ANALYSIS AND APPLICATION OF SOURCE TILTING IN A MAGNETIC FOCUSING BETA-RAY SPECTROMETER

by

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INTRODUCTION

For nearly half a century electron groups of discrete energies have been analyzed with a magnetic field. The theory applicable in these cases follows the relationships describing the motion of charged particles in a magnetic field.

Theoretical arguments show that a current element in a magnetic field $\underline{B}$ experiences a force $\underline{f}$ per unit volume according to the relationship,

$$\underline{f} = \underline{j} \times \underline{B}$$

in e.m.u., where $\underline{j}$ is the current density. Now an electron of charge e moving with a vector velocity $\underline{v}$ constitutes just such a current element. The current density is $q\underline{v}$, where q is the charge per unit volume. Integrating over a small volume element dV containing the charge e, the total force on the charge becomes

$$\underline{F} = e\,\underline{v} \times \underline{B}$$

since $\underline{v}$ and $\underline{B}$ may be considered constant over the small volume element.

The component of velocity perpendicular to $\underline{B}$ gives rise to a circular electron path of radius $\rho = mv/eB$, provided $\underline{B}$ is constant at all points along the path. Inclusion of the component of velocity parallel to $\underline{B}$ results in a helical orbit.

The Magnetic Spectrometer

This principle has found application in determination of internal conversion electron energies and energy distributions of the continuous beta spectra of disintegrating nuclei.

Instruments commonly used are the magnetic type lens spectrometer and the 180 degree magnetic focusing type spectrometer. Attention will be directed here to the latter.

A geometrical property of this type of instrument is that circular trajectories having equal radii and initial tangential directions limited by a small aperature, will intersect within a small region on the focal plane a distance from the source equal to the trajectory diameter.

Now monoenergetic electrons emitted from the source and focused upon the focal plane will produce a certain line shape; i.e., intensity distribution along the focal plane. Some of the parameters affecting the line shape may be seen in Fig. 1, to be source width, slit dimension and position with respect to source, radius of curvature and distance from source to slit.

This investigation is concerned primarily with the analysis of line shapes resulting from the use of tilted sources, another factor affecting line shapes to be discussed later.

Line shapes are of importance in beta-ray spectroscopy since determination of the trajectory radius ρ offers a convenient method of determining the kinetic energy W of monoenergetic electrons by the relation (6)

$$W = -M_0c^2 + c(M_0^2 c^2 + B^2\rho^2e^2)^{\frac{1}{2}}$$

where M_0 is the rest mass of the electron, c is the velocity of light, and B is the value of the magnetic field in gausses. As will be shown later, line shape influences the ability of an observer to discern faint lines on a photographic plate as well as the degree of accuracy obtained in the determination of ρ.

Since the introduction of the semi-circular magnetic focusing spectrometer in 1912 by Danysz, according to Cork, (2), several investigators have analyzed the theoretical and experimental aspects of operation and focusing characteristics.

Some of the early investigators of this problem were Wooster (14), Li (10) and Lawson and Tyler (9). The latter study, however, was limited to the case of a variable field spectrometer. In general, early investigations were approximate solutions. A more recent treatment by Owens (11) is purported to be analytic in some respects as compared with previous work. However, his results fail to show any broadening of the focused electron line as the source height, which is in the direction of magnetic field, is increased. This point will be referred to again in a later section.

A three dimensional treatment is found to give rise to a solution which becomes extremely complicated due to the boundary conditions imposed by the slits and the sample. However, an exact graphic treatment of line shapes has been developed by Fowler et al. (4) for the two-dimensional case. Since this technique was used to determine theoretical line shapes at various times during this experiment, it will be described in more detail.

Consider a two-dimensional case in which a line source perpendicular to the field and parallel to the focal plane emits electrons in a direction perpendicular to the magnetic field.

By referring to Fig. 1, it will be seen that a particular

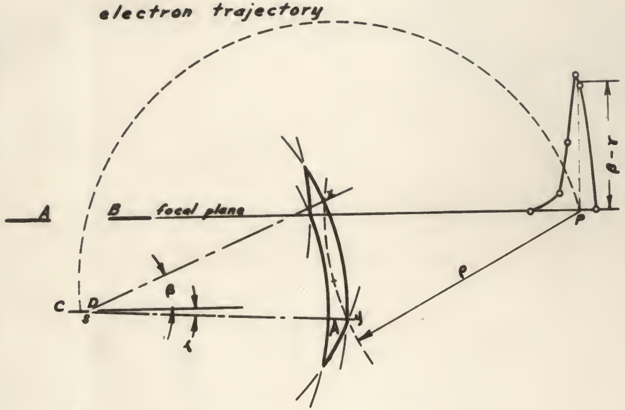


Fig. 1. Construction of theoretical line shape in a two-dimensional spectrometer.

arrangement of slit and sample will determine four unique points, corresponding to the defining edges of the slit A and B, and the extremes of the source, C and D. Now from these four points an arc of radius ρ may be constructed, where ρ is the radius of the trajectory followed by the electrons giving rise to the line shape in question. These four arcs will bound an area A which contains the centers for all trajectories passing through the slits and intersecting the focal plane. The relative intensity at any point P on the focal plane, is proportional to the difference of two angles, β and γ. These are determined from the intersection of an arc of radius ρ with center at P with the perimeter of the area A. These two points of intersection---although there may be more---will be labeled x and y. β is the angle made by the source with a line drawn from the point x to the intersection s of the source and an arc of radius ρ from the point x. In the example shown in Fig. 1, s coincides with D. γ is determined in a like manner. The line shape may be constructed by plotting the value of $(\beta - \gamma)$ in arbitrary units for various points along the focal plane.

Various devices and techniques have been investigated in the constant search for improved resolution without too great a sacrifice of intensity. Magnets having large radii and shaped pole pieces have been constructed to achieve these results (7,13). Geoffrion (5) has given a theoretical investigation of optimum values of spectrometer parameters such as source width and height, divergence angles, and resolution to give the greatest luminosity, the integrated intensity of a focused monoenergetic electron group. Persico and Geoffrion (12) have given a review of literature pertinent to a discussion of various types of spectrometers.

The Tilted Source Technique

Because of the high cost of the instruments of special design mentioned above, it is of interest to consider techniques enabling higher resolution which may be used in conjunction with simpler and more economical spectrometers, such as the 180 degree deflection type spectrometer utilizing a uniform magnetic field.

The question arises as to the focusing characteristics and the line shape occuring when a plane source is tilted; i.e., rotated about its axis of symmetry parallel to the magnetic field. This problem was initially considered by Wooster (14). His analysis, however, was only approximate in that his results showed that a source of infinitesimal width gave rise to a focused line having a low energy tail of infinite length. Furthermore, a source rotated to become perpendicular to the focal plane resulted in infinite discontinuities in analytic functions of relative intensity at points on the focal plane. Later investigations by Li (10) gave similar results. It was shown, however, in these preliminary investigations, that the use of a tilted source resulted in line shapes having greater peak intensities and decreased line widths as compared with line shapes resulting from the use of non-tilted sources. It was implied by Wooster (14) that sources were commonly oriented so that the source plane made an angle α with the focal plane of

60 to 75 degrees.

Since that time tilted sources apparently have not been used. Recently, however, an analysis of the tilted source problem has been made by Fowler and Domotor (3). An exact theoretical treatment was made of a two-dimensional spectrometer in which the line shape was given as a parameter of angular orientation of the source. Reproduced figures from this paper, shown in Figs. 2 and 3, indicate the increased intensity and greatly decreased width of the line as the source is tilted from a zero degree to a 90 degree position. The discontinuities of functions noted in the earlier references do not occur in this analysis, the most peaked line occurring at 90 degrees.

Statement of Purpose

If these theoretical line shapes could be realized experimentally, their use should be expected to give rise to better resolution and greater accuracy of results in current beta-ray spectroscopy.

This thesis describes an attempt made to ascertain the validity of these theoretical results in an experimental manner, and to make applications of the high resolving power anticipated.

EXPERIMENTAL APPARATUS

To illustrate the gross features of the effects of source tilting, a detailed photographic study was made on internal conversion electron spectra by the use of a spectrograph con-

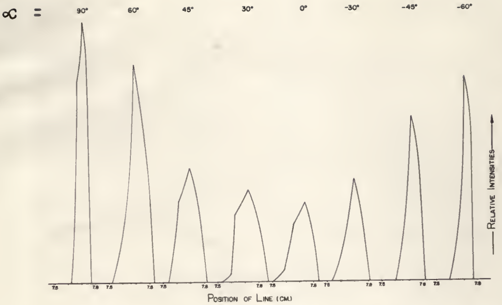


Fig. 2. Variation of line shape with source orientation. Trajectory radius 4 cm, slit width 5 mm, (slit symmetrically spaced over source), source width 1 mm, slit to source distance 2 cm.

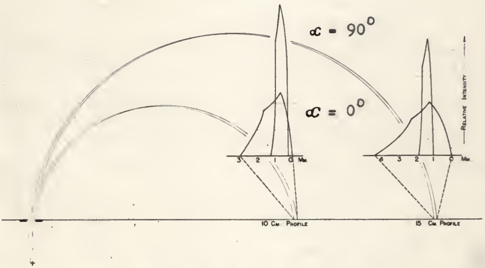


Fig. 3. Comparison of line shapes for α = 0, 90 degrees for trajectory radii 10 and 15 cm. Slit width 4 mm, (slit symmetrically spaced over source), source width 1 mm, and slit to source distance 3 cm.

sisting of a photographic camera and a permanent type magnet. For quantitative observation of line shapes, a similar type of apparatus to be referred to as the spectrometer was used. This instrument was comprised of a camera in which a Geiger-Müller tube was the detector of electrons, and a permanent type magnet.

A detailed description of these instruments and the preparation of radioactive samples will be given in this section.

The Magnets

The magnet for the spectrograph was constructed of soft iron circular pole faces 16 inches in diameter. The yoke likewise was constructed of soft iron having a rectangular cross sectional area of 64 square inches. The air gap could be adjusted but was fixed at 3 inches during this investigation. Permanent fields were secured by the inclusion of cylinders of Alnico, 1 inch in diameter by 3 inches in height, placed between both pole pieces and the yoke in such a way that the magnetic flux passed from the pole piece through the Alnico to the yoke. Excitation currents up to 30 amperes, supplied by a D. C. generator, was conducted through two No. 6 copper coils having 312.5 turns per coil.

Magnetic fields up to 550 gausses between the pole pieces were made uniform by spacing the Alnico cylinders more closely together near the perimeter of the pole pieces to compensate for the fringing flux.

An essential feature of the magnet was its stability. After 24 hours, there was no discernable shift in the value of the magnetic field, based on the appearance of sharp lines in a spectrogram having a long exposure time and also by comparison of spectrograms taken at different times.

The magnet for the spectrometer was identical to that described above except the former was constructed of copper coils having but 200 turns per coil and a fixed air gap of 3 inches. The magnetic field was limited to a maximum value of approximately 500 gausses. These magnets are shown in Plate I, Fig. 1, and in Plate II, Fig. 1.

The Photographic Camera

The camera used for most of the photographic work was constructed of 3/8 inch brass in the shape of a rectangular box. The flat lid was simply clamped into position to seat it firmly on a rubber gasket. The absence of numerous bolts to secure the lid greatly facilitated loading the camera. Following evacuation of the camera, the clamps could readily be removed, atmospheric pressure being sufficient to hold the lid in place.

A brass framework held the radioactive sample frame rigidly in place so that the plane of the sample was 2.0 cm from the slit plane. The focal plane coincided with the surface of a lead block 1.5 inches thick. The lead block served as a frame for the photographic plates and also as a shield to prevent fogging from non-focused radiations.

A very valuable feature of the camera was the inclusion of a valve and stopcock arrangement whereby the camera could

EXPLANATION OF PLATE I

Fig. 1. Photograph of the spectrograph showing magnet yoke and pole faces, exciting coils, and photographic camera.

Fig. 2. A close-up of a photographic camera showing white ribbon radioactive sample, slits, and reproduced film along focal plane.

PLATE I

Fig. 1

Fig. 2

be loaded and evacuated before placing it in the magnetic field. The air scattering which would otherwise have occurred during the pump-down time was thus eliminated.

Commercial No-Screen X-ray film and Kodak Rapid X-ray developer were used exclusively. Films were normally developed for 5 to 7 minutes, fixed for 10 to 15 minutes, washed, rinsed with Even-Flo, and dried under slight tension to prevent warping.

Plate I, Fig. 1, shows the camera used, in an open position. A similar camera is shown in its normal operating position between the magnet pole faces. A close-up of the camera, Plate I, Fig. 2, shows more clearly the vacuum line valve, radioactive sample ribbon, defining slits and focal plane. A reproduced film in its normal position shows the location of prominent lines in one of the spectra examined.

The Spectrometer Camera

The spectrometer camera was likewise constructed of 3/8 inch brass plate. The lid was bolted into position to hold it firmly against a rubber gasket. A vacuum port, flanged to a rigid vacuum line permitted normal evacuation only after the camera was in place between the pole pieces.

The radioactive sample and slits were arranged in a manner similar to that described previously for the spectrograph. The detector, however, was a specially designed rectangular Geiger-Müller tube which could be moved along a threaded spindle in such a way that the Geiger tube window always opened upon the focal plane. The Geiger tube motion was controlled by a nut,

EXPLANATION OF PLATE II

Fig. 1. Photograph of the spectrometer including the magnet, camera with Geiger tube detector, and scaler. Glass system on panel permits tube refilling.

Fig. 2. A photograph of the spectrometer camera showing lead sheets on sides of rectangular Geiger tube and lead blocks around radioactive sample. Control knob outside camera moves Geiger tube along threaded spindle.

PLATE II

Fig. 1

Fig. 2

located outside the camera, and attached to the spindle through a conventional o-ring vacuum seal. A Veeder-Root counter attached to the spindle recorded the position of the tube at any instant.

The camera was normally operated at pressures of around 5 microns of mercury. The tube itself, however, was filled with a 10 percent ethylene, 90 percent argon gas mix (percentages varied slightly for different mixes) with pressures ranging from 10 to 12 centimeters of mercury. Tygon hose connected to the Geiger-Müller tube through the camera wall permitted refilling of the tube without removing the camera from the magnet or changing the tube position.

Five-tenths mil Saran plastic Geiger-Müller tube windows were used in all investigations. Although this window thickness would have caused considerable scattering at low energies, it produced a negligible effect in this investigation since energies of 250 kev or greater were studied.

Plate II, Fig. 2, shows the source in its holder surrounded by lead blocks, the Lucite slits, the Geiger-Müller tube with end window, Tygon hose connections and driving mechanism outside the camera wall.

Plate II, Fig. 1, also shows the spherical bulbs containing Geiger-Müller tube gas mix as well as the stopcock arrangement for filling the tube.

A typical plateau of the Geiger-Müller tube is shown in Fig. 4 which was found to have a 9.8 percent rise per 100 volts over the 135 volt plateau. The plateau length and slope were

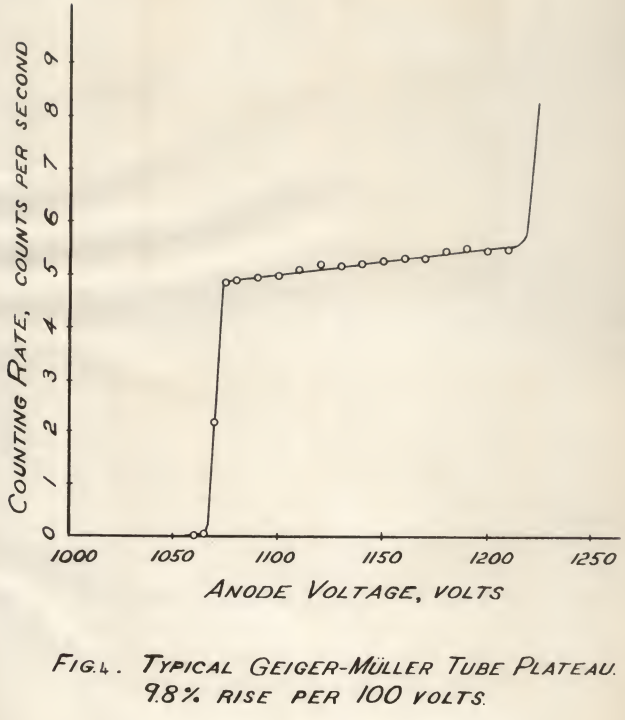


FIG. 4. TYPICAL GEIGER-MÜLLER TUBE PLATEAU.
9.8% RISE PER 100 VOLTS.

altered slightly by continued counting and by different gas mixes or pressures.

The Scaler

Geiger-Müller tube pulses were recorded by a commercial scaler. Normal anode voltages in the neighborhood of 1100 volts were supplied through the camera wall to a Lucite insulated copper bar. A conductor on the Geiger-Müller tube made spring contact with the copper bar for any tube position.

Plate II, Fig. 2, shows the terminal extending from the rear of the Geiger-Müller tube to the copper bar conductor on the camera wall.

The Radioactive Samples

The radioactive isotopes used for this investigation were Ir^{192} and Cs^{137}. These isotopes were of relatively high activity --one prepared sample gave tolerance radiation dosage of 6 mr/hr at 27 inches in air. Consequently, special precautions were observed in preparing and handling the samples to minimize deliterious effects of ionizing radiations. These precautions included protection from radiation and confinement and elimination of contamination.

A source holder of special design was mandatory for these experiments since it was necessary to rotate the plane of the source about a vertical axis. A scotch tape ribbon, on which the radioactive isotope material was placed, was taped rigidly across the open portion of a "C" shaped aluminum piece 1/8 inch thick. This piece was then pivoted in another aluminum frame which was constructed to fit snugly into the camera sample holder. The pivots were located on the extended long axis of symmetry of the scotch tape ribbon.

Two Iridium sources having widths of 0.5 and 3.0 mm were made from sample material in a powder form. The Cesium source width was 1.0 mm and was made from a liquid sample.

ANALYSIS OF DATA

One of the conditions imposed upon the results derived from the theory of tilted sources was that all electron trajectories lie in a plane perpendicular to the magnetic field. The results then apply only to a "two-dimensional" spectrometer. Consequently, it was necessary to adopt experimental methods to approximate this condition and to determine to what extent the source dimension affected the line shape.

It is clear that an electron emitted from a region near either end of the sample, and having a component of momentum in the direction of the field, would be focused on the focal plane closer to the defining slits than would be a like electron having no component of momentum in the direction of field. The effect of the source height dimension is thus seen to be a broadening of the line in a direction towards the slit. Furthermore, this broadening should be greater at the extreme end of the line than at its center.

Photographic Analysis

Z Defocusing. The method used to limit the effective source height in the direction of the magnetic field (hereafter referred to as Z defocusing) was to place defining slits of appropriate dimensions immediately in front of the source.

Lucite slits having Z dimensions of 1.0, 0.5, and 0.2 cm were placed successively in front of the 3 mm Iridium sample in each of the source orientations, having rotation angles about the Z axis (the direction of field) of zero, -45, -60, -85, +45, +60, +85, and +95 degrees, where a positive angle indicates that a line extended along the source, intersects the focal plane to the right of the slit in Fig. 1. A series of photographic plates then gave the qualitative line shape for each angular orientation as a function of the source height.

Analysis of these plates showed little effect as a result of the variation of source height. In some cases the smaller Z dimensioned slit gave somewhat better resolution of a particular region of the spectra. In all cases, however, Z defocusing resulted in loss of intensity and necessitated a corresponding longer exposure time to obtain plates of equal density. Exposure times in the ratio of approximately 1: 2: 3 were required for the 1.0, 0.5 and 0.2 slits, respectively.

Plate III, Fig. 1, shows a typical series of plates. These were taken using the 3 mm Iridium source oriented at +60 degrees for each of the three Z dimensioned slits. Original films of the plates shown in Plate III, Fig. 1, appeared to have better resolution and less "flaring out" at the ends of the lines when

EXPLANATION OF PLATE III

Fig. 1. Comparison of spectrograms to show effects of Z defocusing. Iridium source width 3 mm, α = 60 degrees.

A. Slit height Z = .5 cm
B. Z = 1.0 cm
C. Z = 0.2 cm

Fig. 2. Comparison of spectrograms to show effects of Z defocusing. Iridium source width 0.5 mm, α = 0 degrees.

A. Z = 0.5 cm
B. Z = 1.0 cm
C. Z = 0.2 cm

PLATE III

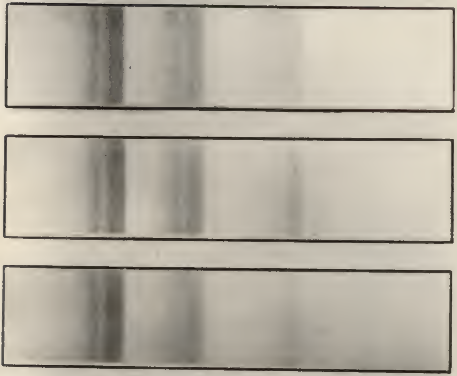


Fig. 1

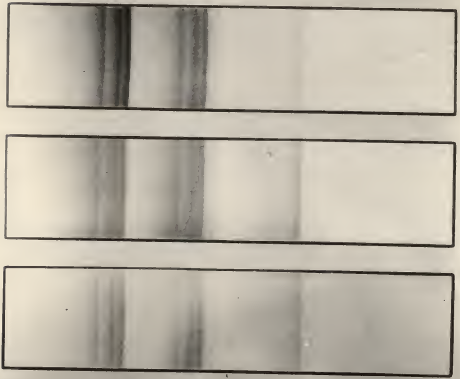


Fig. 2

smaller Z dimensioned slits were used. Divergences from these observations noted in Plate III may be attributed to processes of reproduction of the original film.

It must be borne in mind that the curvature, or lack of it, at the high energy edge of a given line does not indicate the effect of Z defocusing since this curvature would be observed even if a source of infinitesimal Z dimension were used. Rather, this curvature is a function of the radius of the path followed by electrons giving rise to the line.

To make observations independent of this normal line curvature, only a narrow strip across the entire length of the photographic film was examined. This procedure gave results identical with those which would have been obtained if an additional slit of small Z dimension had been placed immediately in front of the film.

Similarly, the 0.5 mm Iridium source in the zero degree position was used with the Z defining slits of the same dimensions as stated previously. The original films showed slightly better resolution when a smaller source height was used. These plates are shown reproduced in Plate III, Fig. 2.

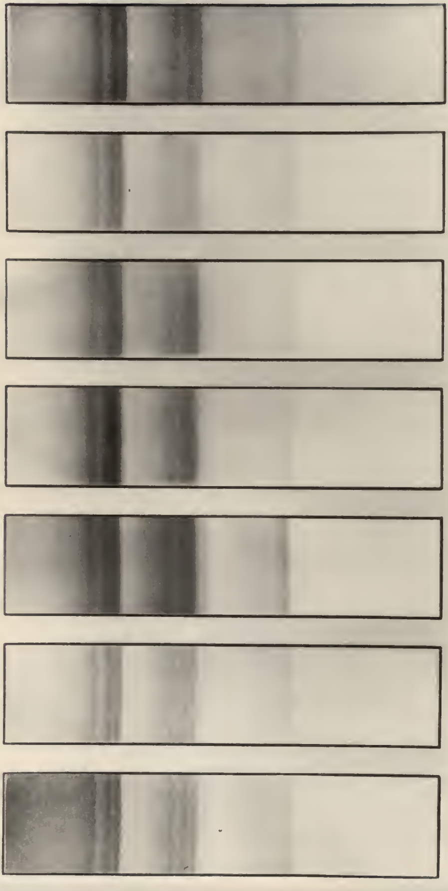
Effects of Source Tilting. A different sampling was made of the set of plates described above to obtain a series of plates having a Z slit dimension of 0.5 cm and successive angular positions of -85, -60, -45, 0, +45, +60 and +85 degrees. Plate IV clearly illustrates the variation of line shape as the source was rotated. At the zero degree position, occurring when the source plane was parallel to the focal plane, prominent K_2 and

EXPLANATION OF PLATE IV

Comparison of spectrograms to show effects of source tilting. Iridium source width, 3 mm. Z slit dimension, 0.5 cm.

A. α = +85 degrees
B. α = +60 degrees
C. α = +45 degrees
D. α = 0 degrees
E. α = -45 degrees
F. α = -60 degrees
G. α = -85 degrees

PLATE IV



A

B

C

D

E

F

G

K_3 as well as L_2 and L_3 lines of the Iridium spectrum are completely unresolved. Notation of these lines is indicated in Plate V, Fig. 1. Rotation of the source to a 45 degree position resulted in a very slight resolution of the K and L lines referred to above. The resolution became more apparent as the rotation was increased to either plus or minus 85 degrees.

It may be observed that lines appear sharper in the -60 and -45 degree positions than in the corresponding plus angle positions. This is seen to be consistent with predicted line shapes shown in Fig. 1. However, this gain is partially lost in the longer exposure time required for the negative angle positions due to the fact that many of the emitted electrons must pass through the scotch tape backing. At a 90 degree position it was anticipated that this loss of intensity would be greatest and consequently an 85 degree position was chosen instead of a 90 degree position.

Again it must be pointed out that some variation of intensities of a given line on different photograms may be attributed to methods of reproducing the original film.

It will be noted that the source used to produce the photograms of Plate IV had a width of 3.0 mm. This source width is perhaps slightly wider than sources normally used in beta-ray spectroscopy but was used to illustrate more clearly the effect of source tilting. Now a source width of 0.5 mm, on the other hand, is close to a minimum width obtainable for the type of source backing material and methods of preparation used. Yet Plate V, Fig. 1, showing plates in which the 0.5 mm source

EXPLANATION OF PLATE V

Comparison of photograms to show effects of source tilting on line shapes.

Fig. 1. Iridium source width, 0.5 mm. Z = 0.5 cm.

A. α = 0 degree
B. α = +85 degrees

Fig. 2. Cesium source width 1.0 mm

A. α = 0 degree
B. α = +60 degrees
C. α = +85 degrees

PLATE V

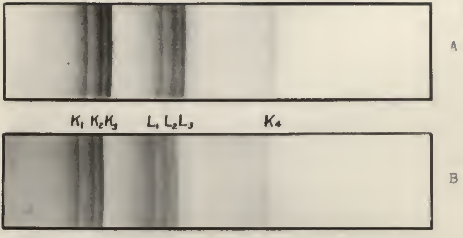


Fig. 1

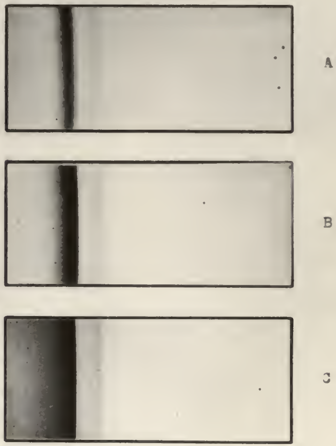


Fig. 2

was used, definitely shows greater resolution and sharper leading edges at the plus 85 degrees position than at the zero degree position.

A similar comparison of effects on line shapes for Cs source positions of zero, +60 and +65 degrees may be seen in Plate V, Fig. 2.

To further verify the results just described, a photo-densitometer analysis was made of the original films reproduced in Plate V, Fig. 1. The light beam of the photo-densitometer could not be made narrow enough to resolve the L_2 or L_3 lines for the zero degree position of the 0.5 mm Iridium source. However, at the plus 85 degrees position, L_1, L_2 and L_3 were partially resolved.

Spectrometer Analysis

A photographic plate is convenient to illustrate the effects of source rotation in that it produces an actual "picture" of line shapes. However, the line shapes so obtained can be interpreted only in a qualitative manner.

A quantitative method of determining line shapes is one in which a Geiger-Müller tube is used as the detector of radiation. By moving the Geiger-Müller tube successively from point to point, the counting rate distribution over any region of the focal plane may be determined.

Initial tests showed that the Iridium sources were emitting gamma radiation of very high intensity which caused a high background count in the Geiger tube. Consequently, lead blocks were packed around the Iridium sample to reduce this gamma-ray background. Even with considerable lead placed directly between the source and Geiger-Müller tube, it was found that gamma rays were causing scattering from the walls of the spectrometer and perhaps from brass parts within the spectrometer. The final arrangement used was a lead block 6.45 cm thick placed between the source and Geiger-Müller tube, lead sheets placed behind the sample, and two sheets of .068 inch lead attached to the top and side of the Geiger-Müller tube. The latter was found to reduce the scattering from the camera walls considerably. The total background with this arrangement varied from 5 to 2 counts per second along the focal plane. Close inspection of Plate II, Fig. 2, will reveal the lead sheets covering the Geiger-Müller tube as well as the lead blocks surrounding the sample.

Earlier analysis of photographic plates had indicated the 378 kev K_4 line occurring in the conversion electron spectrum of Iridium was far removed from other lines of the spectrum. This observation was consistent with a recent publication listing conversion lines in the Iridium spectrum (1). The K_4 line under discussion and other lines to be referred to presently may be seen in Plate V, Fig. 1.

However, spectrometer analysis of the K_4 line indicated the presence of weak lines on the high energy edge and possibly on the low energy tail as well. Presence of such lines would make an accurate analysis of the K_4 line very complicated. Nevertheless, the integrated line shape was obtained at angular positions of zero and ‡85 degrees. A Z defocusing slit of 1.0 cm was placed adjacent to the source while a slit having a width of .015 cm and height of 1.0 cm was used on the Geiger-Müller tube. The line shapes from this analysis are shown in Fig. 5 corrected for gamma-ray background. It is apparent that a great loss in intensity occurred at the +85 degrees position. This is consistent with the observation made earlier that the exposure time at 85 degrees positions was 2 or 3 times that at the zero degree position. On the other hand, this loss of intensity of the line peak is inconsistent with the theory of tilted sources which predicts a peak of greater intensity at the 85 degrees position. This inconsistency was attributed primarily to scattering of electrons and consequent loss of energy in the Scotch tape source backing and in the sample material itself. However, subsequent observation on photographic plates of weak lines adjacent to the K_4 peak on either side of that peak made it possible to attribute some of the low energy tail to the presence of these lines.

It is important to note the decreased length along the abscissa from the line peak to beta background at the +85 degrees position as compared with this distance at the zero degree position. Such sharper leading edges are consistent with the results predicted by the theory of tilted sources.

A similar analysis of the K_4 line was made with the 3.0 mm Iridium source in which results were obtained similar to those described for the 0.5 mm Iridium source.

Attention was directed towards the K_1, K_2 and K_3 lines in another analysis made of the 3 mm Iridium source. In the zero degree position, K_1 was only slightly resolved but K_2 and K_3

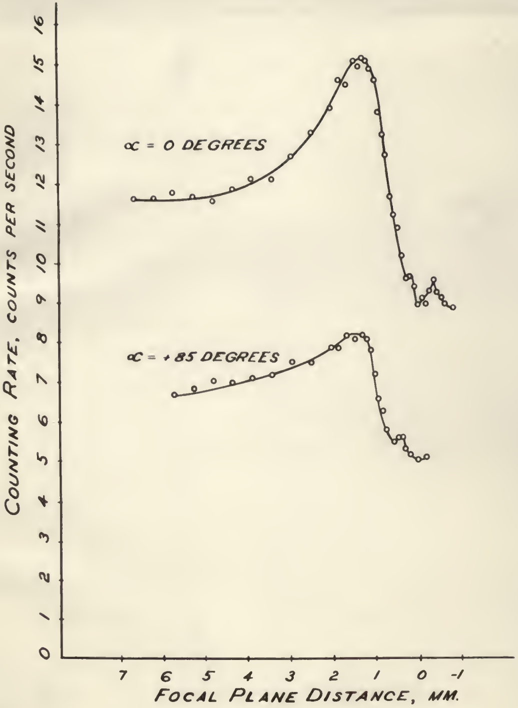


Fig. 5. Line shapes of Iridium K_4 line. Source width, .5 mm. Radius of curvature, 5.15 cm. Slit to source distance, 3.5 mm., slit symmetrically spaced over source. Geiger tube slit .015 cm. Counting rate corrected for gamma ray background. Maximum statistical error, 1.2%.

were unresolved. At the +85 degrees position all three K lines were partially resolved. Again the peak intensity loss was great and the drop off distance from peak to background was appreciably less at the +85 degrees position. It should be pointed out that this resolution of the K lines was accomplished with the spectrometer employing higher value of the magnetic field than that used in obtaining the plates produced in Plate IV. The lines were closer together at the higher field making resolution more difficult. Theoretical line shapes for the K lines in the zero degree position were determined by the graphical method described in the Introduction. It was found that these line shapes overlapped considerably, thus accounting for the poor resolution encountered in this region.

It was felt that the failure to find increased intensity at the line peak when a tilted Iridium source was used was due largely to scattering. Now it should be expected that the effect due to this scattering would become appreciably less if analysis were made of a line comprised of high energy electrons.

Such a line was conveniently found in the conversion electron spectrum of $Cesium^{137}$, having an energy of .6239 mev. This line was presumably free from adjacent lines and was well above the beta background. In fact, the line had been precisely measured (8) and proposed as a convenient standard for calibration of spectrometers because of its long half life of 37 years.

Using a Cs^{137} source, a spectrometer analysis was made of the conversion electron line at source angular positions of zero, +60, and +85 degrees, and using a Geiger-Müller tube slit width of .041 cm and height of 2.5 cm.

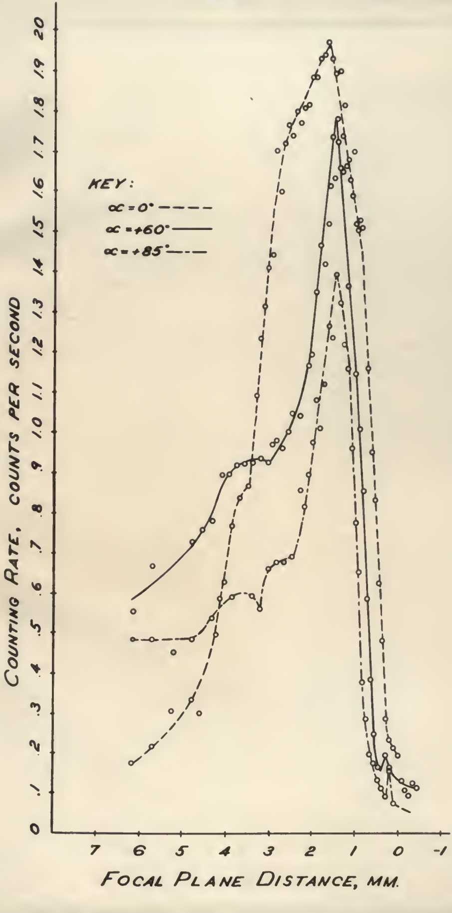
The results of this analysis are shown in Plate VI. The line shape was found to become more peaked as the source was tilted. It is important to note that the focal plane distance from a point of maximum intensity to the high energy edge decreased appreciably as the source was tilted from zero to 85 degrees. Furthermore, Plate VI also shows that although peak intensity was decreased and long trailing edges at 60 and 85 degrees positions were much more apparent as compared with the zero degree position, these features were not as appreciable as in the 378 kev Iridium line analysis described before. In the latter case the peak intensity was cut approximately 50 percent by tilting the source, but in the Cs analysis, the +85 degrees position retained over 70 percent of the peak intensity at the zero degree position. Intensity at the +60 degrees position was over 90 percent of that occurring at zero degree.

Resolution at each of the angular positions may be defined as the line width in momentum units at half maximum divided by the line position in the same units. The ratio of the resolution for zero, +60, +85 degrees positions may then be expressed as ratios of the line widths at half maximum which was found to be 0.90: 1.00: 0.46. This shows that the greatest half maximum line width occurs at the 60 degrees position. Since such a statement is true but misleading, it seems advisable to determine resolution in terms of the line width at some other value than the half maximum value ordinarily used. Line widths measured at .55 of the maximum value have ratios of 1.00: 0.68: 0.49,

EXPLANATION OF PLATE VI

Cs^{137} line shapes for α = 0, +60, +85 degrees. 1 mm source width, 8.41 cm radius of curvature, 2.12 cm slit to source distance. 3.5 mm slit symmetrically positioned over sample. Geiger tube slit width, .040 cm. Intensities corrected for gamma-ray background. Statistical error varies from 1.6 percent at peak to 3.7 percent near base.

PLATE VI


KEY:
∝ = 0°
∝ = +60°
∝ = +85°
COUNTING RATE, COUNTS PER SECOND
0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0
7 6 5 4 3 2 1 0 -1
FOCAL PLANE DISTANCE, MM.

which present a more accurate description of the line widths.

The misleading values of resolution noted above may be seen in Plate VI to be due to the presence of humps on the low energy trailing edge. Again the large integrated area under this trailing edge was attributed to scattering, but an explanation of the humps was not so readily given. This was especially true in view of the fact that no conversion electrons other than the prominent K, L and M lines arising from a single gamma-ray, have been reported previously.

It has been stated that this particular sample was made from radioactive material in solution. There is a possibility that the liquid collected along the edges of the scotch tape backing in such a way so as to give rise to the peculiar line shape observed.

Photographic plates taken of the Cs^{137} source in the spectrometer at each of the angular positions of zero, +60, and +85 degrees are shown reproduced in Plate V, Fig. 2. A striking similarity was observed between the line shapes determined by the spectrometer as shown in Plate VI and those recorded by photographic film in Plate V, Fig. 2. The conspicuous hump on the low energy edge of the spectrometer result was observed as a very apparent line at +60 and +85 degrees. The presence of this line on photographic plates ruled out any possibility of the humps being due to mechanical or electrical sources of variation in the spectrometer analysis.

The theoretical line shape of the Cs line in the zero degree source position was determined by the graphical method described in the Introduction. Values of the parameters used for this solution were the same as those actually used in the experimental analysis. These included 1 mm source width, 2.12 cm slit to source distance, 3.5 mm slit placed symmetrically with respect to the source, and 8.41 cm radius of curvature. The resultant line shape is shown in Plate VII, C, as compared to the experimental line shape in Plate VII, F, normalized for comparison to equal peak intensity instead of equal integrated area. The theoretical line shape was found to be much narrower than the experimental line shape although the line shapes in general were very similar.

An attempt was made to determine the cause of the great increase in the experimental line width as compared to the theoretical value. It was suspected that some of this increased width might be attributed to the slit position, which may have been asymmetrical with respect to the source. Consequently, theoretical line shapes were determined graphically using the same parameter values as stated above except that the slit was shifted about the symmetrical position by steps of .5 mm to the left and to the right. The resultant line shapes may be seen in Plate VII, A, B, C, D and E.

A small displacement of the slit position in either direction was found to reduce the peak intensity but to have no effect upon the high energy cut-off position. The line width at its base was found to be a minimum when the slit was placed 0.5 mm to the left but to be greatly increased at positions to the right of its symmetrical position.

EXPLANATION OF PLATE VII

Line shapes for Cs^{137} K line. 8.41 cm radius of curvature, 1 mm source width, 2.12 cm slit to source distance, 3.5 mm slit width. A-E are theoretical line shapes for various slit position.

A. 1.0 mm to left of source position

B. 0.5 mm to left of source position

C. Symmetrical to source position

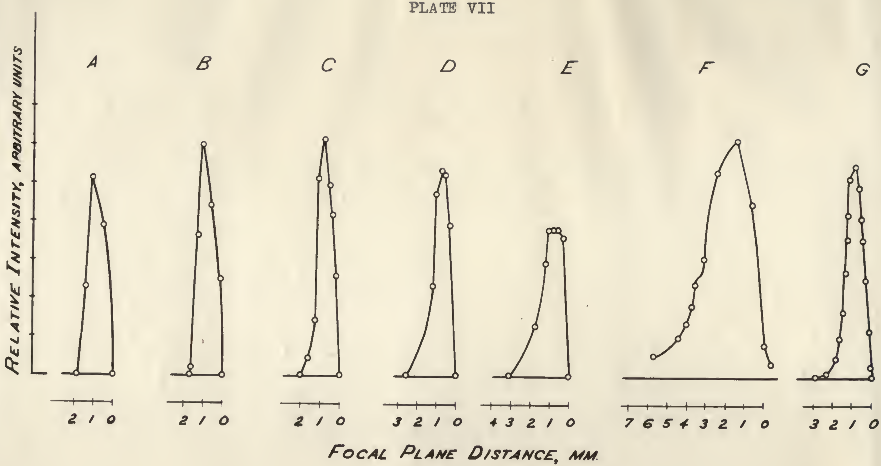
D. 0.5 mm to right of source position

E. 1.0 mm to right of source position

F. The experimental line shape

G. The approximate theoretical line shape of (C) after taking into account the source height

PLATE VII


A
B
C
D
E
F
G
RELATIVE INTENSITY, ARBITRARY UNITS
2 1 0
2 1 0
2 1 0
3 2 1 0
4 3 2 1 0
7 6 5 4 3 2 1 0
3 2 1 0
FOCAL PLANE DISTANCE, MM.

It has been noted that Z defocusing alters line shape and shifts the line position towards the slit. A first order approximation of the effect of Z defocusing was made for the particular case of the Cs line under discussion. The assumption was made that radiation from points on the source produced a constant line shape at any given point on the Geiger tube slit. The shift s in line shape position was then determined by the relation

$$s = \frac{d^2}{\pi \rho}$$

where d is the distance in the direction of the magnetic field between the point of emission and point of detection, and ρ is the radius of curvature.

A source 1.0 cm in height was divided into three equal sections along its length while the slit length of 2.5 cm was divided equally into five parts. At each midpoint of the slit sections, the line shift was determined, considering electrons to come successively from the centers of each of the three source sections. An array of fifteen line shapes was then combined and the total effect determined. The resultant line shape is shown in Plate VII, G. It was found that the line position was shifted slightly towards the slit, the peak became less pointed, and the line was broadened considerably, particularly at its base.

This line shape may again be altered slightly by considering the finite width of the Geiger tube slit. By graphically integrating the area under the curve within vertical columns having a width equal to the Geiger tube slit width of .041 cm, the line shape became broadened slightly, most noticeably on the high energy edge.

The resultant theoretical line shape was found to be much narrower than the experimental line shape. Probably, a like treatment of the line shape of Plate VII, D, would have given a line having a width only slightly less than the experimental curve. Furthermore, continued subdivision of the source and slit would have caused a greater broadening of the line and greater shift in line position. The differences between theoretical and experimental line widths might have been interpreted as being due to the presence of adjacent lines. More likely, however, these differences were due to scattering of electrons in the source material.

APPLICATIONS

It has been pointed out at various times in the preceding discussion that the use of a tilted source results in line shapes having features which might be used to advantage in actual experimentation. In this section, some of these more desirable features will be emphasized, with particular attention being given to the resolution made possible by the use of tilted sources.

Examples of Increased Resolution

In addition to the potential lines on the low energy edge of the Cs K line, faint lines were observed on photographic plates just beyond the high energy edge, when a tilted source was used. Their presence was even more difficult to explain than the humps on the inside edge, without having to label them as genuine conversion lines. Irregularities in source concentration would not be expected to give rise to irregularities beyond the high energy edge.

In previous discussion it has been noted that the distance along the focal plane from the point of maximum intensity to the high energy minimum has been reduced appreciably by tilting the source. This was readily observed in Fig. 5, Plate V, Fig. 1, Plate V, Fig. 2 and Plate VI.

The high energy edge, normally very indistinct in a zero degree position, was made to appear as an extremely sharp and abrupt edge. This is an important feature in the analysis of photographic plates where a sharp edge is desirable for precise determination of the line position. To illustrate this point, suppose it is desired to determine the distance on the photographic film from some fiducial mark to the high energy edge of the Cs K line shown in Plate V, Fig. 2. If the zero degree position photograph were analyzed, it is clear that the high energy edge location will be arbitrarily defined within rather large experimental error. On the other hand, the high energy edge location may be established within much smaller experimental error limits if the +85 degrees position photograph were used.

The sharp high energy edge is important in another respect since it enables the eye to discern faint lines which otherwise would be unobserved. The eye appears to be far more sensitive to faint lines if there is an abrupt change in intensity, even though the magnitude of this abrupt change is extremely small.

The conversion electron spectrum of Iridium has been reported to contain approximately 30 lines (1). By using tilted sources many more lines have been observed. Although some of these new lines may be seen on plates taken with the source in its normal zero degree position, it appears that the use of tilted sources has increased resolution of proximate lines and has made faint lines more apparent.

L Subshell Resolution

In order to illustrate further the resolving power made possible by the use of tilted sources, a spectrometer analysis was made of the Iridium 282 kev L_1 line in an attempt to resolve the L_I, L_{II} and L_{III} subshell lines corresponding to removal of electrons from the L shell having energy levels designated in optical notation by $2^2S_{\frac{1}{2}}$, $2^2P_{\frac{1}{2}}$ and $2^2P_{3/2}$.

The best resolution of the substructure occurred when the 0.5 mm Iridium source was set at the 85 degrees position and a Geiger tube slit width of .015 cm and height of 1.0 cm was used. Fig. 8 shows the result obtained. The pips interpreted as L_I, L_{II} and L_{III} are indicated on the figure.

Similar but more irregular results were obtained in other tests. In some trials a Geiger tube slit width of .028 cm was used.

These subshell levels are of particular interest since the ratios of the luminosity for each of the three subshell lines are proportional to the ratios of internal conversion coefficients. This type of information may then be used in determining the

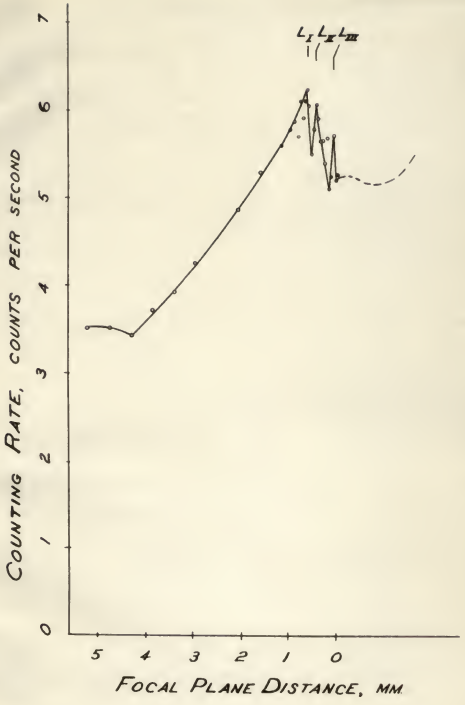


Fig. 8. Subshell structure of Iridium L_1 line. 0.5 mm. source width. 5.0 cm. radius of curvature. 2.12 cm. slit to source. 3.5 mm. slit symmetrically spaced over source. Geiger tube slit width. .015 cm. Counting rate corrected for gamma ray background and approximate continuous beta spectrum. Maximum statistical error, 0.11 counts/sec.

spin change and type of transition occurring in the nuclear disintegration process.

An attempt was made to ascribe an approximate ratio to these conversion coefficients. The gamma background, an assumed continuous beta spectrum, and contributions from adjacent L lines, were successively subtracted from the spectrometer analysis curve. Finally, separation of the L_I, L_{II} and L_{III} lines showed the areas to be in ratio of 11: 12: 8. However, the gross approximations used make the resultant ratios of little value except to illustrate a method of determining such information.

SUMMARY

To show the effects of Z defocusing and source rotation on the line shape in a qualitative manner, a number of photographic plates were obtained using a wide Iridium source, a narrow Iridium source, and a Cesium source.

Photographic plates did not reveal any pronounced effect due to Z defocusing other than the increased exposure time required when a smaller effective source height was used.

The wide Iridium source rotated to various positive and negative angular positions illustrated the characteristics of line widths and leading edges at each angular position. Analysis of these plates indicates (1) the line width and leading edge length decreased as the source was rotated from zero to 85 degrees position, (2) the high energy edge was more abrupt for negative angular positions than for the corresponding positive angular position, (3) the peak intensity decreased as the source

was rotated from zero to 85 degrees positions, (4) peak intensity was lower for negative angular positions than the corresponding positive angular positions.

Points (1) and (2) above were consistent with the results derived from the theory of tilted sources. However, points (3) and (4) were found to be at variance with the theoretical results. These features were attributed to scattering of electrons from the scotch tape backing and from the sample material itself.

The Cesium and narrow Iridium sources exhibited similar results in tests incorporating only positive angular positions.

Spectrometer analysis of Iridium K lines showed that the peak intensity was cut by as much as 50 percent as the source was rotated from zero to 85 degrees. The leading edge length, however, was appreciably less at the 85 degrees position.

Results from spectrometer analysis of Cesium showed a loss of peak intensity on source rotation to +85 degrees but only to a value of 70 percent of the peak intensity at the zero degree position. When a source position of 60 degrees was used, peak intensity was 90 percent that at zero degrees. The line widths measured at .55 maximum decreased as the source was rotated. Ratios of these line widths at source positions of zero, +60 and +85 degrees were found to be 1: 0.68: 0.49, respectively. Below .55 maximum, the low energy edge was spread out as the source was rotated, increasing the line width. The presence of additional lines was suspected as a possible cause of this low energy tail but more likely was due to scattering of electrons.

A theoretical line shape was constructed geometrically under boundary conditions actually used in obtaining the Cs line for a zero degree source position. An attempt was made to incorporate a correction due to the effect of source height on the theoretical line shape to give a line shape corresponding to that obtained with a Geiger tube. The resultant line was found to be somewhat narrower than the experimental line shape.

Practical applications of the tilted source technique have been described. New lines of low intensity in the Iridium spectrum have been made visable while others have been made more apparent. When a tilted source was used, lines were observed in the Cesium spectrum not appearing there when a non-tilted source was used although the presence of these lines was not fully explained.

As a further demonstration of the resolution possible with a tilted source technique, partial resolution was achieved of the L_I, L_{II} and L_{III} lines comprising the 282 kev L_1 line in the Iridium spectrum. The L_I-L_{II} difference was .605 kev while the L_{II}-L_{III} difference was 1.71 kev. From the resultant intensity pattern, the ratios of integrated areas of 11: 12: 8 were obtained as a crude approximation of the ratios of internal conversion coefficients for the L_I, L_{II} and L_{III} lines.

In conclusion, it may be said that source tilting provides a convenient method of increasing the resolving power of a spectrometer and provides a technique which reduces the experimental error in determination of energies of conversion electron groups. This technique further increases the sensitivity of the instrument to lines of low intensity, particularly when a photographic film is used as the detector.

It is important to note that this technique is particularly well adapted for use in the common 180 degree type magnetic focusing spectrometer having a uniform magnetic field. This simple and economical instrument used in conjunction with a tilted source technique provides resolution comparable to that commonly obtained in much more expensive instruments of intricate design.

However, use of the tilted source has resulted in a loss of peak intensity as compared to that obtained with the use of a non-tilted source. Experimental results indicate that this undesirable feature would not occur at higher energies, say, in the mev region. In order to verify this hypothesis, it is planned to extend this experiment to an analysis of Co^{60} having conversion electron energies in the mev range.

Perhaps other methods and materials used in the preparation of sources would produce the desired results. A desirable sample would satisfy the requirements that (1) the surface be plane, (2) the sample backing be rigid enough to support the sample material, (3) be thin to the extent that it produces no appreciable scattering, (4) and be mounted in some rigid framework which itself would cause no secondary radiation.

Analysis of electrons of high energy with techniques and sources as used in this investigation, or of electrons of lower energy analyzed using a sample meeting the requirements stated above, is anticipated to give results in agreement with those derived from the theory of tilted sources.

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ANALYSIS AND APPLICATION OF SOURCE TILTING
IN A MAGNETIC FOCUSING BETA-RAY SPECTROMETER

by

HERALD WESLEY KRUSE

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Studies were made of line shapes of mono-energetic electron groups in a 180 degree magnetic focusing spectrometer.

Experimental investigations were carried out to test an analysis given by Fowler and Domotor (3) on the effect of source tilting. Applications of the tilted source technique are described.

A qualitative analysis of the effects of source rotation was made using photographic film as a detector of radiation, while a quantitative study was made using a Geiger-Müller tube as the detector. The apparatus used in these studies is described in detail.

It was shown that source tilting decreases the line width considerably, the most noticeable decrease being the leading edge drop-off distance. However, at energies below 400 kev the peak intensity was reduced and the line broadened on the low energy side, particularly near its base. These features were not as appreciable at higher energies as in the case of the .6239 mev Cs^{137} line studied.

An application of the increased resolution made possible by the tilted source technique was provided in resolving the L_I, L_{II} and L_{III} lines comprising the 282 kev L_1 line in the Iridium conversion electron spectrum.

Experimental results agree reasonably well with line widths theoretically predicted. However, a lack of agreement occurs between experimental and theoretical peak intensities which is attributed primarily to electron scattering. Results indicate that theoretical line shapes would be found experimentally if electron scattering were eliminated either by using higher energy electrons or appropriate sample materials and preparation.