040 inches at the front end to 0.056 inches at the rear end were molded of type metal (82% lead, 15% antimony and 3% tin). Several of these plates were cut lengthwise to form narrower spacers which were placed between adjacent partitions at the top and bottom so as to form an arrangement of 25 tapering plates and 26 tapering openings. The front and back ends of this collimator are shown in Figure 7. The front opening is just slightly larger than the crystal aperture and the rear large enough to include the umbra and penumbra in the

vertical dimension. The front of the collimator is about 6 inches behind the crystal. The taper of the lead partitions is such that the collimator accepts radiation from a point (actually all points on a vertical line) which is the focal distance of the crystal plus the above 6 inches from the crystal to the front face of the collimator.

The transmission curve of the collimator has the shape shown in Figure 7A when the spectrometer is moved across the central position.

The wings of this curve extend for quite a distance on both sides beyond the point of cut-off defined by the geometry of the device because of scattering from the collimator plates. This curve indicates how the background increases as the spectrometer approaches the zero wavelength setting (i.e. higher energies). From the curve it can be seen that the background would begin to increase appreciably at wavelengths shorter than 3 x.u. (energies greater than 4 mev). It is estimated that it will not be feasible to measure wavelengths shorter than about 4 x.u. (2 to 3 mev energy).

As described above this collimator should transmit 50% of the radiation falling on the front opening since the open and closed spaces are equal in width. In assembling the collimator it was found that the surfaces of the molded plates were slightly wavy, and any irregularity of the surface tends to cut down the open space available between adjacent plates. Every effort was made to correct such

defects during the assembly. The transmission of this collimator was measured using a radium needle as source of radiation and an aperture arrangement so that the radiation could be measured both with and without the collimator in the beam. The transmission was found to be approximately 35%, so that of the number of gamma-rays diffracted by the crystal only about 1/3 are admitted to the geiger counter.

It should be pointed out that this collimation does not affect the spectral resolving power of the instrument, for that depends on the focal pattern of the curved crystal. The collimation takes place after diffraction by the crystal.

C. Crystal and Holder

In Figure 6 is shown the arrangement for holding the quartz crystal against the cylindrical surface of a stainless steel block. Both the convex and the concave surfaces on these blocks were ground to the cylindrical profile by a method which has been described[2]. This is done using a surface grinder with a jig which insures that the generators of the cylindrical surfaces shall be accurately perpendicular to the precision ground top and bottom arfaces of the steel block.

After grinding, these blocks with the apertures in them as shown are lapped by hand against solid cast iron blocks whose curved surfaces have been prepared by the same surface grinder method. The lapping is done in a parallel motion jig in such a way that the edges of the moveable and fixed blocks are always parallel. This insures parallelism

of the generators of lap and crystal holder. Thus the shape will remain cylindrical. The concave lapping block against which the convex surface of the crystal holder is lapped is checked for excellence of focus periodically. This is done by using a slit source of light and a miscroscope at the focus. The focal pattern is observed and when this pattern is suitably narrow, we have found that the crystal holder itself will be as good as the lapping block.

The crystal is then inserted and bent to the cylindrical profile and its concave surface tested optically. Only the convex member of the crystal holder determines the curvature of the crystal by intimate contact therewith. A rubber gasket is placed between the back or concave member and the crystal. The procedure of getting the crystal bent against the cylindrical surface is a difficult one since the smallest speck of dust or other foreign matter on either surface will prevent the crystal from contacting the steel at every point and thus ruin the accuracy of bending. Fortunately this situation is easily detected because of the interference fringes between the polished surfaces of the crystal and the block. The convex or defining member of the crystal holder is provided with ribs which cross the gamma-ray aperture to afford better support and definition to the bent crystal whereas the concave member has an open hole. The interface between the crystal and the ribs is clearly visible through this hole. As the crystal is bent by clamping the back piece (concave surface) against it, these

fringes can be observed (through the aperture in the back block) to spread out and the effect of any particles between the two surfaces is immediately noticed. The cleaning process consists of brushing the surfaces with a camels hair brush. Since the crystal will charge up when it is brushed and will pick up particles from the air, this brushing was done in the presence of a weak source of gamma-rays (namely Co^{60}).

When the crystal has contacted the metal block over the whole width of aperture, as evidenced by the fringe pattern, the focal pattern of the polished faces of the crystal is observed with the above mentioned optical set up. This of course does not test the focus of the atomic planes as used in the spectrometer but will give a good indication of this if the specimen is a perfect monocrystal accurately cut as shown in Figure 9.

To test the focusing of the various regions of the bent crystal optically, a mask was placed in front of the crystal. This mask contained 5/16 inch diameter holes in a horizontal line which could be placed over any of the 3 apertures of the crystal holder (see again Figure 8) keeping the other two covered. This gives five lines in the focal pattern as seen in the microscope. These five rays can be traced through the focal plane to determine how nearly they all meet in a point. First their separation is measured (with traveling eyepiece of the microscope) ahead of the focus and then behind the focus. The pattern obtained for the central aperture of the crystal holder is shown at the

top of Figure 10. The pattern from the other two apertures is similar and overlaps this nearly exactly. From this it can be seen that at the position of best focus the focal pattern is about 0.06 millimeters wide (corresponding to 0.06 x.u. on spectrometer).

To determine whether or not the atomic planes are parallel to the generators of the cylindrical surface the spectrometer is used as is shown on the left in Figure 2. The crystal in its holder is set up in place on the spectrometer with the center of the crystal above the pivot point P (see Figure 1) and the holder is leveled by means of a precision level. (The pivots of the spectrometer have all been previously rendered exactly vertical by means of levels.) An x-ray tube illuminates a fluorescer placed as at A in Figure 2 and on a piece of film the K spectrum is recorded on both sides of the central position (at the correct positions to receive the K spectrum of the fluorescer). If the atomic planes are not vertical, the spectrum on one side will be lower on the film than the spectrum taken on the other side. When the planes are vertical the spectra from either side will be on the same horizontal line on the film. To facilitate this test the length of the vertical spectrum line is made very short by a lead aperture stop placed at the crystal.

The test of the focal pattern of the crystal as it is used for the spectrometer is made with x-rays. A tungsten target x-ray tube is placed on the spectrometer with the

target directly behind a slit at the source position. This slit is made about 0.001 inch wide (0.025 millimeters) and the intensity from the x-ray tube is sufficient to give a convenient counting rate in the detector when the spectrometer is set at the position corresponding to the wavelength of the $K\alpha_1$ line of the tungsten. An aperture system is placed in front of the crystal which permits observation of the focus of eighteen different zones of the crystal as shown in the diagram in Figure 10. The position of the $K\alpha_1$ line of tungsten is determined for each of these sections of the crystal and from the known position of the aperture, a ray may be constructed from that zone of the crystal. The actual pattern obtained is shown in the lower part of Figure 10. This is a superposition of rays from all the eighteen zones of the crystal. The position of the slit for these measurements was along the solid line shown but it was determined from this pattern that the best focus would be two millimeters to the rear. Adjustment of this distance is possible and by this procedure one obtains the best place to locate the source. It can be seen that the focal pattern is 0.07 x.u. wide (0.07 millimeters in space). It should be kept in mind that distances left and right in the figure are exaggerated a hundredfold. The crystal aperture is shown full size. The center pivot for the focal circle (R in Figure 1) is adjustable and is set so as to be half way between the crystal and the best focus. This adjustment is made to $\pm$ 0.001 inches.

The crystal used for the tantalum measurements and the January 1950 gold measurements was 2 millimeters thick as compared with a 1 millimeter thick crystal used previously. It was feared that this thicker crystal might crack after being bent but it did not do so. The edges were carefully polished and rounded to remove any nicks or scratches where a crack might start. A detailed study has been made of the reflection properties of these crystals by Lind, West and DuMond(3).

D. Geiger Counter and Cosmic Ray Shielding

The detector for this spectrometer is a geiger counter in which it is possible to count a certain fraction of the gamma-rays passing through it. The shape of this counter can be visualized from Figure 11. It has a square cross section since the diffracted beam of gamma-rays coming from the crystal and passing through the collimator is nearly square (it is rectangular due to the penumbra).

The efficiency of this counter for detecting gamma-rays is increased by placing in it plates, spaced every $\frac{1}{4}$ inch of its length, in which the gamma-rays may eject electrons by either the photoelectric effect or the Compton effect (above an energy of 500 kev). It is these electrons which cause the count pulse.

A representative counter is the following one which was used for the majority of the tantalum 182 wavelength measurements. The plates are copper, 0.005 inch thick each with four $\frac{1}{2}$ inch diameter holes for the anode wires. There

are 30 of these plates. The anode wire is 0.002 inch diameter tungsten wire which is fed through Stupakoff insulators at one end and down the center of the holes in the plates. At the other end, and inside the counter case, the anode wire passes around two glass rod insulators and back through another set of holes. Thus only 2 anode wires are used, each wire going through two sets of holes. The aluminum window on the front end of the counter is sealed with a lead gasket between it and the front flanged face of the counter. This window and gasket are held down by a square frame which is screwed onto the front face of the counter as shown in Figure 11. This counter was filled with a gas mixture as follows: 5% ethylene for a quench gas and 95% argon to a total pressure of 38 centimeters. This counter has a plateau from 1160 V to 1400 V. It has been operating since January 1950 and still seems to be working satisfactorily. A large number of counters of this type were built before a successful one was obtained. The difficulty with the unsatisfactory ones was that they would give multiple pulses and within a day have no plateau at all, even though they were not used for counting. It was our opinion that it was the cathode surface that was causing the effect. Lead plates and tantalum plates were tried but neither would work satisfactorily. When they were copper plated an improvement could be noticed but it only prolonged their life by a few days. Unfortunately the reason for the success of the counter that turned out satisfactorily is not known.

Its preparation was in all essential respects that we know of identical to the preparation of the unsuccessful examples. Great care as to cleanliness in all cases was observed.

In order to reduce the background counting rate, the counter assembly was surrounded by 4 inches of lead on all sides as a protection from local radiation. To reduce the cosmic ray background, the counter is surrounded by a set of rectangular counters completely surrounding four sides of the gamma-ray counter which however do not receive any of the gamma-ray beam coming through the collimator. A cosmic ray which passes through the main counter will also pass through one or more of these shielding counters and by means of an anti-coincidence circuit, a count in the main counter is not registered if it is simultaneous with a pulse from the shielding counter. This arrangement is shown in Figure 12. Because these shielding counters are in anti-coincidence with the main counter they have come to be referred to as anti-coincidence or "A.C." counters. These counters have reduced the background counting rate by a factor of two. The background counting rate with no source present with the counter described above fluctuates around a value of about 80 counts per minute.

Although the counter is self quenching, a quench circuit is used, which acts as a pulse former and feeds into the scaler through the anti-coincidence circuit. These circuits are shown in Figures 13 and 14.

III Comparator Calibration of the Wavelength Screw

The wavelength screw is the one which moves carriage D relative to carriage C in Figure 1, and displacements along this screw from the zero wavelength position are strictly proportional to wavelength. As mentioned before, each revolution of this screw can be read to 0.001 of a revolution by means of an accurately divided drum and vernier indicator. The design is such that each revolution of this screw corresponds quite closely to an x.u. of wavelength and so the spectrometer is capable of giving readings to 0.001 x.u.

The characteristics of this wavelength screw were checked by a comparator method. A frame holding a National Bureau of Standards calibrated glass decimeter scale with a total interval of 100 millimeters was fastened to carriage D (see Figure 1) and a viewing microscope was fastened to carriage C. Readings on the decimeter scale were compared with the readings on the screw drum as carriage D was moved relative to C by turning the screw. These readings were taken over a region of 600 screw revolutions (300 on each side of center) and a calibration curve drawn for the wavelength screw giving the correction to be applied to a screw reading in any spectrometer position within this range. It is used to give the correction to apply to the difference between two different spectrometer settings. Within each revolution there is another effect which we shall call the periodic effect, which indicates the variations from linearity within

one revolution. This periodic error was checked also by using this decimeter scale, but only every 20th revolution. This correction does not vary appreciably from one revolution to another, but a gradual change is noticed over many revolutions.

There is one more correction to be taken into account. The source is situated on top of the beam PD (Figure 1) which places it about 12 inches above the "self-aligning" ball bearings by means of which carriage D rolls on C. The drive for carriage D is the nut riding on the wavelength screw which is below the ball bearing wheels of D. Thus any irregularity or eccentricity in these ball bearing wheels or minute particles on the tracks causes a motion of the source relative to the position it would have if the carriage D moved with no tilting. The reading on the screw, then, may not correspond exactly to the position of the source. To correct for this, a precision level was placed crosswise on the beam during the calibration mentioned above and its readings taken as the screw moved along. This gives a reference level reading to go with the calibration curve for the screw. This level is kept in place on the beam and readings taken during wavelength measurements. The difference in level readings at 2 spectrometer settings is compared with the level difference between the same two settings during the calibration run and a correction applied on the basis of this, since knowing the distances involved, the displacement of the source may be gotten from two level

readings. The magnitude of this correction will later be seen to be of the order of 0.010 x.u. in some cases. It can be either a positive or negative correction.

IV Absolute Calibration of Wavelength Screw

The above corrections give the deviations from linearity of the screw but the actual conversion of the number of (corrected as above) screw revolutions to the number of x.u. of wavelength must be done in another way. For this the x-ray tube with a tungsten target was placed on the spectrometer with a slit at the source position. Readings were taken to determine the screw position of the tungsten $K\alpha_1$ line. Several independent runs were made to establish this. This value for the tungsten $K\alpha_1$ line which is now in terms of corrected screw revolutions, is compared with the accurate wavelength measurement made by West[4] with a two crystal spectrometer in this laboratory. This gives the factor by which the screw revolutions must be multiplied to give the number of x.u. wavelength. This gives the wavelength in terms of Siegbahn wavelengths and must be corrected by another factor to give the wavelength in milliangstroms or centimeters. This latter conversion can be obtained from reference (5).

Wavelength measurements are made on the spectrometer as follows: Counting rates are taken for a given length of time at a series of spectrometer settings spaced sufficiently close together in the region of the wavelength being measured to give a satisfactory line profile. In a plot, then, of counting rate vs. spectrometer setting an increase will be seen when the spectrometer setting corresponds to a wavelength of radiation emitted by the source.

The width of this line profile will be discussed below. This procedure is repeated on the other side of zero so that two line profiles are obtained which are a distance apart corresponding to twice their wavelength. This eliminates the necessity of knowing exactly the zero position. The difference between the spectrometer readings at these two line profiles is corrected as above to give the true wavelength of the radiation.

V Line Widths

The instrumental causes of line broadening are (1) the geometric source width, (2) the intrinsic diffraction pattern characteristic of the quartz crystal, (3) the focal aberration due to the failure of all the zones of the crystal to focus at one point. These latter two aberrations can be determined from measurements as in Figure 10. The spectral distribution of the radiation has been approximated in only one case[6], for the annihilation radiation from Cu^{64}. In the case of most gamma-ray sources the natural line breadth is too narrow to be resolved by this instrument.

VI Automatic Observer

To make it possible to take readings with the spectrometer for 24 hours a day, which is very important for short half life sources an arrangement has been devised for automatically taking readings and advancing the spectrometer. This was built by J. Kohl.

This automatic observer will accumulate the counter pulses for a preset time interval and at the end of this interval will move the spectrometer to the next position which can be preset in advance according to a predetermined schedule. The automatic observer prints the accumulated number of counts together with the time and the spectrometer setting. The accuracy of the spectrometer setting is determined by a gold contact riding on a segmented disc fastened to the drum on the wavelength screw. This segmented disc has 50 accurately divided slots which are filled with insulating material. The gold contact, then, rides alternately on conducting and insulating sections. The contact and disc are so connected that the motor driving the spectrometer will stop when this contact passes from a conducting to an insulating section if the preset program indicates that it should stop. This programing is done with a microswitch riding on 16 millimeter movie film. Each time the gold contact encounters a conducting section this film is advanced a given amount and if a hole has been punched in the film so that the microswitch opens when the film advances, then the spectrometer will stop when the

gold contact rides off that conducting section. So the positions at which the spectrometer stops can be preset by punching appropriate holes in the film which passes under the microswitch. The timing circuits are controlled by a synchronous motor which closes a microswitch for a short time interval every minute.

VII Geiger Counter Design

In designing multi-cellular geiger counters it is desirable to choose the thickness of the plates so as to give maximum efficiency for the energy of gamma-rays being measured. A counter designed for a given energy gamma-ray will be useful for a range of energies on either side of the design energy. However to cover the range of energies which it is possible to measure with the spectrometer several geiger counters need to be employed. A set of three counters will cover the range of energies if they are designed as follows:

1. Counter designed for 0.75 mev which will be useful from 0.5 mev to 1.3 mev (✓)
2. Counter designed for 0.25 mev which will be useful from 0.10 mev to 0.5 mev
3. Counter designed for energies lower than 100 kev

An additional counter would be needed if it was desired to measure energies around 2 mev. None of these have been encountered so far. The counter for energies lower than 100 kev is filled with Xenon since for these energies absorption in the gas is large and plates are not needed.

The design of the counter is affected by the following considerations:

1. the material of the absorbing plates (for conversion of the gamma-rays into electrons)
2. the range of electrons in this material

3. the gamma-ray absorption coefficient of the material

The number of plates used and their thickness will be determined from the above.

The length of the counter case and the minimum possible spacing between plates will determine the maximum number of plates that can be gotten into the counter. The length of the counter case was decided to be about 8 inches (Figure 11) and the minimum spacing was set by the 1/4 inch spacers.

The thickness of the plates for optimum efficiency should not be greater than the range of the gamma-ray secondaries produced in the material and in fact, as is shown later, the thickness should be slightly less than this range. The most complete data available for the range of electrons is that for the range in aluminum obtained from Professor Fowler[8]. The extrapolation to the range in copper was made by taking into consideration only that the range is inversely proportional to the ratio $\rho Z/A$ where ρ is the density. For the extrapolation from aluminum to copper (from $Z = 13$ to $Z = 29$) it is felt that this is satisfactory to the accuracy desired here. Heitler[7] gives a curve for the range of electrons in lead if it is desired to work with materials near lead.

Table I gives the electron ranges in millimeters for several energies. Figure 17 gives the range plotted as a function of energy. The ranges in aluminum are taken from

Professor Fowler's curves. The range of gamma-ray secondaries produced in aluminum refers to the thickness of absorber which reduces the electron intensity to 0.8% (down by a factor of 2^7).

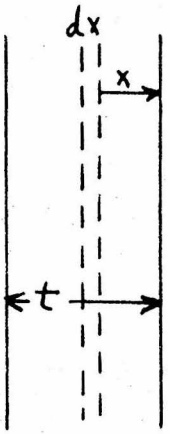
In the counter designed for use between 0.5 and 1.0 mev the gamma-ray secondaries will be produced almost entirely by the Compton effect. For the energy range 0.1 to 0.5 mev it will be a combination of the Compton effect and photoelectric effect.

Since each plate absorbs a small fraction of the gamma-rays, the last counter cell (after the beam has gone thru 25 or 30 such plates) sees a beam of reduced intensity. For this reason the plates at the rear of the counter do not give as many conversion electrons as the first few plates. If the counter contained just one cell (one conversion plate), the maximum efficiency would be obtained if this plate were made equal in thickness to the range of the electrons in the material for the energy gamma-rays being measured. However if there are many cells the efficiency may be increased somewhat if the plates are made less than the range thickness as shown below.

Let the efficiency (relative) per plate be e_o, the range of the electrons in the material be R and the thickness of the plate be t. Let us call μ the linear gamma-ray absorption coefficient resulting in electrons. Then the efficiency per plate:

$$d\varepsilon_0 = \mu\, dx\, \frac{R-x}{x}$$

(assumes ejected electrons all go forward)



assume $t \leq R$

$$\varepsilon_0 = \int_0^t \mu\, \frac{R-x}{x}\, dx$$

$$\varepsilon_0 = \mu t \left(1 - \frac{t}{2R}\right)$$

Now if there is a total of N plates (25 to 30 in the counter) we have for the total efficiency:

$$\varepsilon = \sum_{n=1}^{N} \varepsilon_0 e^{-\mu n t} = \sum_{n=1}^{N} \mu t \left(1 - \frac{t}{2R}\right) e^{-\mu n t}$$

$$\varepsilon = \mu t \left(1 - \frac{t}{2R}\right) \frac{e^{-(N+1)\mu t} - e^{-\mu t}}{e^{-\mu t} - 1} = \mu t \left(1 - \frac{t}{2R}\right) e^{-\mu t}\, \frac{e^{-N\mu t} - 1}{e^{-\mu t} - 1}$$

if $\mu t \ll 1$

$$\varepsilon = \left(1 - \frac{t}{2R}\right)\left(1 - e^{-N\mu t}\right)$$

That this has a maximum can be seen by taking the slope as a function of t which gives:

$$\frac{d\varepsilon}{dt} = (1 + 2RN\mu - N\mu t) e^{-N\mu t} - 1$$

now $N\mu t$ is small (of the order of 0.05) so we can write:

$$\frac{d\varepsilon}{dt} = (1 + 2RN\mu - N\mu t)(1 - N\mu t) - 1$$

$$= N\mu t^2 - (2 + 2RN\mu)t + 2R$$

for $t = R$ this is less than zero and for $t = 0.1R$ (for example) it is greater than zero. The maximum can be found between these values of t, as will be seen in a special case.

A. Counter Plates for 700 kev Gamma Radiation

From reference 9 the linear absorption coefficient for 700 kev gamma-rays in copper is nearly 0.6 cm^{-1}. The range of the gamma-ray secondaries is 0.16 mm. (from Table 2). The number of plates in the counter is to be 30. A plot of the equation above giving the relative efficiency as a function of individual plate thickness is shown in Figure 16. From this it can be seen that the plates should be made 0.16 mm. thick. The copper plates used in the counter were 0.125 mm. (0.005 inches) thick and so would be most efficient for an energy slightly less than 700 kev. For heavier materials, like lead, where the absorption coefficient is high and the range of the secondaries is low, the optimum thickness and range differ by a larger amount than in this case of copper.

This copper counter with the 0.005 inch plates was used successfully for the tantalum measurements from 150 kev to 1120 kev.

VIII Application of Spectrometer to Measurement of Gamma-Ray Wavelengths

A. Gamma-Rays Following Beta Decay of Iodine 131 (I^{131})

A "carrier-free" source of I^{131} obtained from Oak Ridge was used for these measurements. The iodine was precipitated onto an aluminum backing thus forming a thin source.

The geiger counter used in these measurements was one containing 9 lead plates, each 0.015 inches thick. The curved quartz crystal was 1 millimeter thick and made use of the (310) planes which were perpendicular to the faces of the crystal slab as discussed previously.

Table 3 gives the results of the individual measurements before and after correction for the small errors in the screw and in the carriage mechanism of the instrument as mentioned previously. Each "reading" measures the distance in revolutions of the wavelength screw between the centers of two complete line profiles, as reflected to the left and to the right of the (310) planes of the quartz crystal. This, divided by two and by the instrument screw conversion factor (1.00023 revolutions per x-unit) gives the wavelength in x-units (Siegbahn scale). This is then converted to absolute units (10^{-11} cm) in the column λ_g, by means of the factor $\lambda_g/\lambda_s = 1.00203$ and the final column gives the energy in kev from the formula kev = $(12394.8 \times 10^{-11})/(\lambda_g \text{ cm.})$.

When these measurements were started only the 364 kev and 80 kev lines had been reported. After measurements

on these two lines were nearly completed a Physical Review arrived containing a new disintegration scheme of F. Metzger and M. Deutsch[10], showing at least two additional lines. The stronger of these at 264 kev was immediately sought and, in spite of considerable source decay, it was still possible to obtain one precision measurement of this line. Two weeks later, Owen, Moe and Cook published[11] results indicating four gamma-ray lines from this same source, giving a different decay scheme. In both of these cases the work was done with a magnetic Beta-ray spectrometer, the precision of the energy determinations being probably of the order of a percent or so. The higher precision of the 2-meter focusing spectrometer offers an opportunity to test and discriminate between these two schemes. Figure 19 shows the two decay schemes.

It is easy to verify that the energies of the 80 and 284 kev lines add up to equality with that of the 364 kev line to a part in 4500 which is about the precision to be expected from the single observation on the weak 284 kev line. The precision measures assigned in Table 3 are based chiefly on possible systematic errors in the calibration of the instrument rather than on the excellent reproducibility. These results then give strong positive support to the Metzger and Deutsch scheme. The additional lines will be measured when a new source is prepared.

It was possible to estimate the intensity ratios for these three lines knowing the reflection coefficient of

the crystal at the different wavelengths and the geiger counter efficiency. This was possible thru the work of D. A. Lind. (See references 3 and 12.)

B. Measurements of the 1.1 and 1.3 mev Gamma-Ray Lines Following Decay of Co^{60}

A source of Cobalt in the form of a metal strip 1.25 inches high, 0.004 inches thick and 0.40 inches deep was prepared and sent to Oak Ridge for irradiation. The half life of this isotope is 5 years. The reaction of preparation and decay is as follows:

$$_{27}Co^{59} + {}_0n^1 \xrightarrow[\text{(slow)}]{} {}_{27}Co^{60} + \gamma$$

$$\downarrow 5 \text{ yrs}$$

$$(_{28}Ni^{60})^* + \beta^- + \nu$$

$$\hookrightarrow {}_{28}Ni^{60} + \gamma \left(\begin{matrix}1.1\\1.3\end{matrix} \text{ Mev}\right)$$

An activity of 50 millicuries was obtained and used for the measurements.

For these measurements a new crystal holder (as shown in Figure 8) with much larger aperture than the first was used. The quartz crystal used was the same as previously (1 mm. thick, 310 planes). A new collimator was put into use for the first time for these measurements. It has been described and is shown in Figure 7. Its transmission characteristic is shown in Figure 7A.

Figure 20 shows some of the spectral curves obtained by reflections from both sides of the crystal planes. Run 1 (not shown) was exploratory in nature to locate the 1.3 mev line. Run 2 shows the 1.3 mev line of Co^{60} while runs 4 and

5 show both the 1.1 and 1.3 mev lines. In run 2, a single line profile of the 1.1 mev line (not plotted) was also run on the right hand side only. The source was taken out of its holder after run 2 to permit temporary study of a sample of Ta^{182} received at that time. The Co^{60} source was then replaced in the instrument and another exploratory run (No. 3 not shown) was made to relocate the lines. This removal and replacement of the source accounts for the slight shift in the line positions on the instrument scale, a shift corresponding to a displacement of the source in the source holder of about 0.07 mm. However the separation between the reflections from the two sides of the crystal planes (which is used as a measure of the wavelength) is very reproducible from run to run.

The scales at the top of Figure 20 show the Bragg angles of reflection in minutes of arc and also the displacement of the wavelength screw carriage in millimeters. It is to be noted that the lines do not occur at exactly the same readings on the two sides. This is because the zero on the wavelength screw does not coincide exactly with the Beta point (the point on the focal circle to which the reflecting planes would converge if produced). The ordinate scales for the different runs are indicated by numbers giving the total number of counts observed at each setting for a standard counting interval which was 1000 seconds for all the runs plotted. Figure 21 shows 3 more runs taken on the 1.1 mev line alone. This gives a good idea of the reproducibility

of the measurements, when the instrument is working at its best. Figure 22 shows a detail of one of the lines.

Table 4 shows the results of the wavelength measurements of the two gamma-ray lines of Co^{60}. It is to be noted that less weight has been assigned to the 1.3 mev wavelengths obtained from the exploratory runs 1 and 3. This is because these curves were taken with a shorter counting interval than the rest, their primary object being to locate the positions of the lines sufficiently accurately to permit planning an economical schedule of settings for the more careful runs. Also, less weight was assigned to the 1.1 mev wavelengths obtained in runs 2, 4, and 5 than in the three later very satisfactory runs 6, 7, and 8. In run 2 the wavelength of the single 1.1 mev line had to be determined by measuring its distance from the neighboring 1.3 mev line. Also the counting interval in this case was only five minutes. In run 4 there were counter troubles which were not extremely serious but sufficient to make repetitions of some of the readings desirable. Such repetitions required reversing the direction of travel of the screw carriage to reach a previous setting and then proceeding as before. It has been found that such a procedure in the middle of a run may result in minute but detectable hysteresis effects which may lead to small errors in the wavelength readings. There was a suspicion also in run 5 that the beta-point of the instrument might have shifted ever so slightly in going from the reflections on one side to those on the other.

Checks were therefore made on the 1.1 mev wavelength in runs 4 and 5 by measuring the separations from the adjacent 1.3 mev lines. In the case of run 5, it was found that a slight beta-point shift had indeed occurred and therefore in this run the wavelength differences from the adjacent 1.3 mev lines together with the average value of these latter were used (instead of the separation between right and left hand orders) and only half weight was assigned to this individual value. All of these deviations are small and give no cause for alarm regarding the reliability of the final average results.

The 1.3 mev line at 9 x-units is the shortest wavelength so far studied with the spectrometer and it was of interest to measure the integrated reflection coefficient of the (310) planes of the quartz crystal at this wavelength for comparison with the data at longer wavelengths. The total counting rate in the directly transmitted beam was determined by setting the spectrometer at "zero wavelength" so that the primary beam was directly transmitted through the crystal and collimator to the counter. This beam is far too intense to be measured by the counter directly, so it is necessary to introduce absorbing sheets into the beam and plot the counting rate as a function of absorber thickness and extrapolate to zero thickness. One-half of this direct beam counting rate is associated with each of the two lines since the spectra show that they are quite closely equal in intensity. The counting rate at the peak of the line can

then be compared with this central beam counting rate to give the fraction of gamma-ray photons diffracted by the crystal. On this basis, it was found for the 1.1 mev line, 4.97 counts in the diffracted beam per 10,000 counts in the direct beam; and for the 1.3 mev line, 4.12 counts in the diffracted beam per 10,000 counts in the direct beam. This does not give the integrated reflection coefficient (see reference 3) but it gives a basis from which the latter can be calculated. The integrated reflection coefficient has been shown to diminish as λ^2 for wavelengths from $\lambda = 200$ x.u. to $\lambda = 9$ x.u.

C. Measurement of the 411 kev Gamma-Ray Following Beta Decay of Gold 198 (Au^{198})

Preliminary results for gold have already been published(7) but several sources of gold have been measured since then and the agreement is very good. Gold is a very satisfactory source for checking the operation of the spectrometer because of the high specific activity available in sources irradiated at Oak Ridge (5000 curies per gram for gold). This makes it possible to get sufficient activity into a source that is only 0.001 inches wide (0.025 mm.) with which it is possible to check the resolution of the quartz crystal.

The gold sources used were in the form of gold plating 0.001 inches thick on an aluminum backing. The source was 30 mm. high and 2 mm. deep. This gives about 30 mg. of gold in which an activity of 150 millicuries was

obtained. The half life is 2.7 days. The nuclear reaction involved is as follows:

$$_{79}Au^{197} + {}_{0}n^{1} \text{ (slow)} \longrightarrow {}_{79}Au^{198} + \gamma$$

$$\downarrow 2.7 \text{ days}$$

$$(_{80}Hg^{198})^{*} + \beta^{-} + \nu$$

$$\downarrow$$

$$_{80}Hg^{198} + \gamma\,(411 \text{ kev})$$

Table 2 gives the results obtained from the gold measurements. This represents measurements made on two samples of gold, one in June 1949 and the other in January 1950. The measurements in June 1949 were made using the new collimator and crystal holder described above and the 1 millimeter thick quartz crystal. The measurements in January 1950 were made using the 2 millimeter thick quartz crystal. This 2 millimeter crystal was found to have a reflection of 0.87% at this wavelength (i.e. out of every 1000 photons incident upon the crystal 8.7 of them undergo Bragg reflection). The geiger counter used for these January 1950 measurements was one composed of 25 tantalum plates 0.003 inches thick which had been copper plated with a thickness of copper not exceeding 0.0001 inch on each side. This counter was satisfactory only for a time long enough to obtain three runs. After this it began giving more and more spurious counts. These spurious counts would come in bursts as if triggered by a bona-fide count. Refilling the counter would not improve it at this stage of its deterioration.

Figure 16 shows a typical line profile obtained for the Au^{198} gamma-ray. These two profiles represent one run, one profile taken in reflection from one side of the (310) planes of the quartz crystal and the other profile taken in reflection from the other sides of the same planes.

D. Check of Spectrometer Screw Factor

To check the spectrometer screw factor (that is, the factor which converts the revolutions of the wavelength screw into Siegbahn x-units), a slit was placed at the source position on the spectrometer and a tungsten target x-ray tube set up to illuminate the slit from the rear. In this way three runs were made of the tungsten $K\alpha_1$, x-ray line with the slit of the order of 0.001 inches wide or less. One of these line profiles is shown in Figure 15.

The spectrometer readings were taken and corrected in the usual way. The corrected spectrometer readings (revolutions of the wavelength screw) obtained were as follows:

Run 1	208.639
Run 2	208.636
Run 3	208.630
Average	208.635 screw divisions

From reference 4, West's value for the wavelength of the tungsten $K\alpha_1$, line as obtained with the 2 crystal spectrometer is 208.575 ± 0.008 x-units. Thus the screw factor is $\frac{208.635}{208.575} = 1.00029 \frac{\text{screw division}}{\text{x-units}}$. The value previously used differs from this by only 6 parts in 100,000.

8. Gamma-Rays Following Beta-Decay of Tantalum 182 (Ta^{182})

A source of tantalum in the form of a metal strip 0.004 inches thick, 0.20 inches deep and 1.2 inches high weighing about 275 mg. was prepared and sent to Oak Ridge for irradiation for four months. The half life is four months. The nuclear reaction taking place is as follows:

$$_{73}Ta^{181} + {}_{0}n^{1}\ (\text{slow}) \longrightarrow {}_{73}Ta^{182} + \gamma$$

$$\downarrow 4 \text{ months}$$

$$(_{74}W^{182})^{*} + \beta^{-} + \nu$$

$$\downarrow$$

$$_{74}W^{182} + \gamma\,(\text{many})$$

Much previous work has been done on the gamma-ray spectrum of tantalum (actually W^{182}) using beta-spectrometers. See references 14 through 22. The precision study of the gamma-ray spectrum should make the energy levels fairly certain.

The sample obtained from Oak Ridge had nearly 500 millicuries of high energy activity (1 mev). A survey meter gave 2½ Roentgen/hr at one foot.

The three high energy lines were measured first and the results of the individual measurements on each line are given in Table 5. Four runs were made on each of the lines. The spectrum of the high energy lines is shown at the top in Figure 23. Since the 1189 kev line is weak and is so close to the 1224 kev line, its center was found by a special procedure. The background counting rate was subtracted from the readings thus giving the lines on a level (instead of sloping) plot. Since the 1189 kev line sits on

the tail of the 1224 kev line, the finding of the center of the line (or its true peak) is not as straightforward as in the case of a line which is symmetrical about the center line. In this plot of the 1189 and 1224 kev lines the low energy tail of the 1224 kev line is approximated by assuming the line is symmetrical. This tail has also been approximated by comparison with the 1.17 mev line of Co^{60} plotted to same scale. This standard line profile (1.17 mev line of Co^{60}) matches almost exactly the wavelength of this tantalum line and has the same width. This tail (which slopes under the 1189 kev line) is then subtracted from the 1189 kev line to give the true profile. The center of this true profile can be found in the usual way or by comparison with the 1.17 mev line of Co^{60} plotted to same scale.

The geiger counter, described above, with the 0.005 inch thick copper plates was used for all these measurements. It is estimated that it gave 10^8 counts during all of the tantalum runs.

Because of the variety of wavelengths reported (see Table 3) in the lower energy range it was decided to make a survey of the whole wavelength region in which lines had been reported. This survey would never have been undertaken if it had not been that the automatic observing mechanism had just been completed. The automatic observer (which as described above gives a printed record of the counts) was set to take 20 minute readings every 0.04 x-units from 30 x-units to 82 x-units. This is 1150 settings and took nearly a month to

complete, with the automatic observer going night and day. This of course could never be attempted for a sample with a short half life.

This survey gave evidence of 6 lines in this wavelength region. Figure 24 shows this survey plotted to a small scale. A spectral interval requiring 100 hours of robot operation to explore is shown in the figure. Weaker lines than those reported may of course exist but at least we can say that these six lines are the only ones which this spectrometer will resolve with certainty above the background with the present counting interval (20 minutes to a setting) and the given source strength. As can be seen in Figure 24, there are no other places where the counting rate is high enough to cause suspicion of a line. The 198 kev line is the weakest line, being only 1 1/5 times the background counting rate.

After the wavelengths of the lines were obtained from the survey, it was only necessary to make runs on each line (a determination on both sides of zero for each run) to determine the wavelengths of these six lines.

Table 6 gives the results of measurements on these 6 lines. Six determinations each, were made on the 264, 198, and 152 kev lines and five determinations on the others. For each determination, the spectrometer readings were corrected as described before (i.e. corrected for level error, periodic error, systematic error, screw factor and Siegbahn to milliangstrom factor).

Most of the runs were made using 20 minute counting intervals at each point. As the source decreased in strength it was necessary to use 40 minute intervals for the weaker lines. The weighting factors in Tables 5 and 6 were assigned on the basis of the number of counts recorded, in other words on the statistical errors involved.

Table 7 gives a composite picture of all 9 of the gamma-ray lines from tantalum^{182} which have been determined to date. The ± error given is the probable error defined as 0.6745 times the standard deviation.

According to reference 22 there are eight more gamma-ray lines of lower energy, all of which are within the reach of the spectrometer. Because of their low energy and the high density of tantalum, the absorption in the source is high and the depth in the source from which radiation will escape is very small (of the order of 0.07 mm. for the 74 kev line). For this reason a high specific activity (millicuries per milligram of material) is necessary so that there will be enough intensity coming from this thin layer to be detected with the spectrometer. The specific activity available at Oak Ridge is not sufficient. A factor of ten over that available at Oak Ridge would be satisfactory and the chain reacting pile at Chalk River, Canada would supply this but it is impossible at the present time (due to international rulings) to have samples irradiated there. Thus the remainder of the tantalum spectrum will have to be postponed until a sample of suitable activity can be obtained.

Table 8 compares the reported values of the energies of the gamma-ray lines from tantalum^{182}. In reference 22, Cork et al have essentially corrected their interpretation of the electron lines as reported in reference 19. For this reason the lines reported in reference 19 are not included in Table 8. It is to be noted that after reinterpreting their electron spectrum Cork et al (reference 22) report only those lines which our gamma-ray spectrometer detected. Previously many more lines were reported in this region. It thus appears that in the low energy region (below 113 kev), the lines reported by Cork (and shown in Table 8) are probably the only ones which will be detected with the gamma-ray spectrometer.

Figure 25 shows Cork's decay scheme as reported in P. R. 78 95 (1950) (reference 22). The transitions indicated by dotted lines are those he arrived at by a double interpretation of certain electron lines. The transitions marked with a star (*) are presumably the ones detected in this thesis.

1. Rough Determination of the 113 kev Line

Because of the longer wavelengths of the other reported lines, the sensitivity of the geiger counter is low and extremely long runs would be necessary to detect these lines if indeed they could be detected at all. However, using 30 minute runs it was possible to get a profile of the 113 kev line on one side of zero only. This was done after all the runs had been completed and of course the source had decayed about one half life. A line profile was obtained with which it was possible to find the center of the line. By taking differences of this line position from the positions of the 6 other lines, a wavelength of 109.27×10^{-11} cm. was arrived at. This gives an energy of 113.4 kev which is probably reliable to $\pm$ 0.1 kev.

2. Revision of Cork's Decay Scheme on Basis of Present Measurements

It is to be noted that the seven lines reported above will determine uniquely all the levels given by Cork in Figure 25. It is necessary to have the 113 kev line to do this, and the levels determined from this will not be as precise as the others. Knowledge of this 113 kev line is used in determining only three levels (the 113.4 level, the 120.6 level and the 342.7 level).

Since the levels have been determined with the 7 lines measured it is possible to predict the other lines a little more accurately if this level scheme is the correct one. It would, of course, be necessary to know the other lines as accurately as the ones already measured in order to check this level scheme completely.

Figure 26 shows this level scheme of Cork's, modified by the 6 lines known precisely and one line not so precisely (113 kev). In the figure, the values not determined, but only inferred from similar transitions observed by Cork, are given in parenthesis.

It is thus very desirable to continue this work on the gamma-ray spectrum of Tantalum^{182} when higher, specific activity source strengths become available. The activity that would be necessary can be determined from the following considerations. The solid angle subtended by the crystal is about 3×10^{-5}. The crystal gives about 5% reflection at a wavelength of 165 x-units. (This was

measured using the lead $K\alpha_1$ radiation excited by fluorescence.) The reported tantalum line at 75 kev (165 x-units) has a mass absorption coefficient of 9.4 which is the highest of any of the reported lines in this region because it is just on the short wavelength side of the K critical absorption edge of tantalum. The distance in which the intensity of this radiation is reduced to 1/e of its value is 0.067 millimeters. If a sample 0.2 mm. thick and 30 mm. high is used there will be 6.7 milligrams down to this level (0.067 mm.). A counting rate of 5 counts per minute in this weaker line, if the background counting rate were not more than ten times this value (i.e. not greater than 50 counts/min.) would be satisfactory. If we assume the counter has an efficiency of 10% (perhaps a xenon filled proportional counter) and that the collimator transmits 30%, the number of millicuries activity in this line would need to be:

$$\text{millicuries} = \frac{5}{(3.7\times10^{7})(60)(0.05)(3\times10^{-5})(0.10)(0.30)} = .05$$

This gives the activity which would be necessary in this particular line (75 kev). To determine the total activity which would be necessary is difficult, but on the basis of the present sample a fair estimate would be that this line might contain 0.5% of the total activity. This would mean the total activity would be 10 millicuries and in 6.7 mg. this would call for a specific activity of 1.5 millicuries per milligram. The specific activity of the present sample (irradiated at Oak Ridge) was 0.4 millicuries per milligram

after 4 months irradiation. Thus an irradiation of 4 months with a neutron flux which is at least 4 times as great as that at Oak Ridge should be sufficient to determine these lower energy lines.

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TABLE 1

Range of Electrons (Millimeters)

MEV	R_{Al}	R_{Cu}	Range of gamma-ray secondaries in Al.	Range of gamma-ray secondaries in Cu.
0.1	.13	.042	.05	.016
0.2	.25	.08	.10	.03
0.3	.35	.11	.16	.05
0.4	.55	.17	.25	.08
0.5	.72	.23	.35	.11
0.6	.90	.29	.45	.14
0.7	1.08	.35	.58	.18
0.8	1.27	.41	.70	.22
0.9	1.45	.46	.85	.27
1.0	1.65	.52	.98	.31
1.5	2.65	.85	1.75	.56
2.0	3.70	1.17	2.60	.83
3.0	5.90	1.89	4.40	1.41

TABLE 2

GOLD 198 RESULTS

Date	Run Number	Column A Corrected screw divisions	Column B Column A multiplied by 1.00203/1.00029 $\lambda \times 10^{-11}$ cm.	Column C Column B divided into 12395×10^{-8} Energy in mev
June 1949	1	30.101	30.155	411.043
	2	30.096	30.150	411.111
	6	30.118	30.172	410.811
	7	30.112	30.166	410.893
	8	30.101	30.155	411.043
Jan. 1950	1	30.076	30.128	411.411
	2	30.063	30.115	411.598
	3	30.068	30.120	411.520
		30.092 ± 0.007	30.145 ± 0.007	411.178 ± 0.1

The $\pm$ error is the probable error

TABLE 3

Results of Independent Measurements on Iodine 131 Before and After Corrections for Small Errors in the Screw and in the Carriage Mechanism of the Instrument

Run No.	Reading	Corrections: Screw	Corrections: Periodic	Corrections: Level	Corrected reading	Wt.	Average	X.U. (Siegbahn)	λg in 10^{-11} cm	Energy kev
1	67.950	-0.001	+0.001	+0.014	67.964	1				
2	67.940	-0.001	+0.001	+0.002	67.942	1				
3	67.921	-0.001	+0.001	+0.006	67.927	1				
4	67.950	-0.001	+0.001	+0.010	67.960	1			34.033 ±0.01	364.18 ±0.1
5	67.933	-0.001	+0.001	+0.004	67.937	1	67.946	33.965		
1	308.785	+0.002	+0.002	+0.008	308.797	1				
2	308.785	+0.002	+0.001	+0.010	308.798	1			154.071 ±0.01	80.133 ±0.005
3	308.765	+0.002	+0.001	+0.018	308.786	½	308.795	154.362		
1	87.090	-0.002	+0.003	-0.006	87.091	1	87.091	43.535	43.622 ±0.02	284.13 ±0.1

TABLE 4

Wavelength Measurements of Two Gamma-Ray Lines From Co^{60}

1.3 Mev line			1.1 Mev line	
	Screw Reading (Double)	Weight Factor		Screw Reading (Double)
Run 1	18.570	0.5	Run 6	21.111
Run 2	18.595	1.0	Run 7	21.118
Run 3	18.578	0.5	Run 8	21.121
Run 4	18.585	1.0	Average	21.117
Run 5	18.573	1.0		
Aver.	18.582		Correc. Results	$(10.578 \pm 0.005) \times 10^{-11}$ cms 1171.8 Kev ±1.0
			Runs 2,4,5 Corrected Results	$(10.583 \pm 0.005) \times 10^{-11}$ cms 1171.3 Kev ±1.0
Correc. Results	$(9.308 \pm 0.005) \times 10^{-11}$ cms 1331.6 Kev ±1.0		Average 6,7,8 Weight 1 2,4,5 Weight 0.5	$(10.580 \pm 0.005) \times 10^{-11}$ cms 1171.5 Kev ±1.0

TABLE 5

High Energy Lines of Tantalum 182

Run No.	Weight	Wavelength cm x 10^{11}	KEV	
1	1	10.127	1223.96	
2	2	10.123	1224.44	$10.121 \pm .002 \times 10^{-11}$ cm
3	2	10.121	1224.68	
4	2	10.118	1225.04	1224.6 ± 0.3 kev
	Average:	10.121	1224.61	
1	1	10.432	1188.17	
2	2	10.434	1187.94	$10.425 \pm .006 \times 10^{-11}$ cm
3	2	10.418	1189.77	
4	2	10.418	1189.77	1189.0 ± 0.6 kev
	Average:	10.425	1189.02	
1	1	11.060	1120.70	
2	2	11.035	1123.24	$11.056 \pm .010 \times 10^{-11}$ cm
3	2	11.063	1120.40	
4	2	11.069	1119.79	1121.1 ± 1.0 kev
	Average:	11.056	1121.08	

$\pm$ Error gives probable error

TABLE 6

Data on Six Ta^{182} Lines

Run No.	Weight	Wavelength in cm x 10^{11}	KEV	
1	1	46.961	263.94	
2	2	46.952	263.99	46.946 ± 0.008 x 10^{-11} cm
3	2	46.926	264.139	
5	2	46.957	263.965	264.026 ± 0.05 kev
7	2	46.941	264.055	
8	2	46.945	264.032	
	Average:	46.946	264.026	
1	1	54.085	229.18	
2	2	54.046	229.34	54.063 ± 0.008 x 10^{-11} cm
3	3	54.059	229.286	
5	2	54.066	229.257	229.270 ± 0.035 kev
8	2	54.069	229.244	
	Average:	54.063	229.270	
1	1	55.849	221.937	
2	2	55.808	222.10	55.820 ± 0.011 x 10^{-11} cm
3	2	55.818	222.061	
5	2	55.830	222.013	222.053 ± 0.04 kev
8	1	55.799	222.136	
	Average:	55.820	222.053	
1	2	62.526	198.24	
2	2	62.516	198.27	62.512 ± 0.010 x 10^{-11} cm
3	3	62.506	198.301	
5	3	62.520	198.256	198.282 ± 0.035 kev
6	2	62.483	198.374	
8	2	62.518	198.263	
	Average:	62.512	198.282	
1	1	69.114	179.34	
2	2	69.080	179.43	69.105 ± 0.010 x 10^{-11} cm
3	2	69.113	179.344	
5	3	69.112	179.346	179.365 ± 0.03 Kev
8	1	69.111	179.349	
	Average:	69.105	179.365	
1	1	81.334	152.40	
2	2	81.308	152.44	
3	2	81.326	152.411	81.314 ± 0.008 x 10^{-11} cm
4	2	81.303	152.454	
5	2	81.306	152.449	152.434 ± 0.014 Kev
8	2	81.320	152.422	
	Average:	81.314	152.434	
9	1	109.27	113.4 ± 0.1	

± Error gives probable error

TABLE 7

Wavelengths and Quantum Energies of Ta^{182} Gamma-Ray Lines

β Decay, Half Life 120 Days

No. of runs averaged	Wavelength in cms.	Quantum Energy Kev.
4	$10.121 \pm 0.002 \times 10^{-11}$	1224.6 ± 0.3
4	$10.425 \pm 0.006 \times 10^{-11}$	1189.0 ± 0.6
4	$11.056 \pm 0.010 \times 10^{-11}$	1121.1 ± 1.0

Region from 1121 to 345 Kev not yet explored.

Region from 345 to 263.9 Kev explored without revealing any clear-cut evidence of lines.

6	$46.946 \pm 0.008 \times 10^{-11}$	264.026 ± 0.05
5	$54.063 \pm 0.008 \times 10^{-11}$	229.270 ± 0.035
5	$55.820 \pm 0.011 \times 10^{-11}$	222.053 ± 0.04
6	$62.512 \pm 0.010 \times 10^{-11}$	198.282 ± 0.035
5	$69.105 \pm 0.010 \times 10^{-11}$	179.365 ± 0.03
6	$81.314 \pm 0.008 \times 10^{-11}$	152.434 ± 0.014
$\frac{1}{2}$	$109.27 \pm 0.08 \times 10^{-11}$	113.4 ± 0.1

$\pm$ error gives probable error

TABLE 8

Comparison of Reported Values for Gamma-Ray Lines of Ta^{182}

(All values are in kev)

Gamma-ray spectrometer values (present)	Goddard and Cook P.R. 76 1419 (1949)	Beach, Peacock and Wilkinson P.R. 76 1585 (1949)	Cork, Keller, Rutledge and Stoddard P.R. 78 95 (1950)
1224.6	1234	1237	
1189.0	1190	1219	
1121.1	1120	1133	
		324	
264.026	261	264	262.3
		255	
229.270		243	228.0
222.053	220	222	221.1
198.282	209	198	197.5
179.365	180	172	178.4
		165	
152.434	151	157	151.5
		141	(143.2)
		132	(133.8)
		122	
113.4		112	113.2
	103	98	99
	84	82	84.4
	71		74.8
			67.2
			65.3
			58.4
			46.0

SCHEMATIC DIAGRAM OF SPECTROMETER

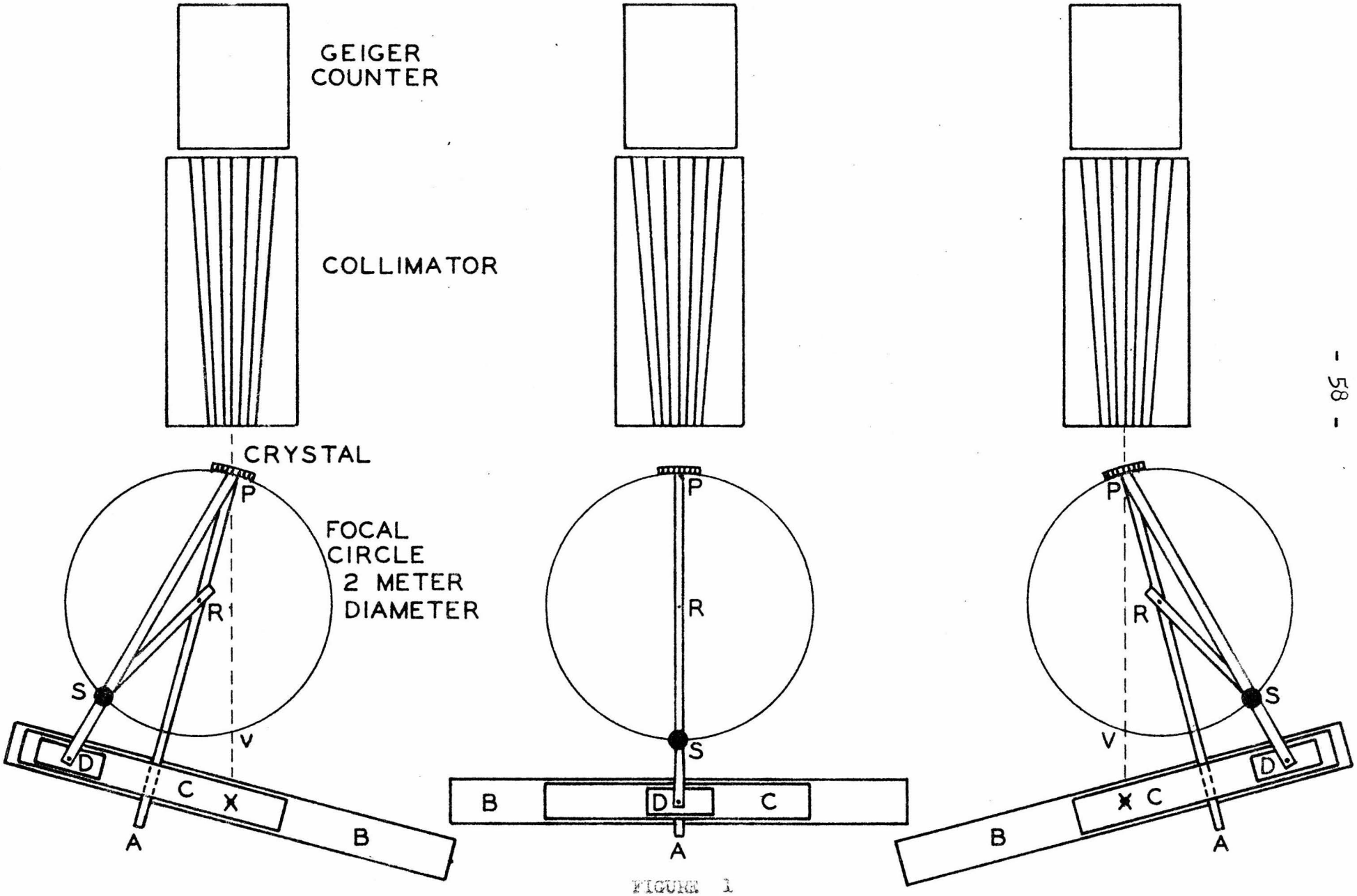


FIGURE 1

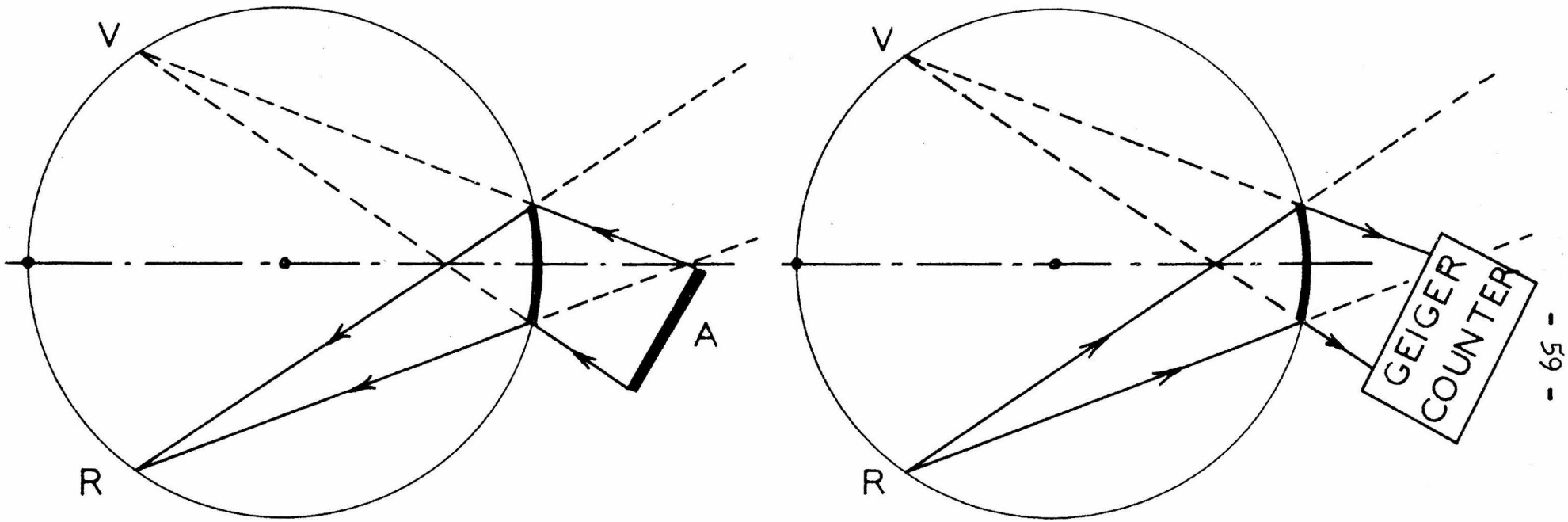


Figure 2. Two ways of using the transmission-type curved-crystal spectrometer. An extended source may be placed at S, in which case spectral lines will be focused as at R. This case is appropriate for the study of fluorescence excited in a screen placed at A. For gamma-ray spectra the source may be placed at A, and the intensity, measured in a geiger counter, is thus plotted as a function of the position of the source R on the focal circle

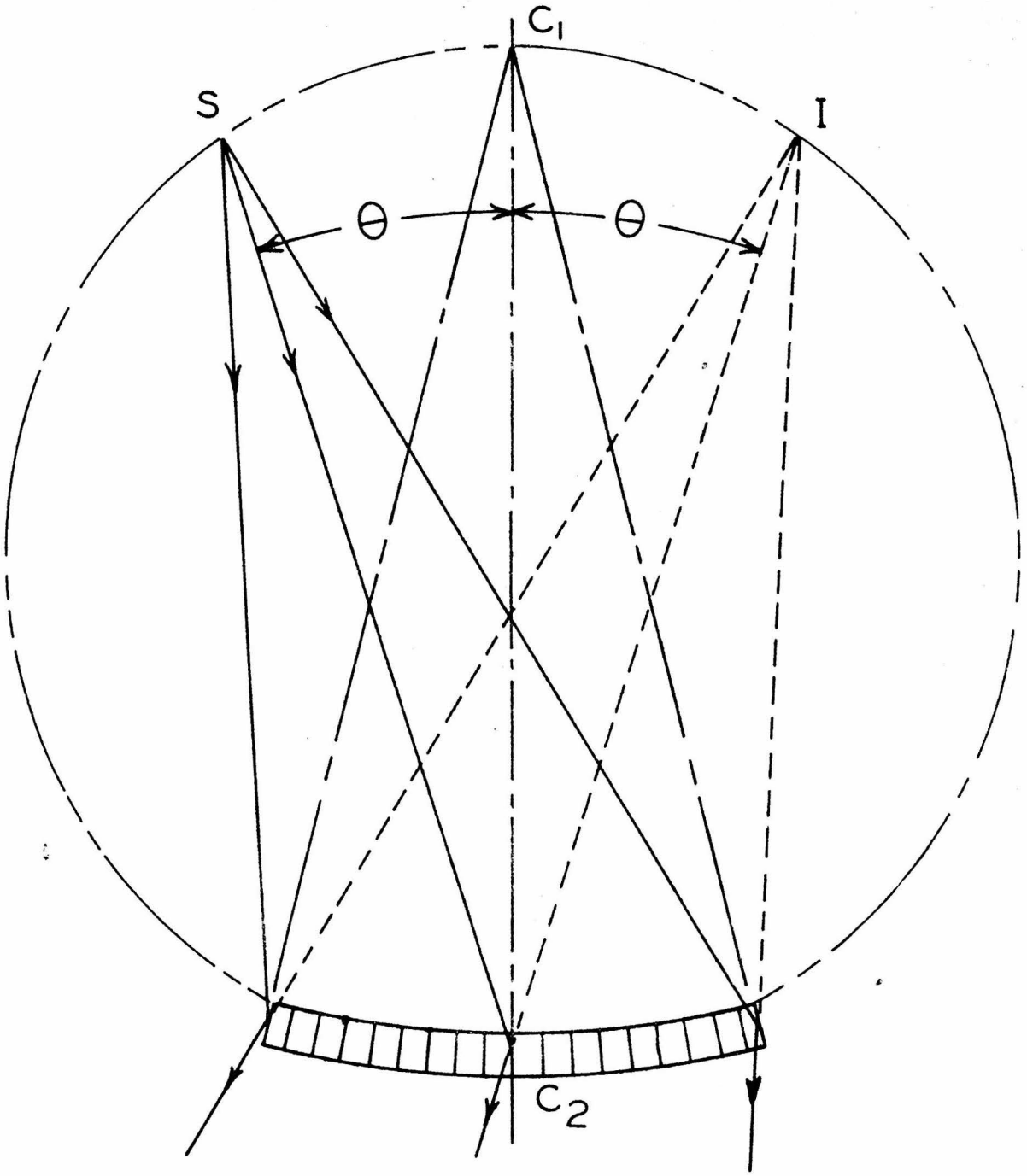


Figure 3. The fundamental geometry of the curved-crystal focusing spectrometer used in transmission is shown. The crystal lamina is bent to a radius equal to the diameter of the focal circle. S represents the source position; C_1 the intersection of the atomic planes on the focal circle and I the virtual source of the radiation after diffraction by the lattice. The neutral axis of the bent crystal is tangent to the focal circle at C_2. This geometry is not exact because the neutral axis should coincide with the focal circle over the whole crystal.

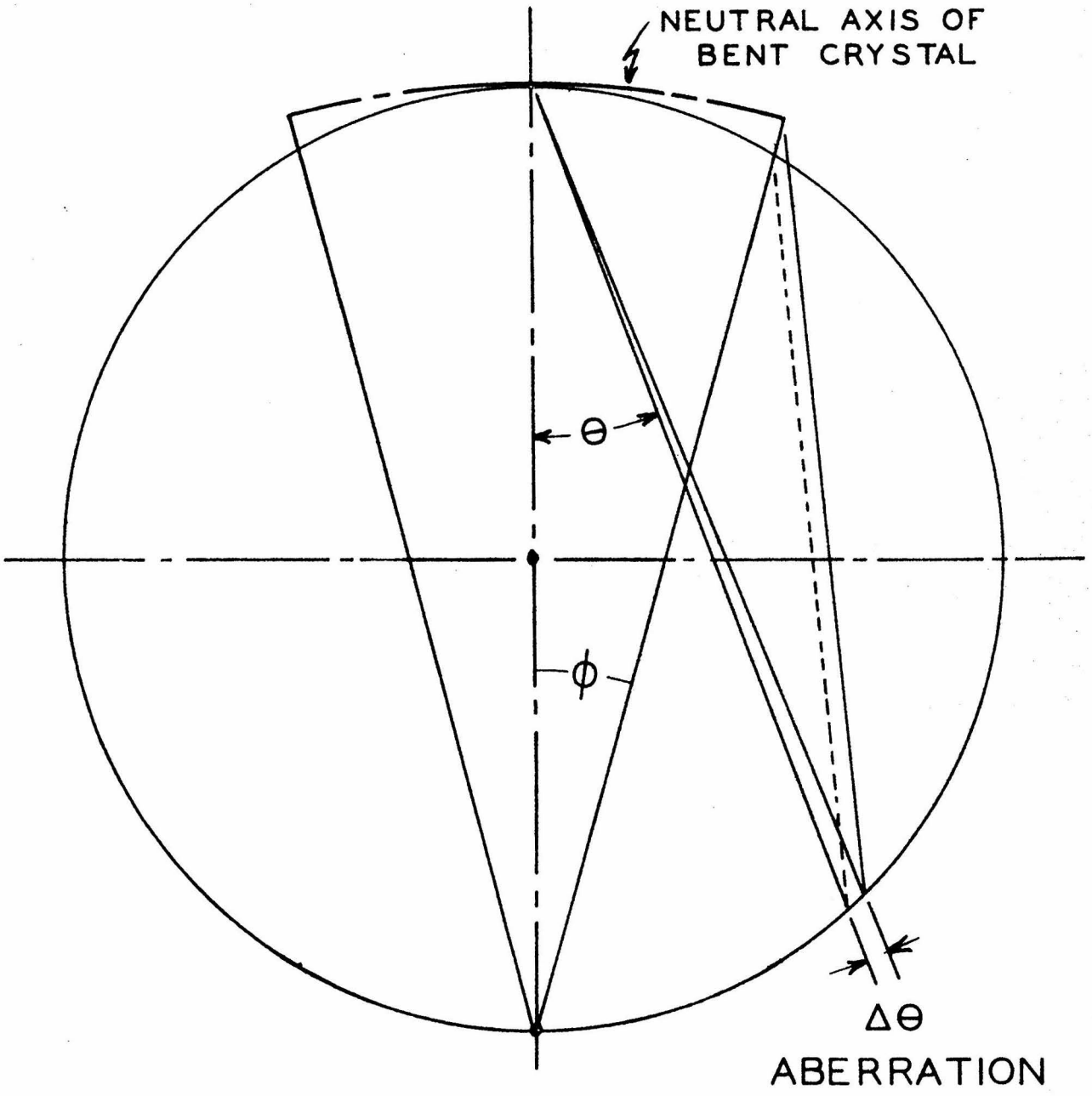


Figure 4. Geometry determining the line broadening or aberration in the transmission-type spectrometer which results from the fact that near its extremities the neutral axis of the lamina fails to coincide with the focal circle. The aberration $\Delta\theta$ results in a corresponding wavelength aberration $\Delta\lambda$. For small θ and ϕ this aberration is extremely small.

SOURCE SHIELD

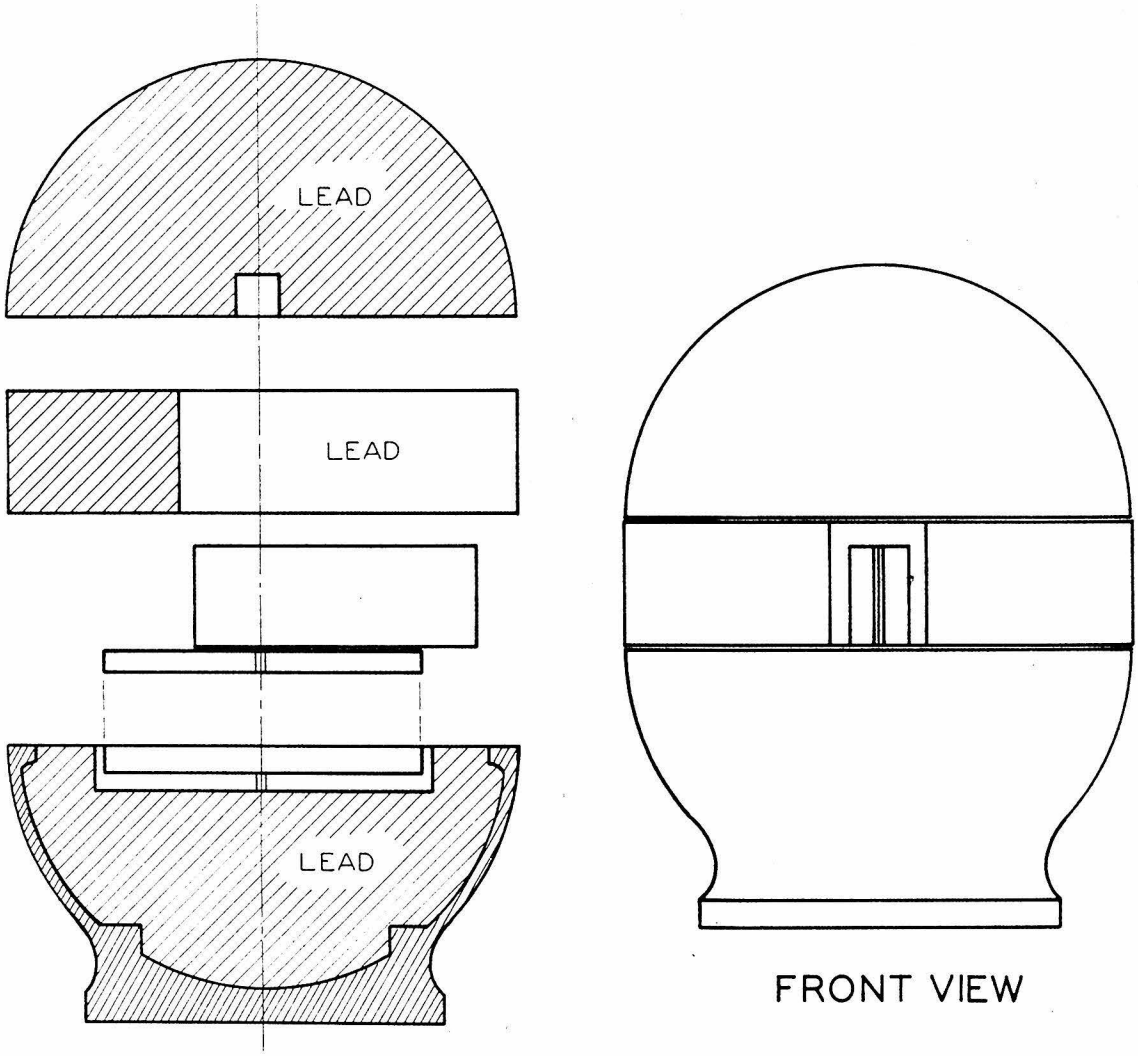
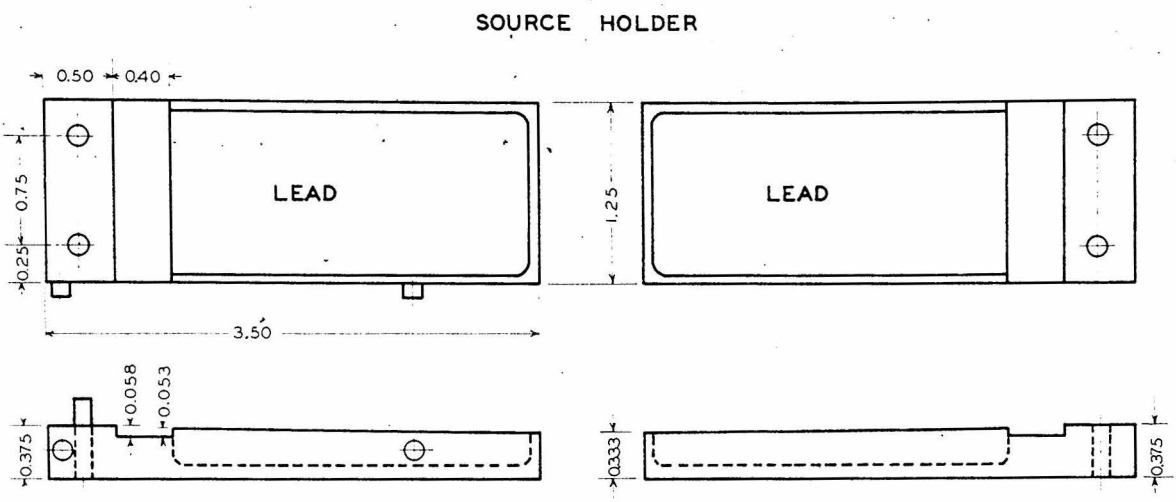


Figure 5


SOURCE HOLDER
0.50
0.40
0.75
0.25
LEAD
1.25
LEAD
3.50
0.058
0.053
0.375
0.333
0.375

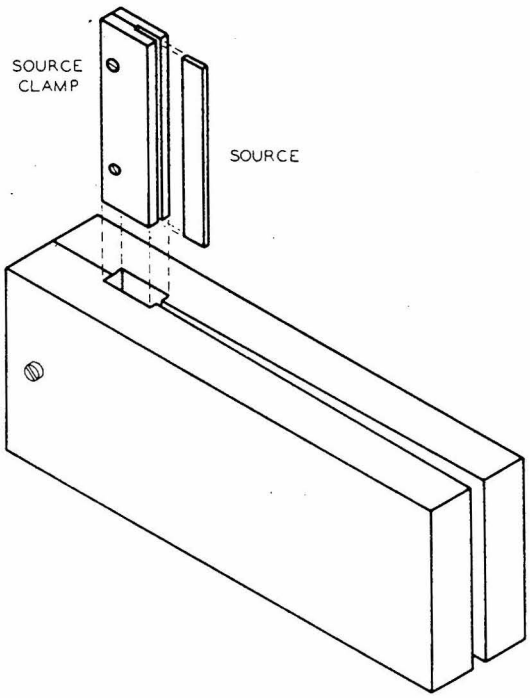
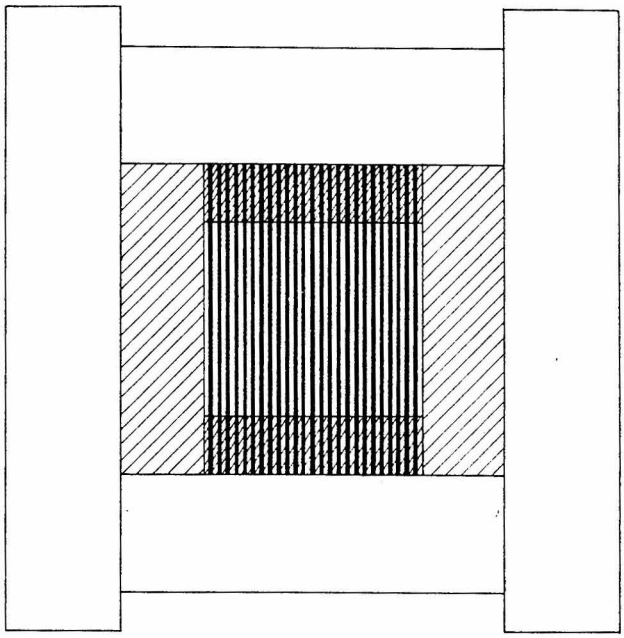

SOURCE CLAMP
SOURCE

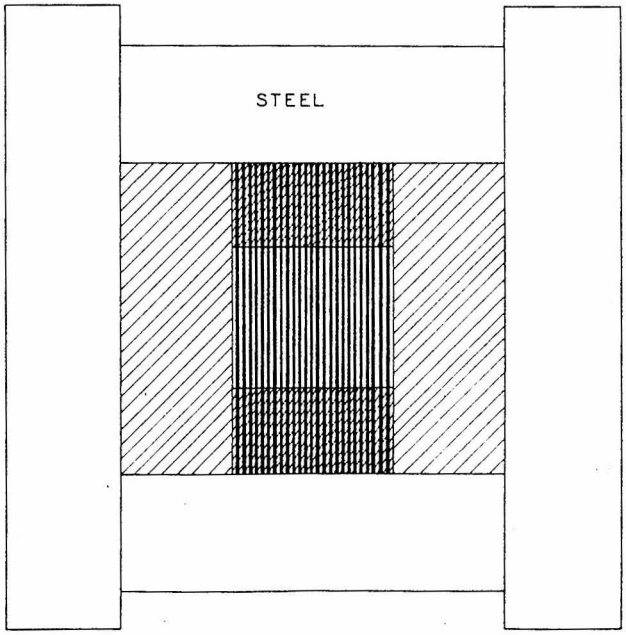
Figure 6

COLLIMATOR



REAR VIEW

SHADED SECTIONS ARE MADE OF LEAD



FRONT VIEW

Figure 7

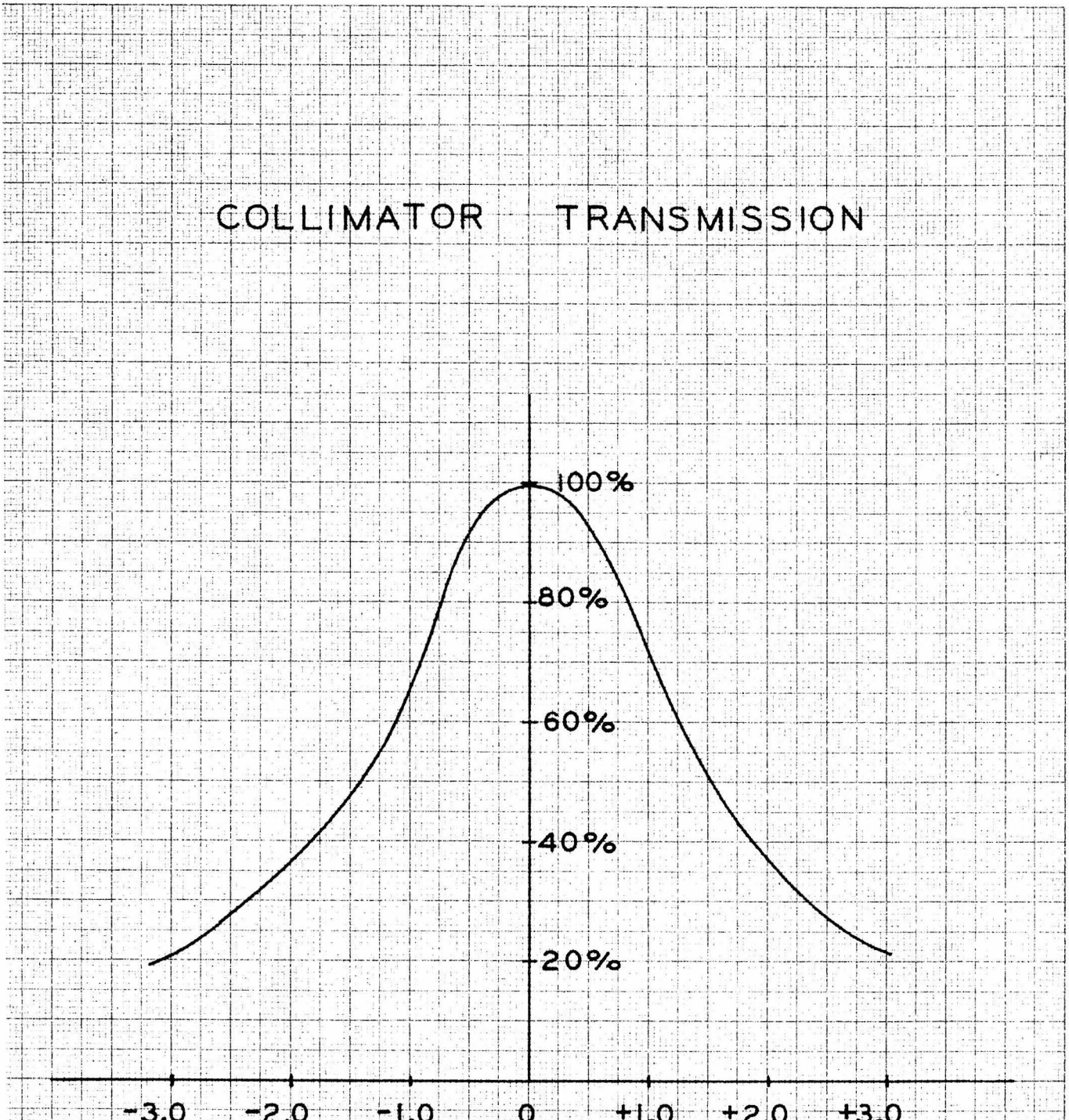
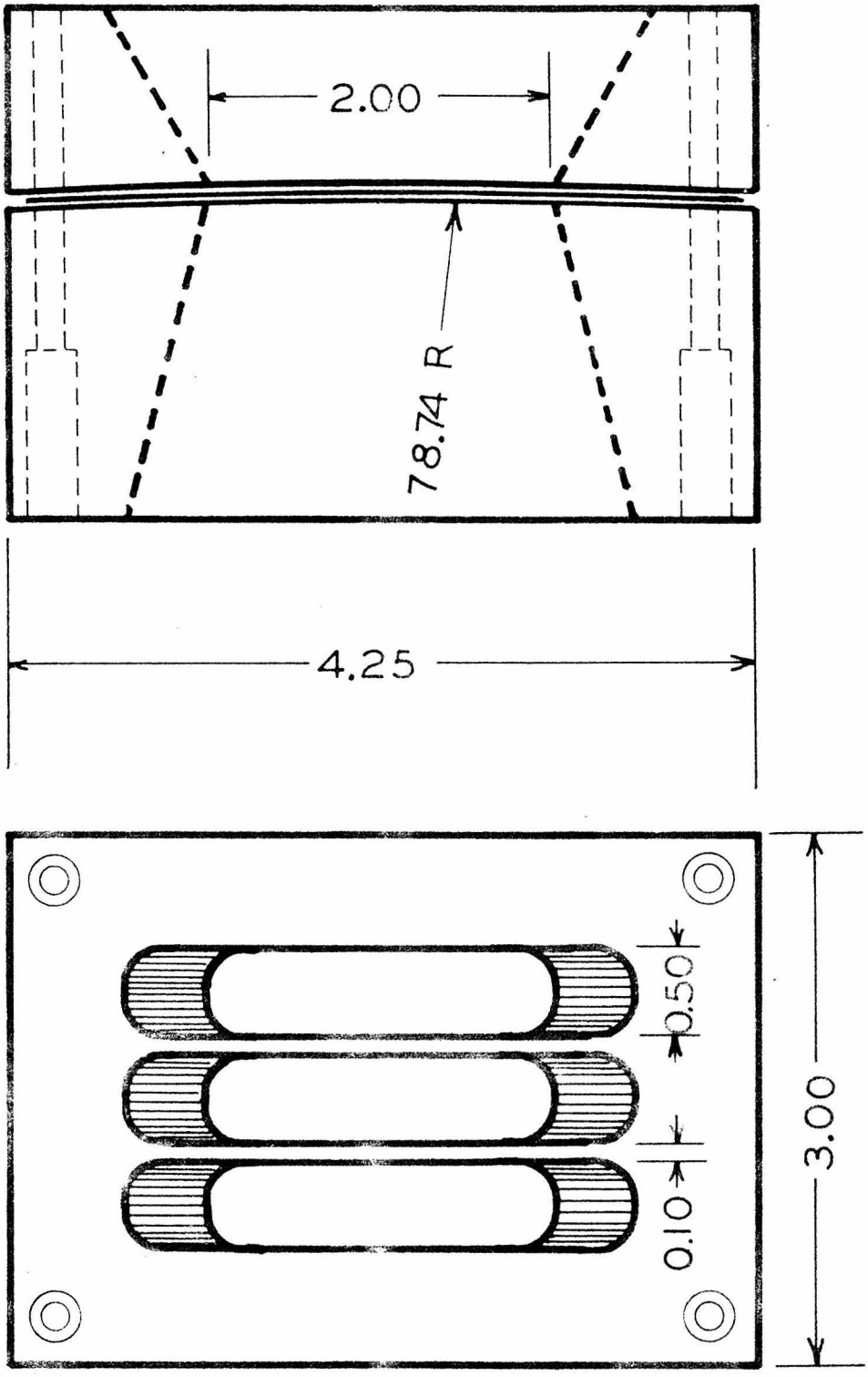

COLLIMATOR TRANSMISSION
100%
80%
60%
40%
20%
-3.0
-2.0
-1.0
0
+1.0
+2.0
+3.0
X-UNITS

Figure 7 A

Figure 8

CRYSTAL HOLDER



FRONT VIEW

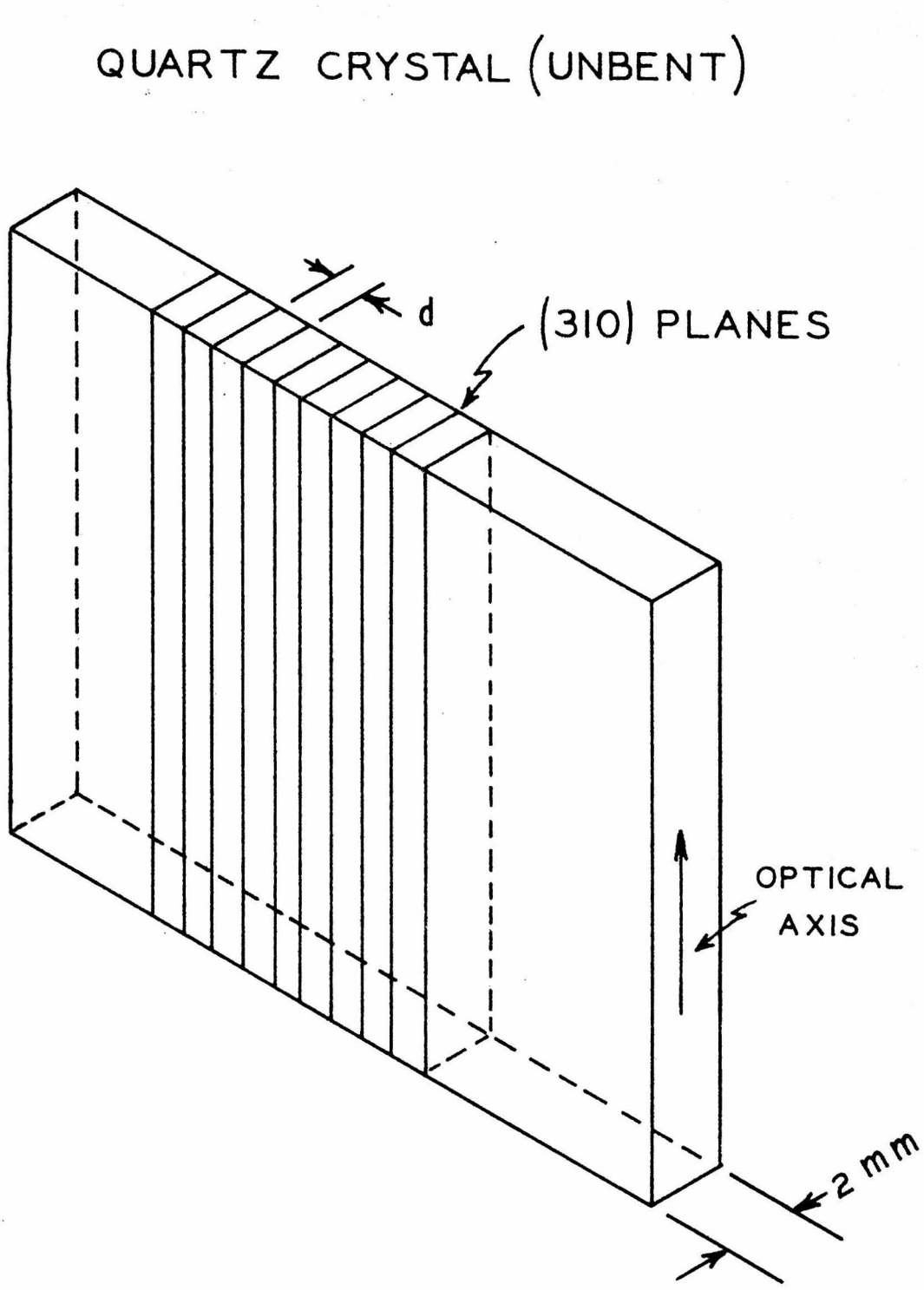
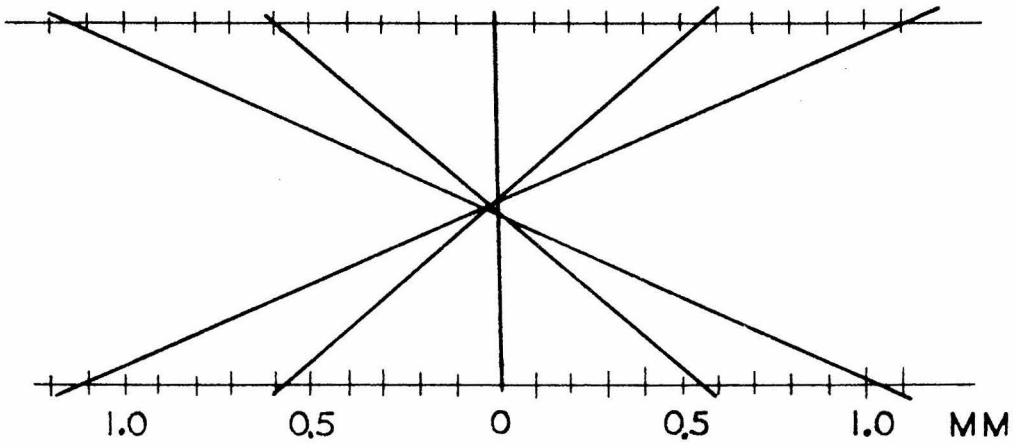
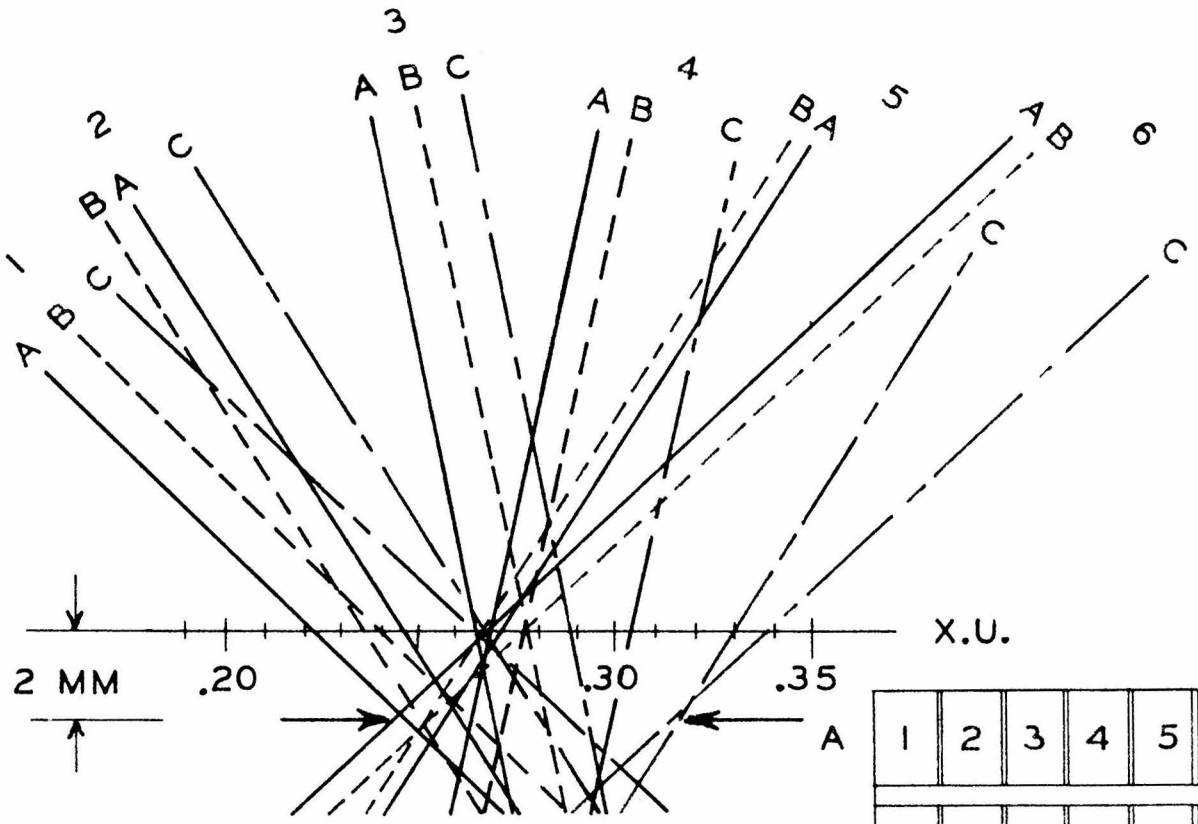


Figure 9 . The (310) lattice planes of Quartz lie so that they are parallel to the edge of the crystal and normal to the major faces. The crystal is bent elastically so that the optic axis, and therefore the (310) planes, lie parallel to the generators of a right circular cylinder.

Figure 10

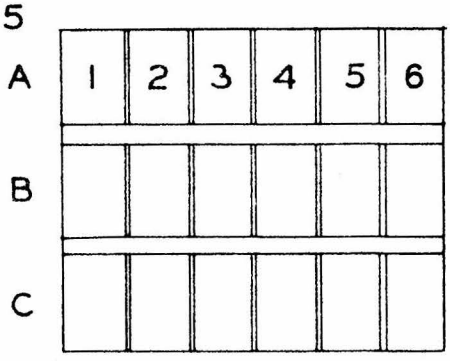


OPTICAL FOCUS

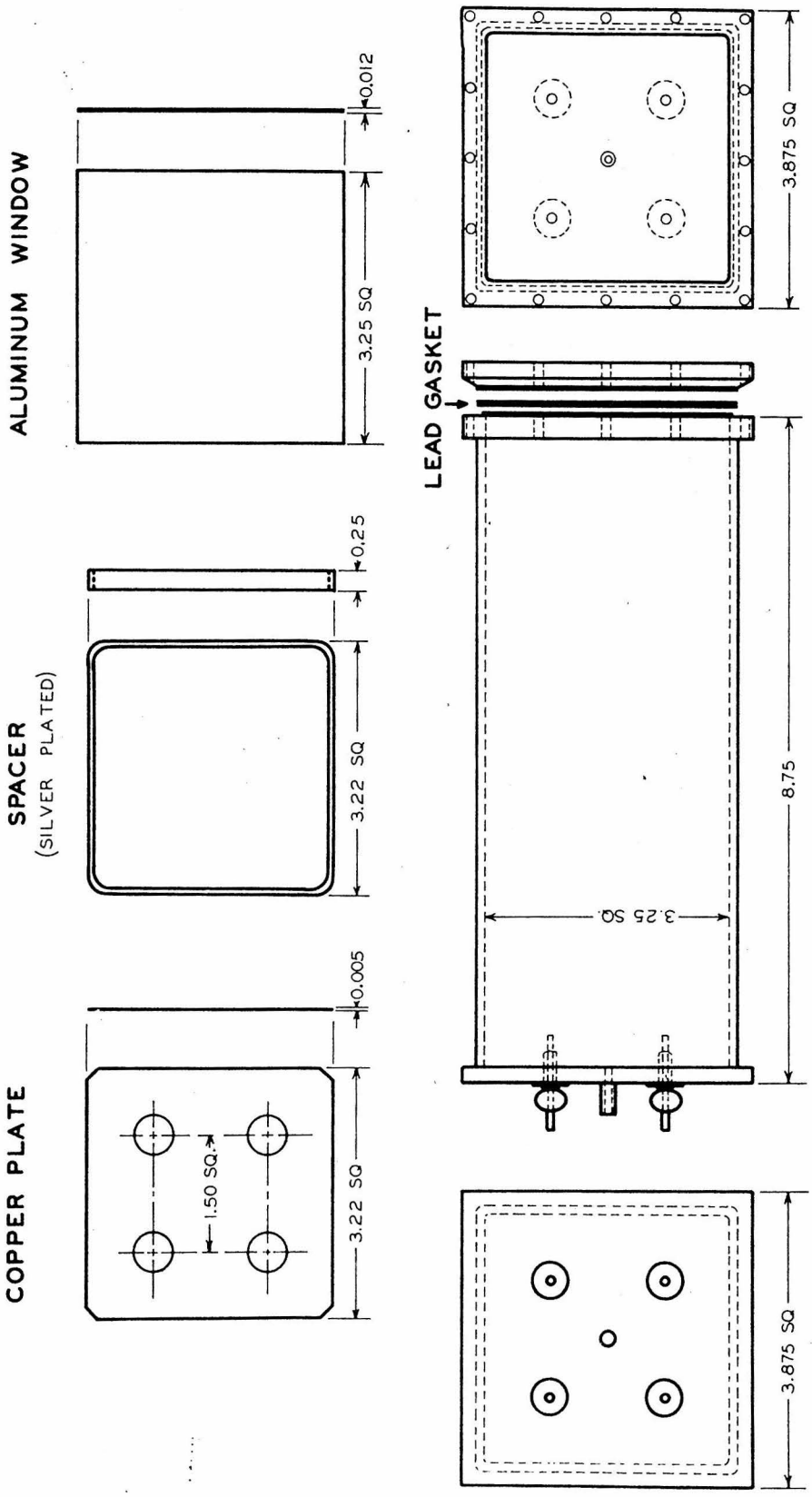


X RAY FOCUS

BEST WIDTH 0.07 X.U.



CRYSTAL APERTURE



COUNTER CASE

Figure 11

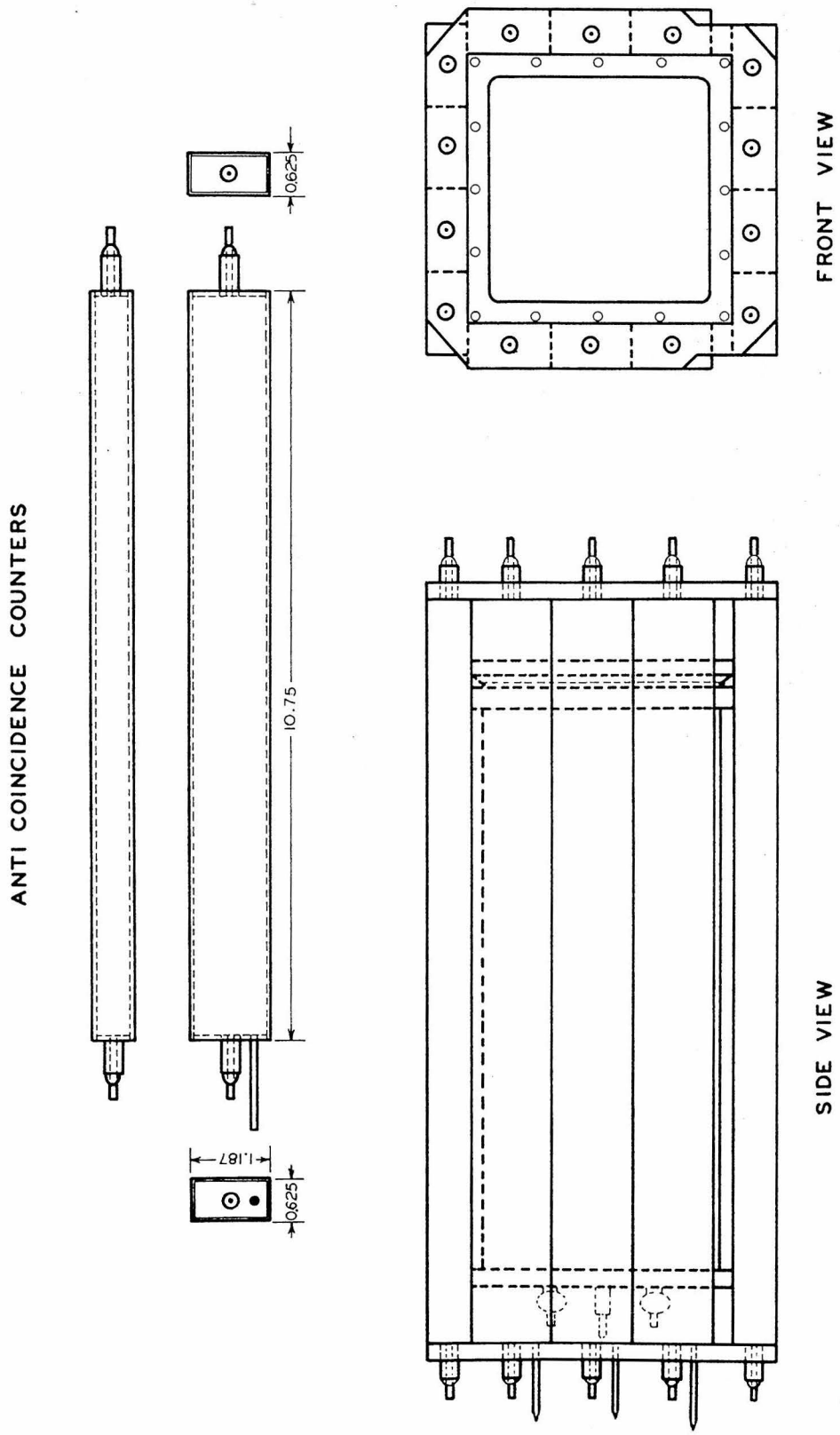
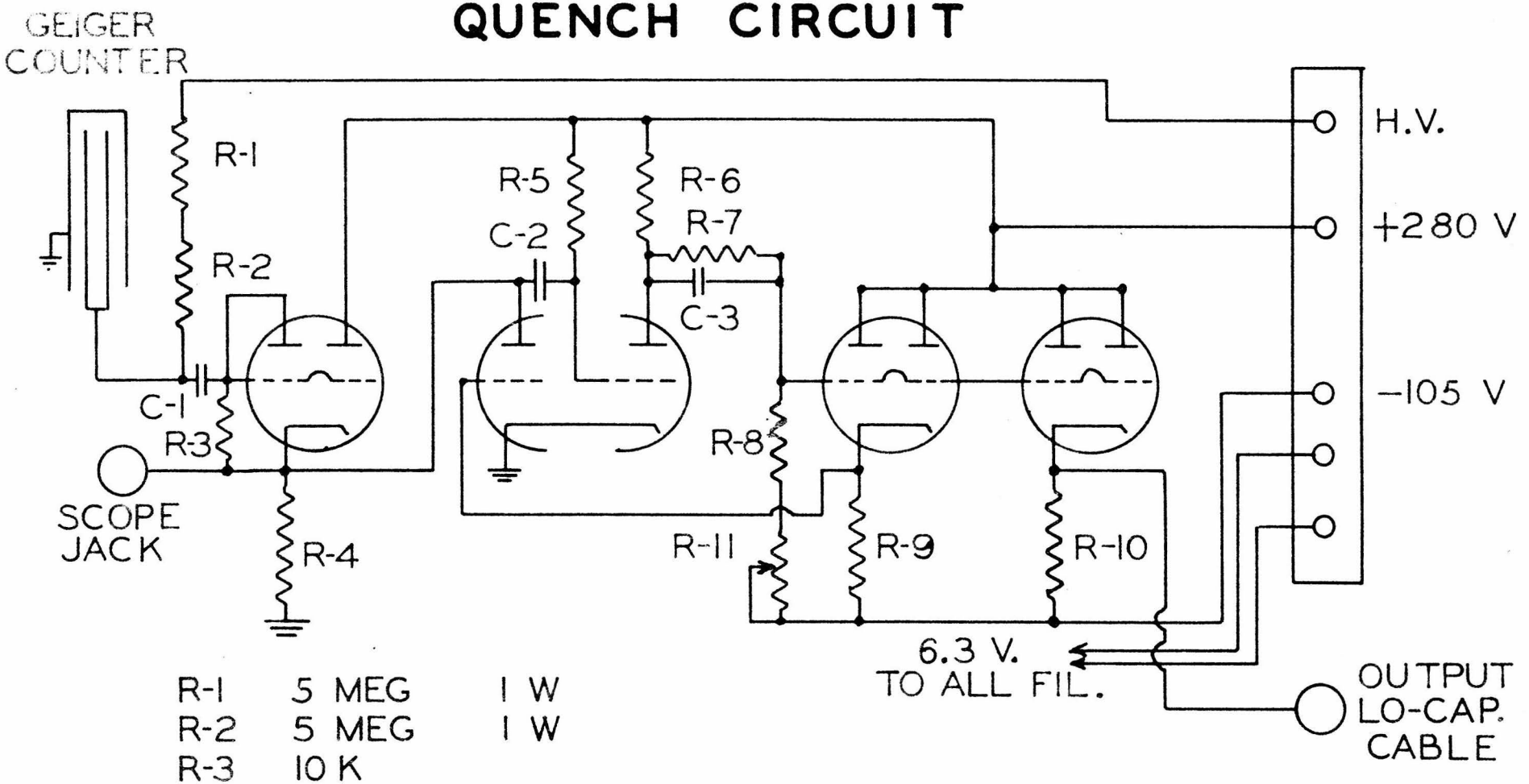

ANTI COINCIDENCE COUNTERS
0.625
10.75
1.187
0.625
FRONT VIEW
SIDE VIEW

Figure 12

QUENCH CIRCUIT

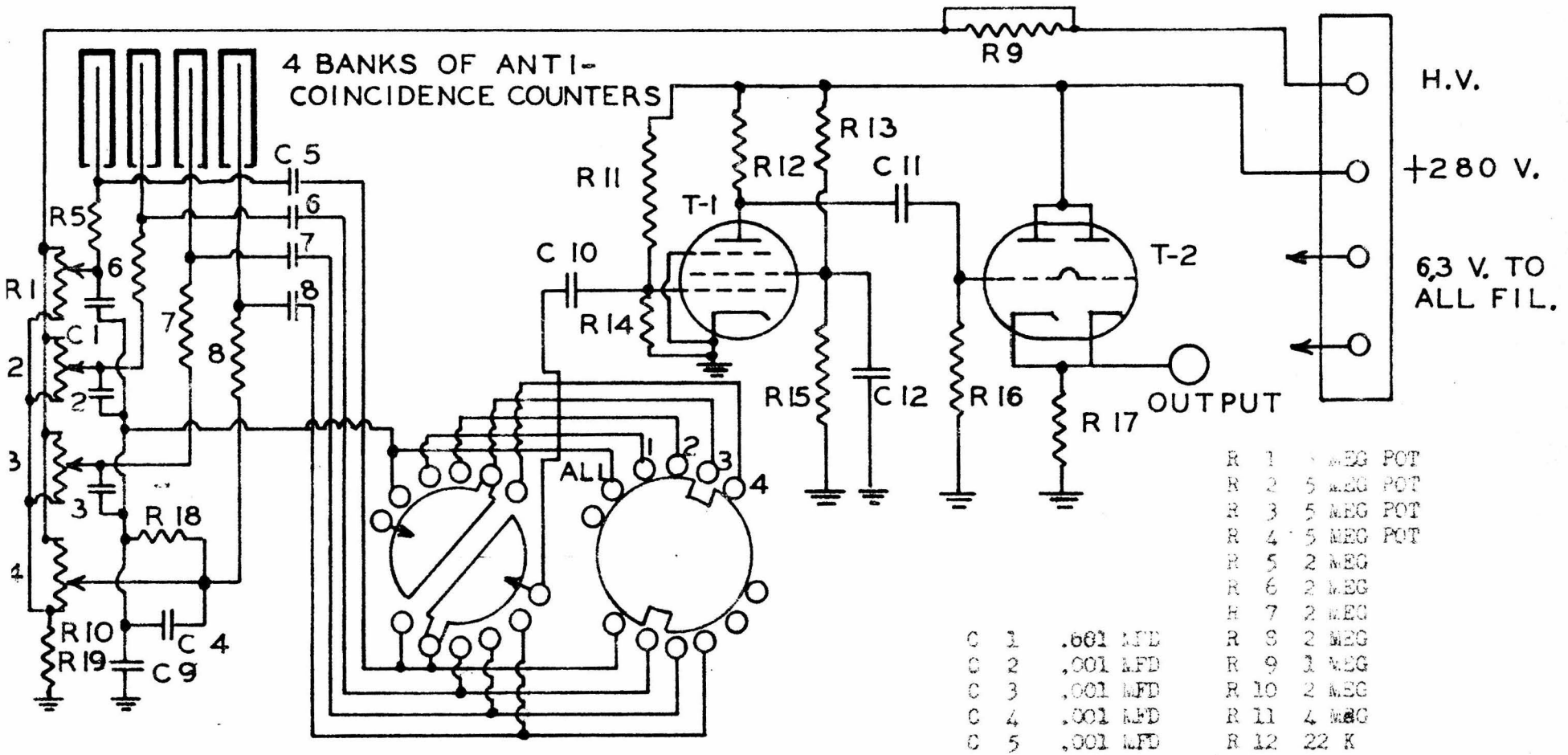


R-1	5 MEG	1 W
R-2	5 MEG	1 W
R-3	10 K	
R-4	50 K	2 W
R-5	150 K	1 W
R-6	20 K	10 W
R-7	200 K	1 W
R-8	150 K	1 W
R-9	200 K	1 W
R-10	200 K	1 W
R-11	50 K POT	

C-1	.002 MFD	2500 V
C-2	001 MFD MICA	500 V
C-3	100 MMFD	500 V

ALL TUBES ARE 6J6

Figure 13

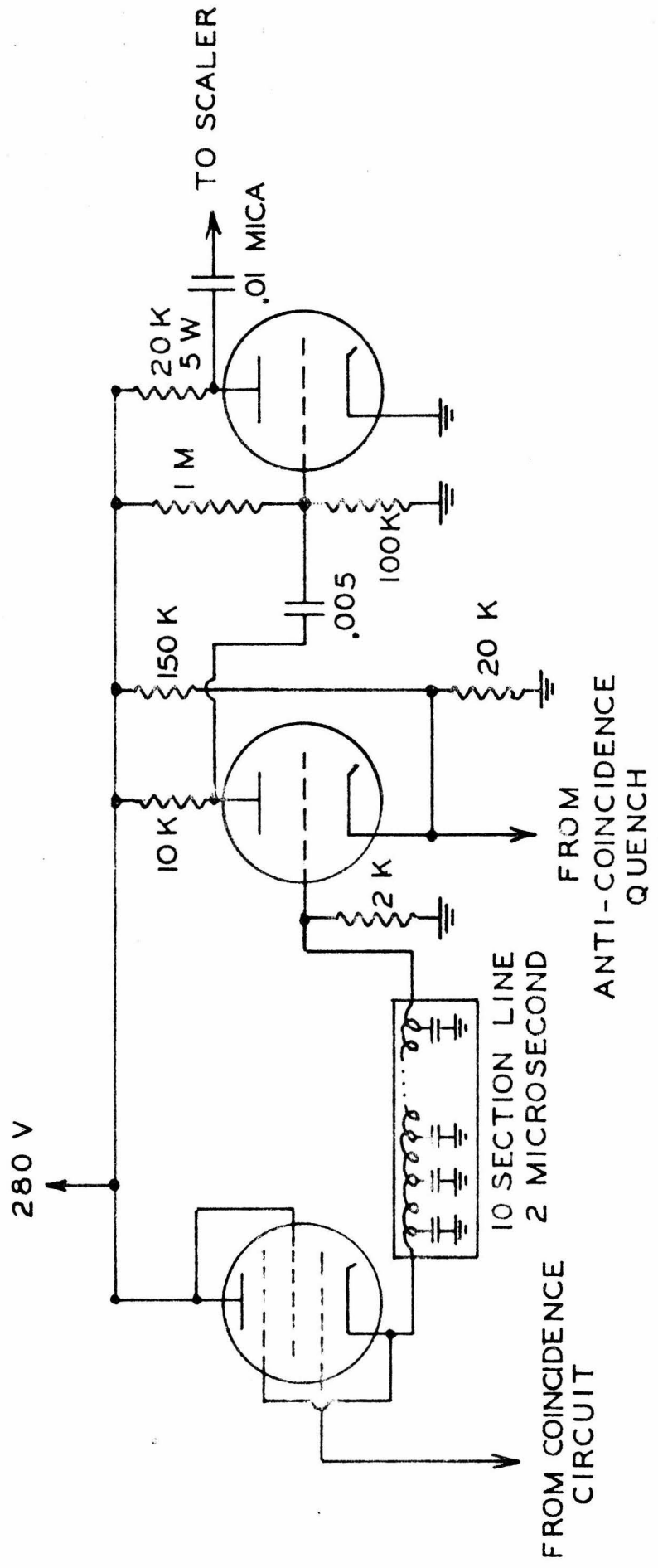


T 1 6SH7
T 2 6SN7

C 1	.001 MFD	R 1	½ MEG POT
C 2	.001 MFD	R 2	5 MEG POT
C 3	.001 MFD	R 3	5 MEG POT
C 4	.001 MFD	R 4	5 MEG POT
C 5	.001 MFD	R 5	2 MEG
C 6	.001 MFD	R 6	2 MEG
C 7	.001 MFD	R 7	2 MEG
C 8	.001 MFD	R 8	2 MEG
C 9	.001 MFD	R 9	1 MEG
C 10	100 MMFD	R 10	2 MEG
C 11	.001 MFD	R 11	4 MEG
C 12	.01 MFD	R 12	22 K
		R 13	75 K
		R 14	500 K
		R 15	50 K
		R 16	500 K
		R 17	200 K
		R 18	7.5 MEG
		R 19	1 MEG

ANTI-COINCIDENCE QUENCH CIRCUIT

Figure 13 A

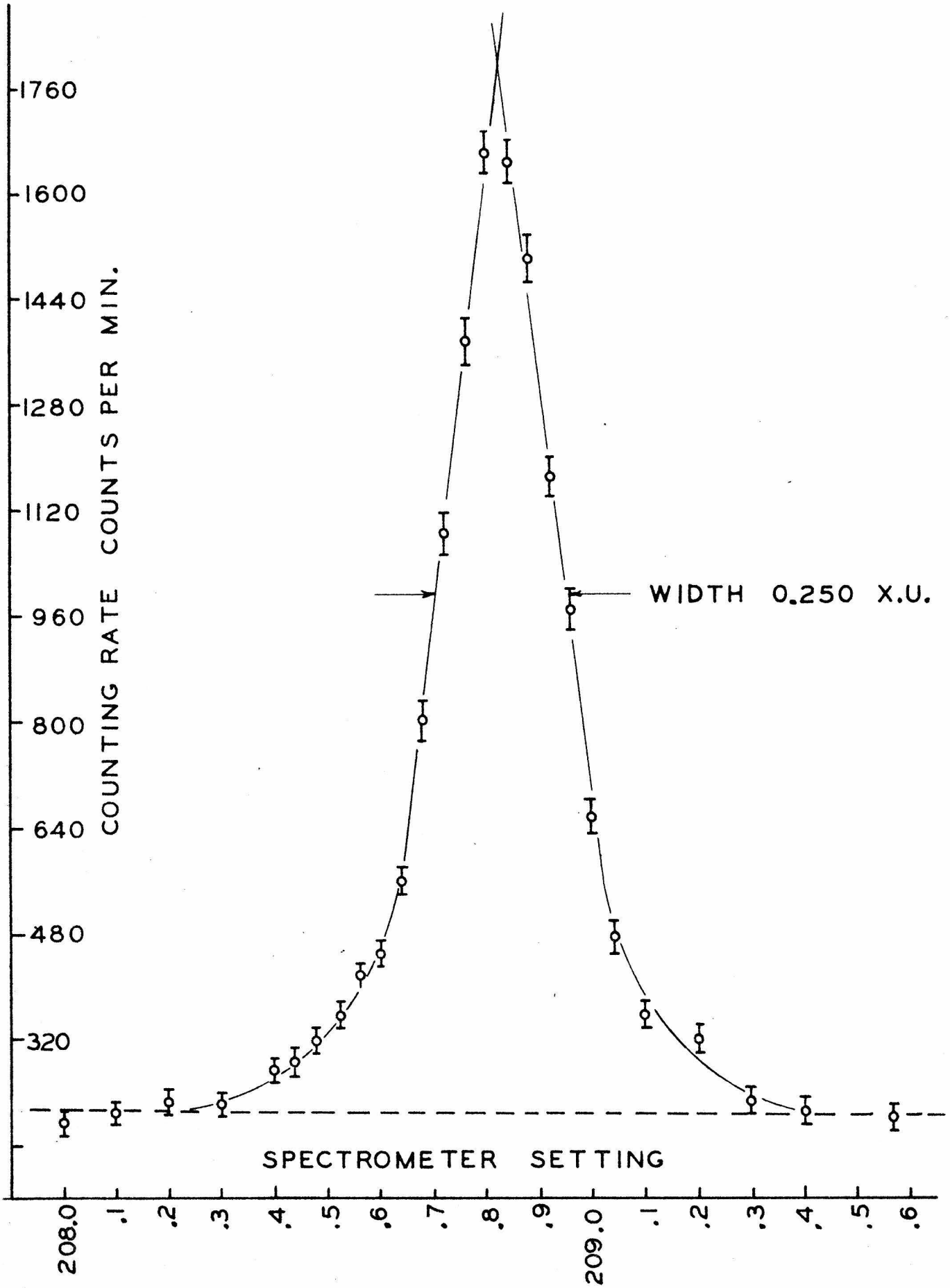


ANTI-COINCIDENCE CIRCUIT

Figure 14

Figure 15

TUNGSTEN K α_1 X-RAY LINE



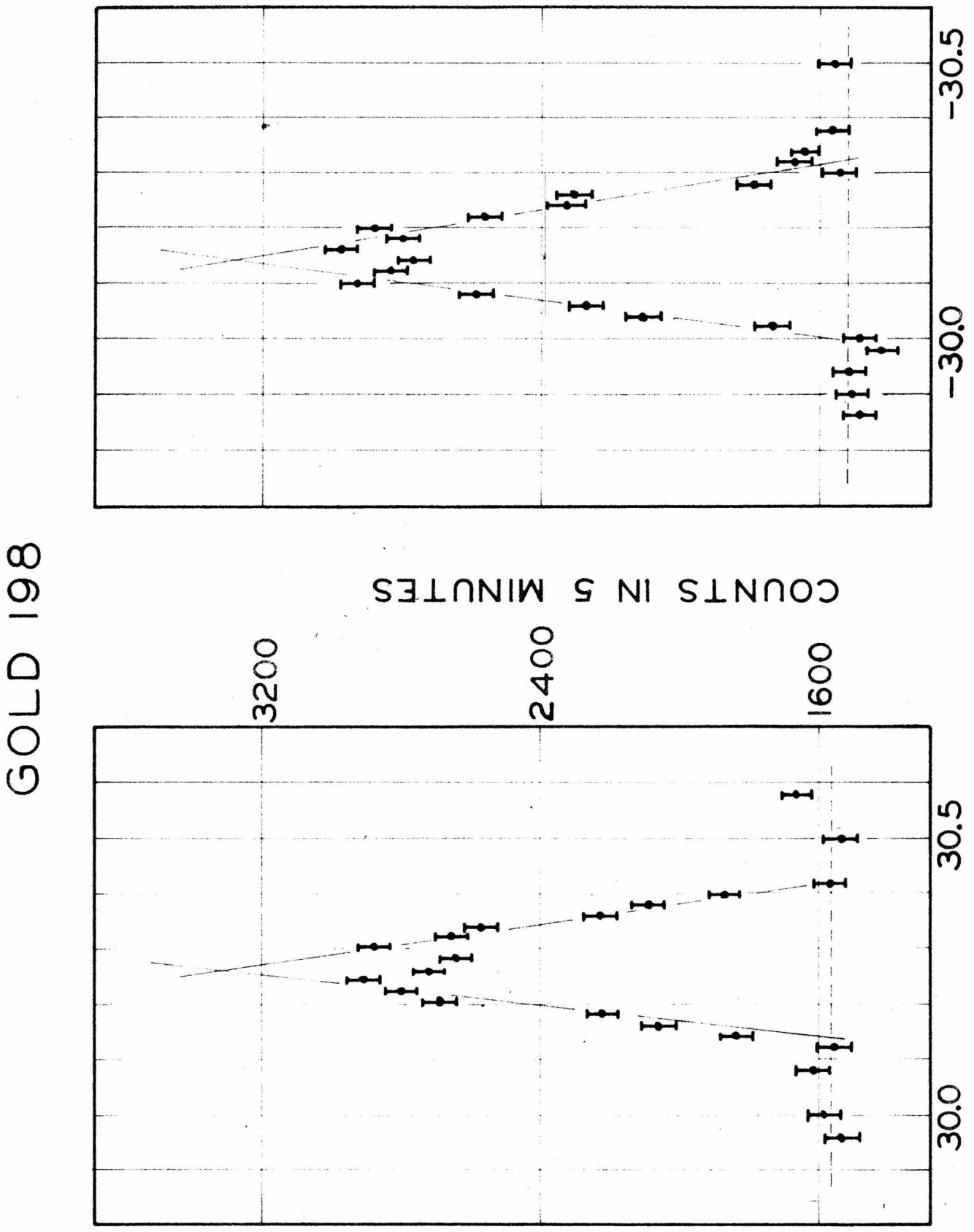

GOLD 198
COUNTS IN 5 MINUTES
3200
2400
1600
30.5
30.0
-30.5
-30.0
WAVELENGTH IN X-UNITS

Figure 16

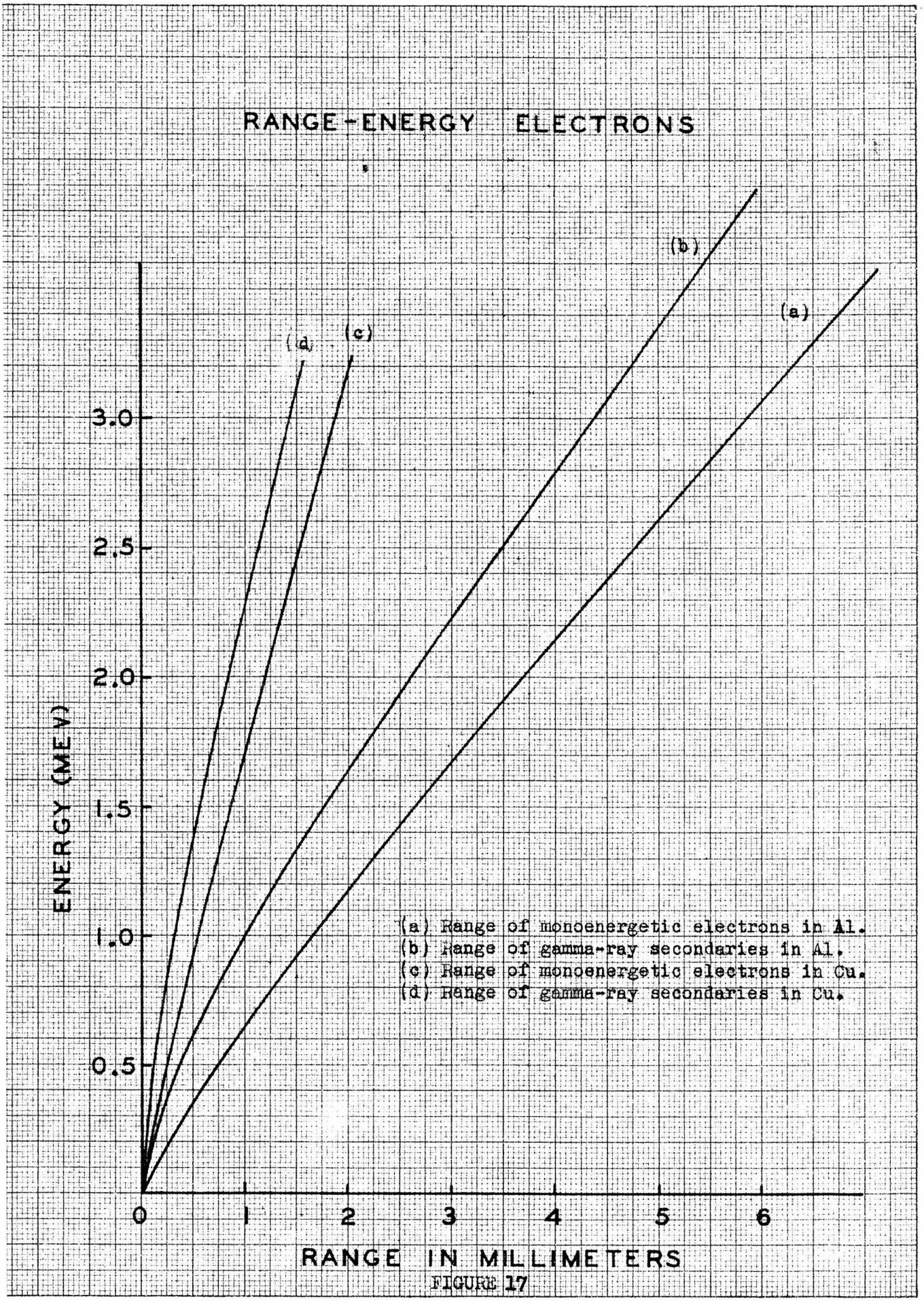

RANGE-ENERGY ELECTRONS
(b)
(a)
(d)
(c)
3.0
2.5
2.0
1.5
1.0
0.5
ENERGY (MEV)
0
1
2
3
4
5
6
RANGE IN MILLIMETERS
(a) Range of monoenergetic electrons in Al.
(b) Range of gamma-ray secondaries in Al.
(c) Range of monoenergetic electrons in Cu.
(d) Range of gamma-ray secondaries in Cu.

FIGURE 17

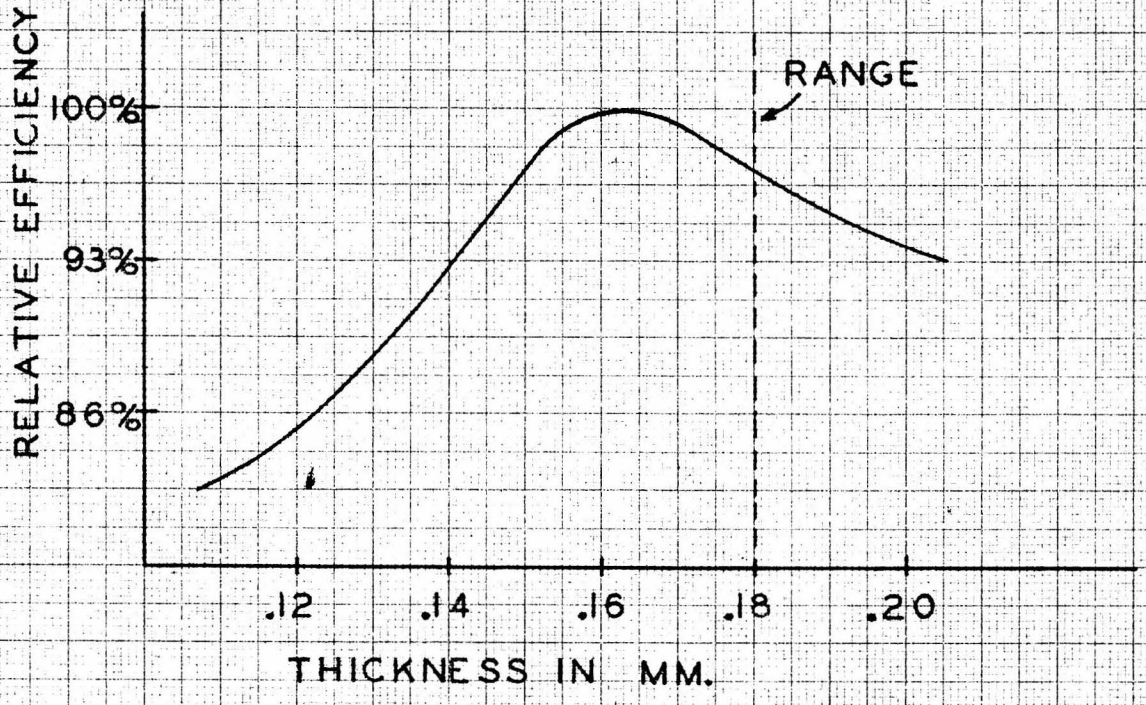
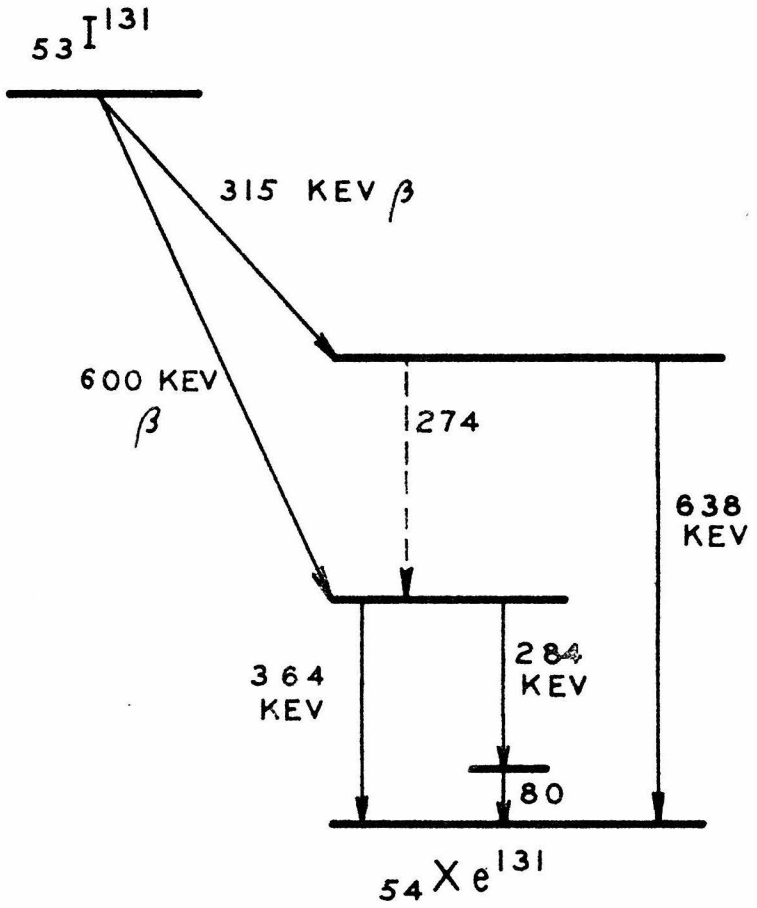
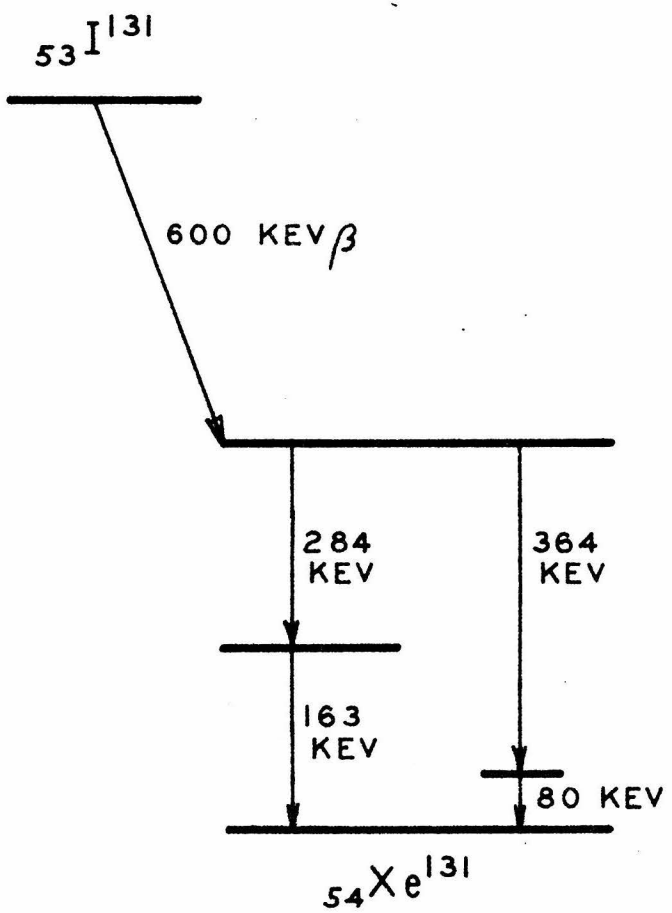

RELATIVE EFFICIENCY
100%
93%
86%
RANGE
.12
.14
.16
.18
.20
THICKNESS IN MM.

FIGURE 18



METZGER AND DEUTSCH



OWEN MOE AND COOK

FIGURE 19. Disintegration Schemes of I 131

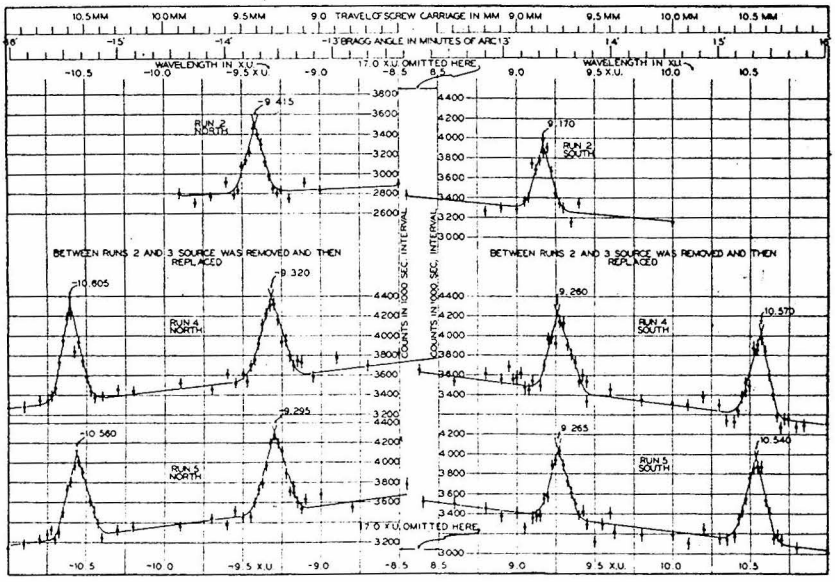


Figure **20.** Three spectral curves showing the 1.1 and 1.3 Mev lines from Co^{60} as reflected from both sides of the planes of the curved crystal. Run 1 (not shown) was exploratory, to locate the 1.3 Mev line. Run 2 shows the 1.3 Mev line while runs 4 and 5 show both 1.1 and 1.3 Mev lines. The source was removed from its holder after run 2 to permit temporary study of another much shorter-lived source which had just been received, Ta^{182}. The Co^{60} source was then replaced in the instrument and another exploratory run (run 3, not shown) was made to relocate the lines. This removal and replacement of the source accounts for the slight shift in the wavelength position of the lines on the instrument scale, a shift corresponding to a displacement of the source in its holder of about 0.07 mm. The separation however between the respective reflections from the two sides of the crystal planes (which is used as the measure of the wavelength) is very reproducible from run to run. Scales at the top show the Bragg angle in minutes of arc and displacements of the screw carriage L (relative to Q) in millimeters. The wavelength scales shown are in nominal milliangstroms. Their differences are converted to true milliangstroms (10^{-11} cm) by multiplying by 1.00179, the factor determined by the X-ray calibration. More than three times the total width of this figure is omitted from the wavelength scale in the space at the counter. The ordinate scales are indicated by numbers giving the total number of counts accumulated at each setting in a 1,000 sec time interval.

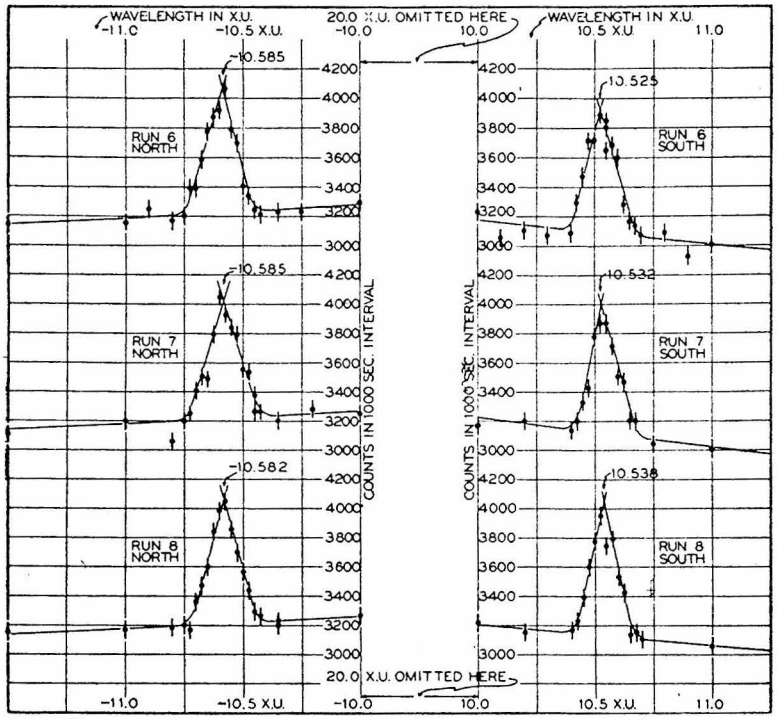


Figure 21. Three more runs taken on the Co^{60} 1.1 Mev line alone. Here the source was not disturbed and this gives a good idea of the reproducibility of the measurements, when the instrument is at its best. The scales on this figure are similar in all respects to those of Figure 5.

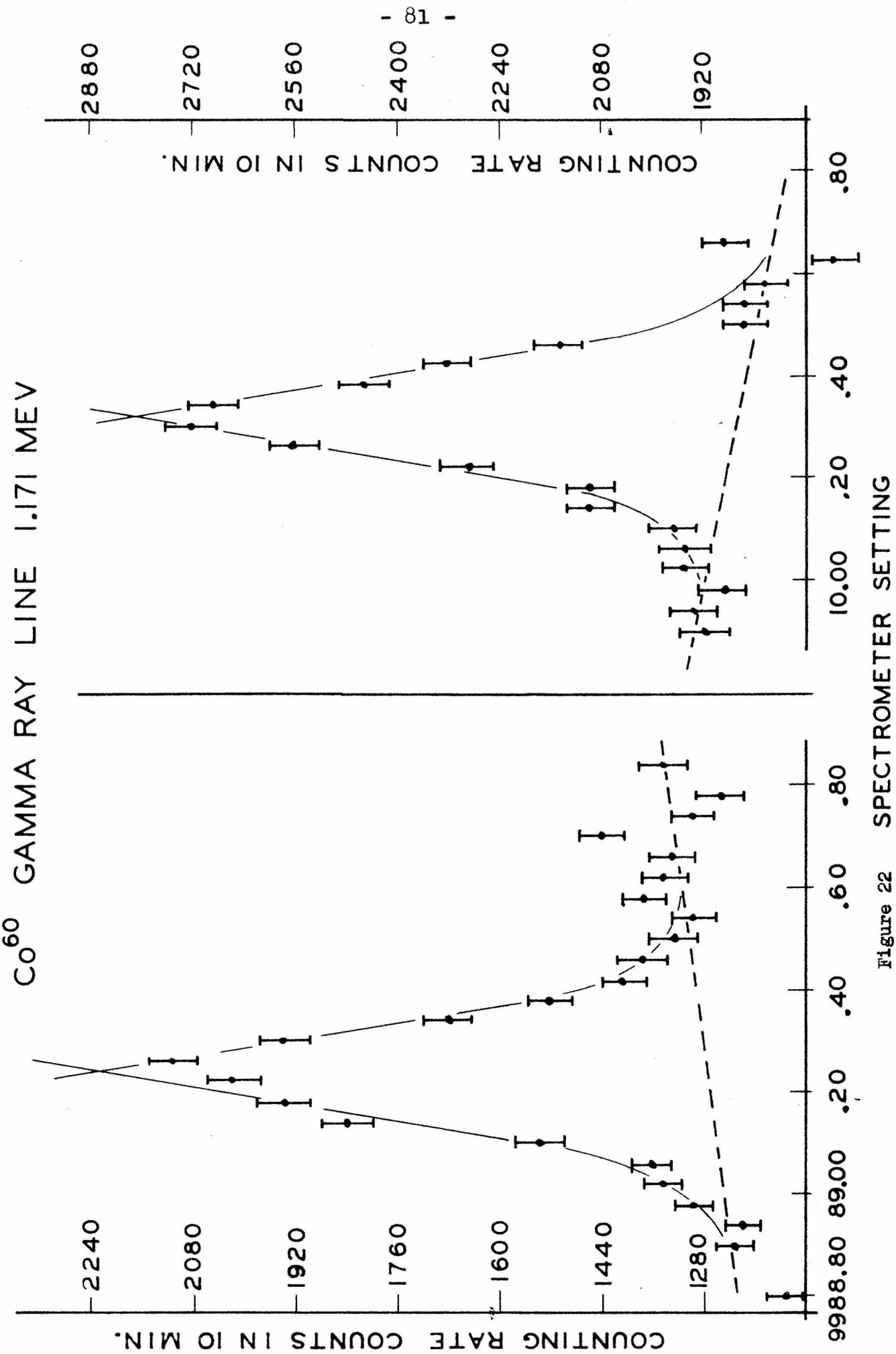
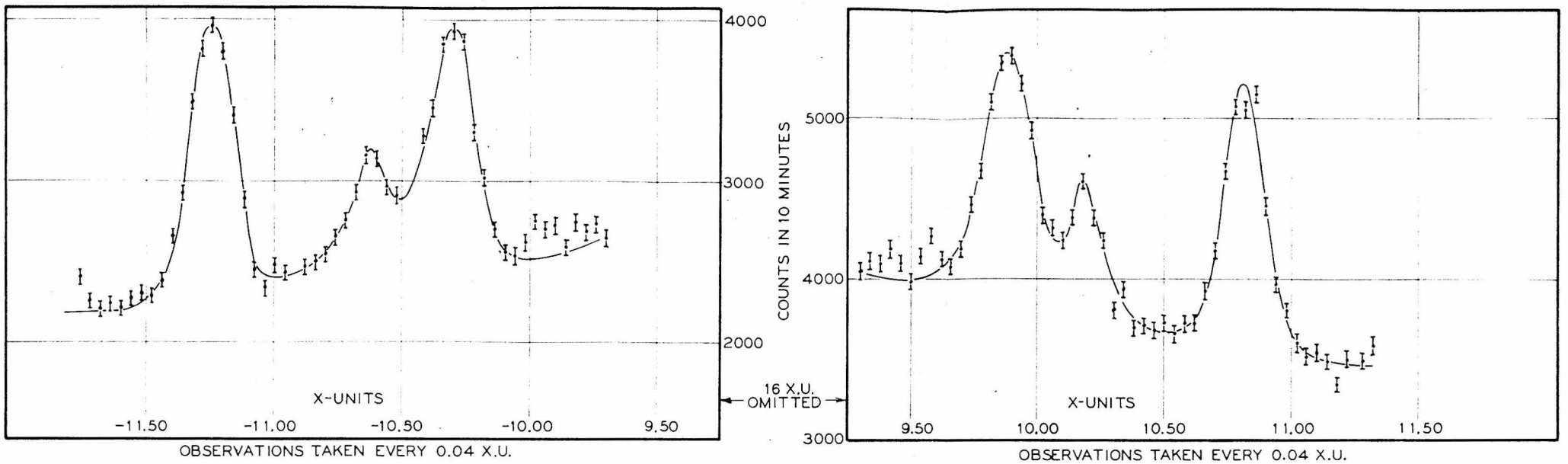
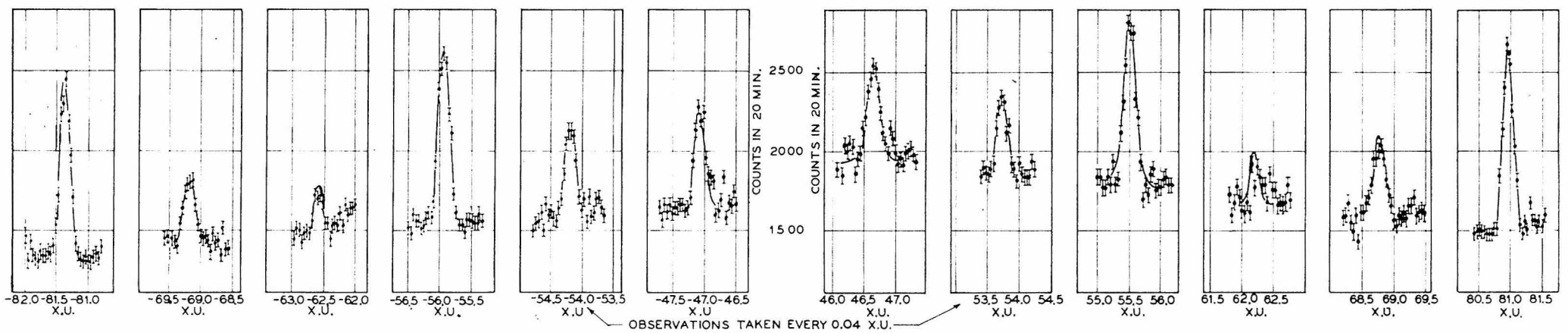

Co^{60} GAMMA RAY LINE 1.171 MEV
COUNTING RATE COUNTS IN 10 MIN.
2880
2720
2560
2400
2240
2080
1920
9988.80
89.00
10.00
.20
.40
.60
.80
SPECTROMETER SETTING
COUNTING RATE COUNTS IN 10 MIN.
2240
2080
1920
1760
1600
1440
1280

Figure 22


4000
3000
2000
X-UNITS
-11.50
-11.00
-10.50
-10.00
9.50
OBSERVATIONS TAKEN EVERY 0.04 X.U.
COUNTS IN 10 MINUTES
16 X.U. OMITTED
5000
4000
3000
X-UNITS
9.50
10.00
10.50
11.00
11.50
OBSERVATIONS TAKEN EVERY 0.04 X.U.


COUNTS IN 20 MIN.
2500
2000
1500
-82.0 -81.5 -81.0 X.U.
-69.5 -69.0 -68.5 X.U.
-63.0 -62.5 -62.0 X.U.
-56.5 -56.0 -55.5 X.U.
-54.5 -54.0 -53.5 X.U.
-47.5 -47.0 -46.5 X.U.
46.0 46.5 47.0 X.U.
53.5 54.0 54.5 X.U.
55.0 55.5 56.0 X.U.
61.5 62.0 62.5 X.U.
68.5 69.0 69.5 X.U.
80.5 81.0 81.5 X.U.
OBSERVATIONS TAKEN EVERY 0.04 X.U.

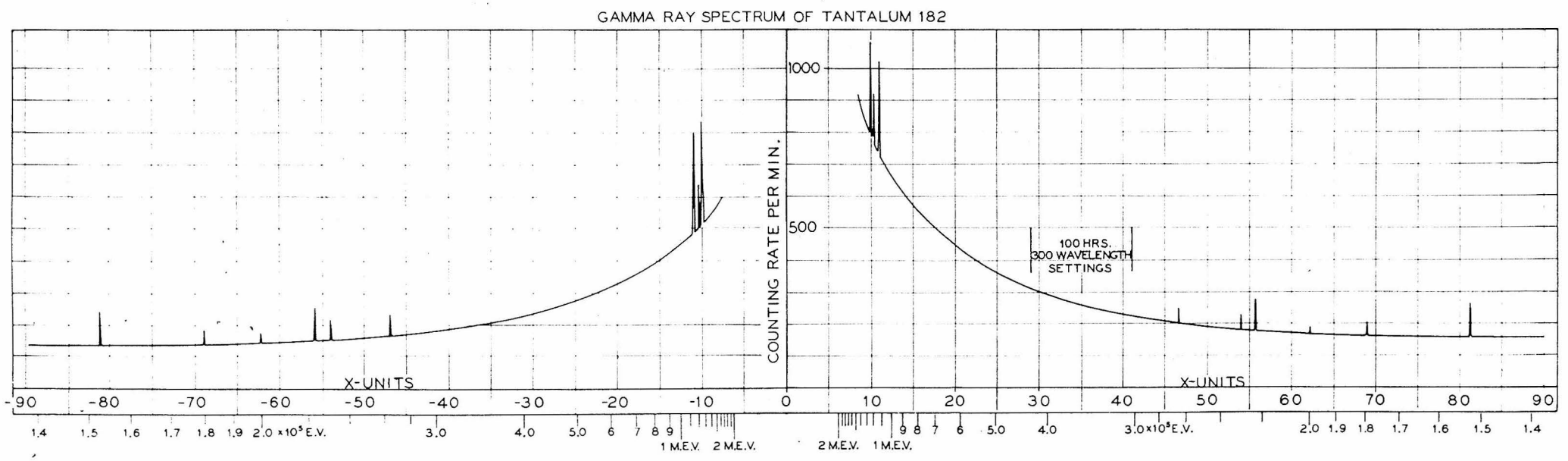

GAMMA RAY SPECTRUM OF TANTALUM 182
COUNTING RATE PER MIN.
1000
500
X-UNITS
-90 -80 -70 -60 -50 -40 -30 -20 -10 0
1.4 1.5 1.6 1.7 1.8 1.9 2.0 x10⁵ E.V.
3.0
4.0
5.0
6
7
8
9
1 M.E.V.
2 M.E.V.
100 HRS.
300 WAVELENGTH SETTINGS
10 20 30 40 50 60 70 80 90
X-UNITS
2 M.E.V.
1 M.E.V.
9
8
7
6
5.0
4.0
3.0 x10⁵ E.V.
2.0
1.9
1.8
1.7
1.6
1.5
1.4

Figure 23

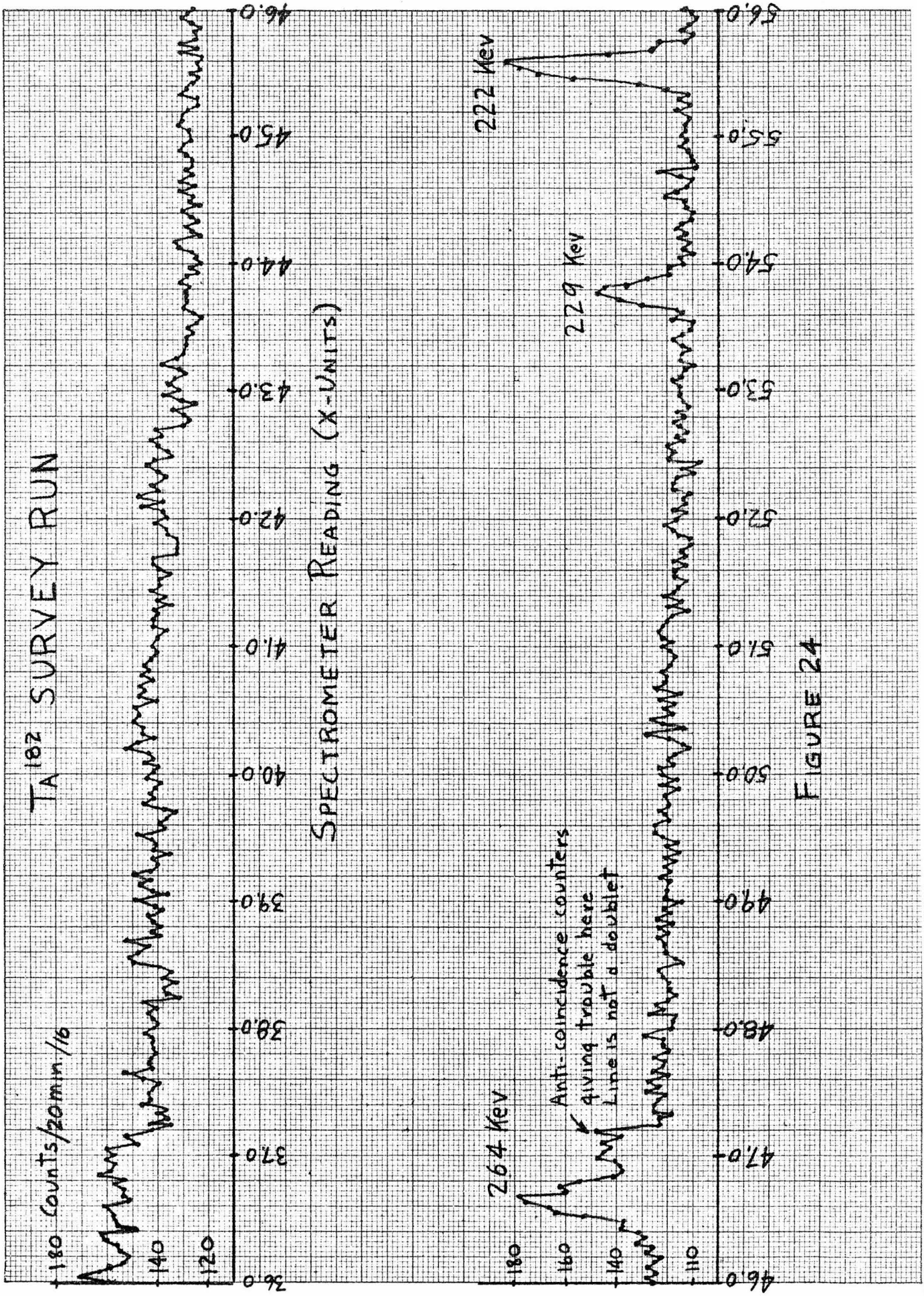

Ta 182 SURVEY RUN
Counts/20min./16
180
140
120
36.0
37.0
38.0
39.0
40.0
41.0
42.0
43.0
44.0
45.0
46.0
Spectrometer Reading (X-Units)
264 Kev
Anti-coincidence counters giving trouble here
Line is not a doublet
229 Kev
222 Kev
180
160
140
110
46.0
47.0
48.0
49.0
50.0
51.0
52.0
53.0
54.0
55.0
56.0

FIGURE 24

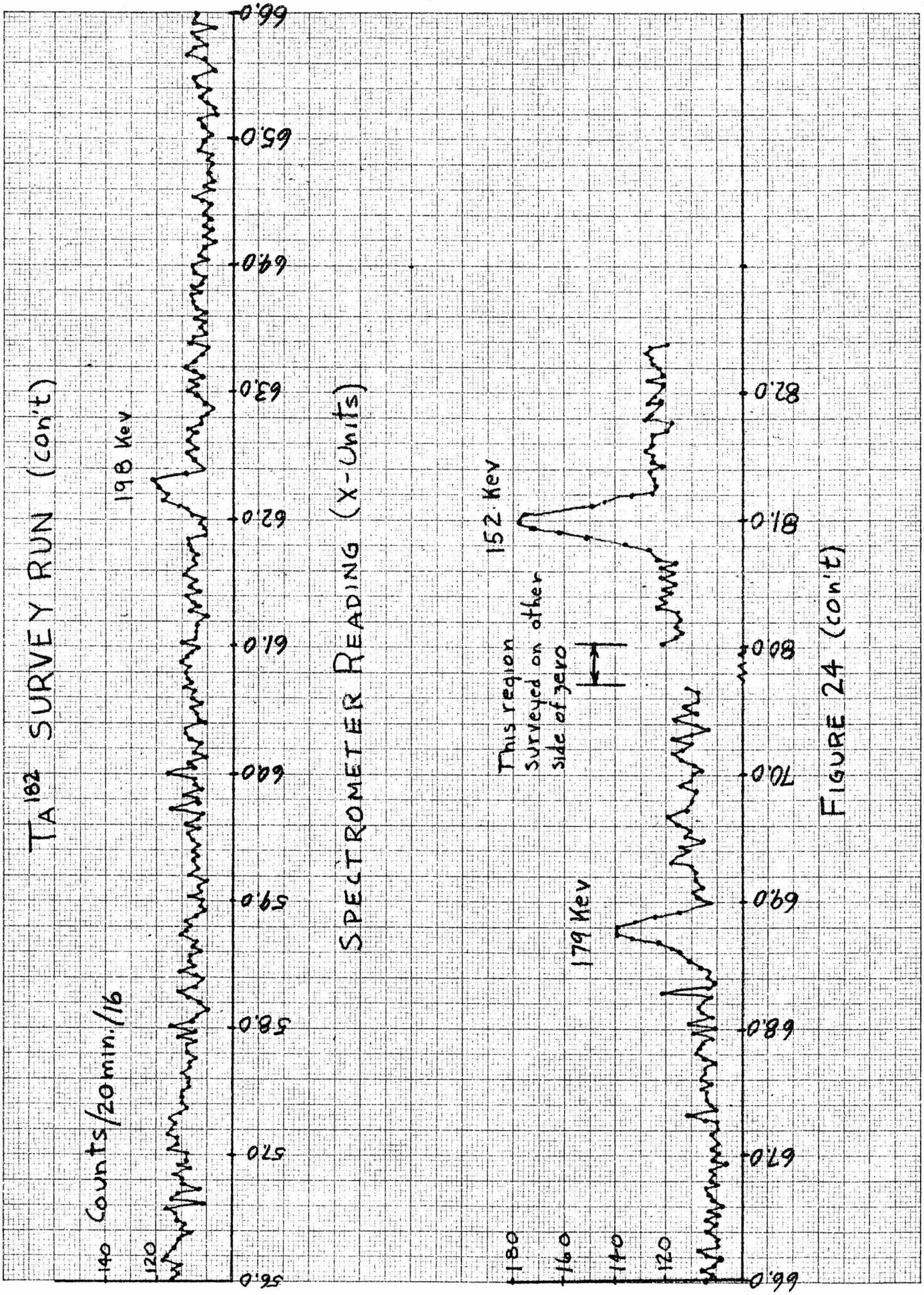


FIGURE 24 (con't)

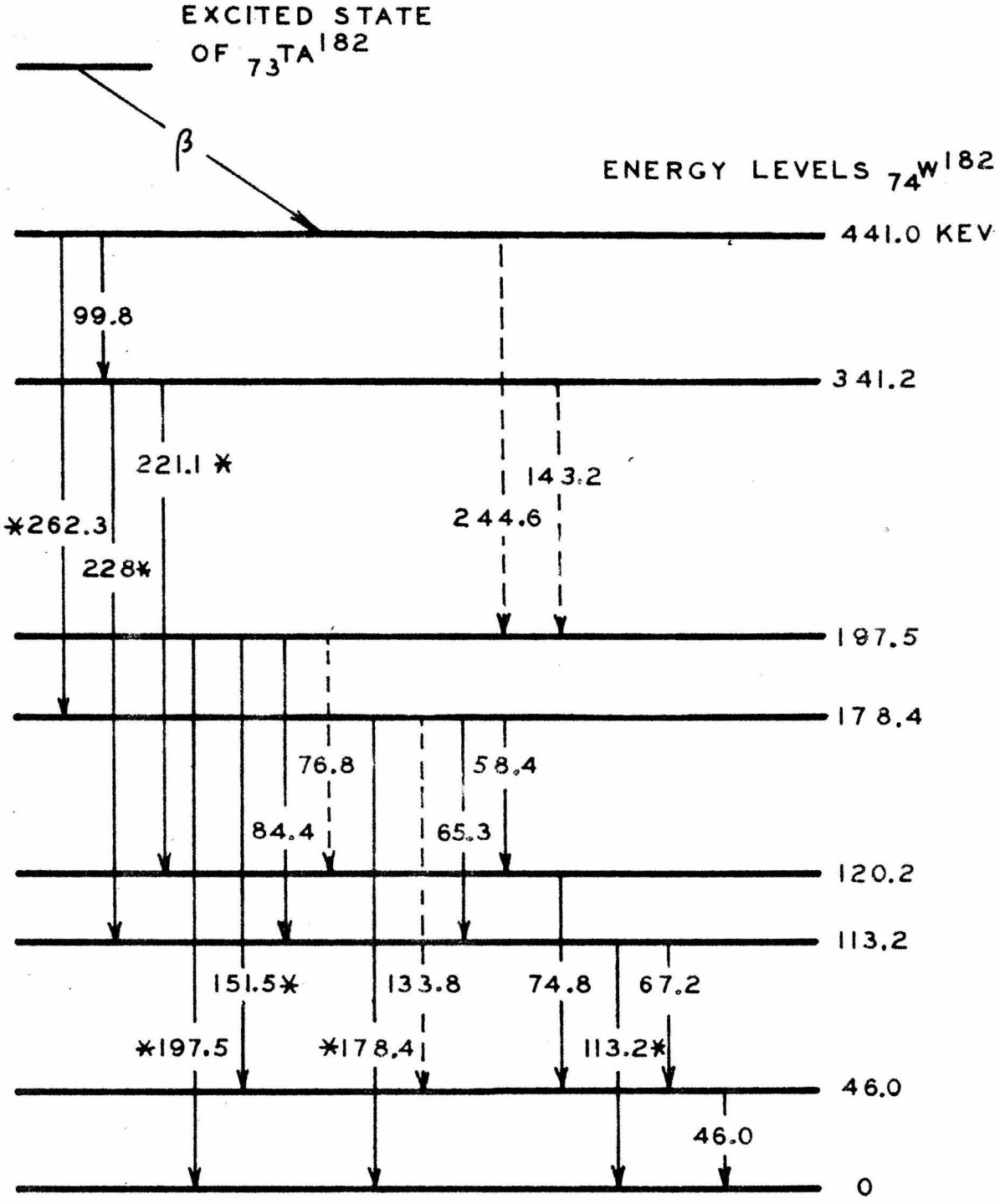


FIGURE 25. Excited levels (kev) in W 182 following beta-emission from Ta 182 according to Cork, Keller, Rutledge, and Stoddard. (See reference 22)

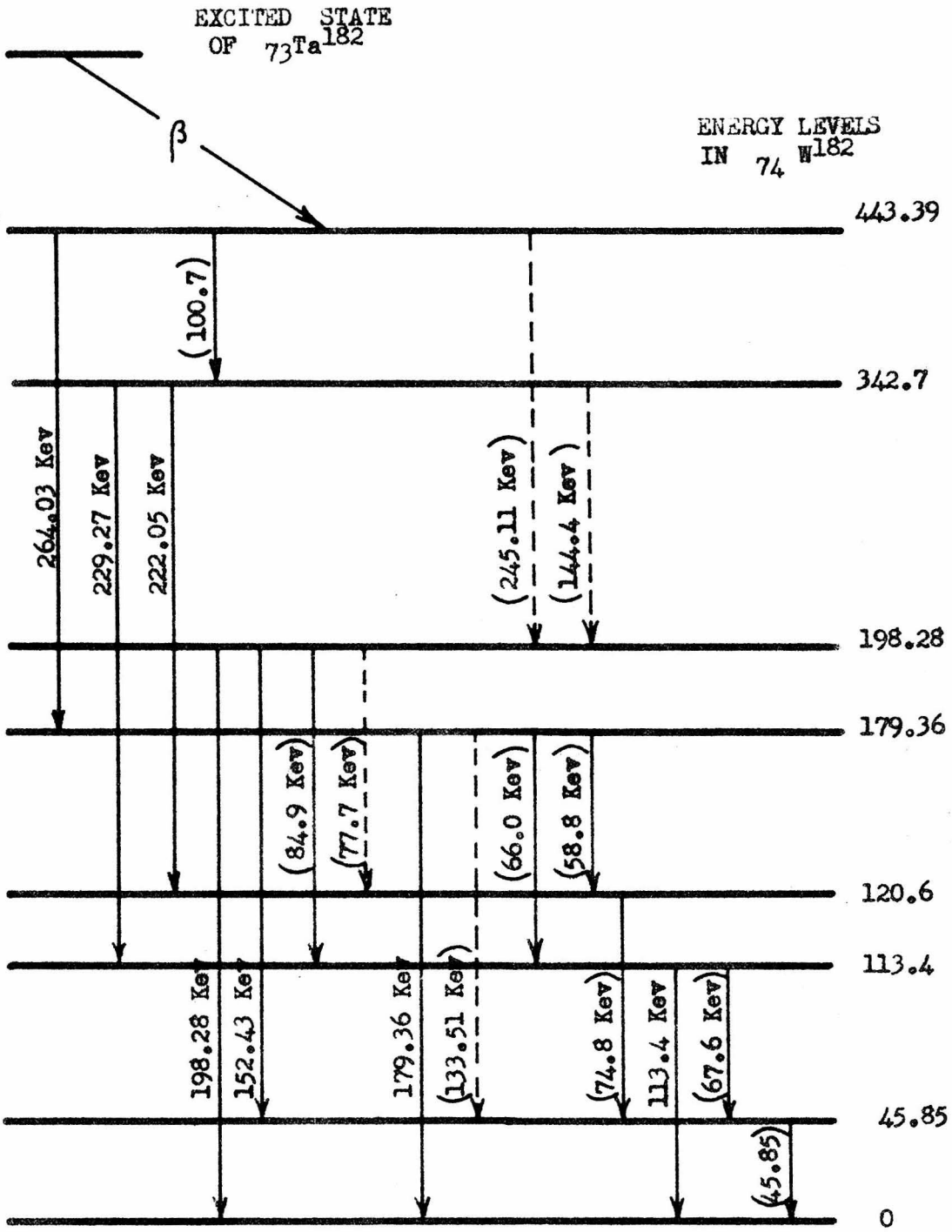


FIGURE 26. Excited levels (kev) in W 182 following beta-emission from Ta 182. Revision of level scheme of Cork et al on the basis of present measurements.