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EMISSION OF THE CONTINUOUS X-RAY ENERGY FROM THIN ALUMINUM FOILS

THESIS FOR DEGREE OF MASTER OF SCIENCE

MICHIGAN STATE COLLEGE
HOWARD RICHARD KELLY

1940

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EMISSION OF THE CONTINUOUS X-RAY ENERGY FROM THIN ALUMINUM FOILS

by

Howard Richard Kelly

A Thesis

Submitted to the Graduate School of Michigan State College of Agriculture and Applied Science in partial fulfilment of the requirements for the degree of

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Howard K. Kelly

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INTRODUCTION

One of the more difficult problems in x-rays that has interested physicists concerns the nature of the emission process which gives rise to the continuous x-ray spectrum. An attempt was made to explain it on a classical basis in 1909 by Sommerfeld (1). He used Stokes' hypothesis, which assumes a rectilinear deceleration of a cathode ray by the atoms of the target, and his predictions were unquestioned as to validity for a number of years. However, in 1928, experimental data published by Kulenkampff (2) showed Sommerfeld's theory to be incorrect, and the same paper pointed out why the rectilinear deceleration hypothesis was false.

Immediately following the published experimental data by Kulenkampff, Sommerfeld worked out a new theory, based on the new wave mechanics (3). This still required that the radiation arise from the deceleration of an electron, but allowed transverse components of acceleration, under which the electron could follow a hyperbolic path. Sommerfeld's theory has been extended by Scherzer (4) to allow for relativistic corrections, and Sauter (5) has developed a wave mechanical relativistic theory. Meanwhile, Kramers (6) worked out a theory using the Bohr correspondence principle.

The development of these theories is still far from completion, and depends on having more experimental

data to show which parts of the theory are correct and which parts need revision. This dependence on experiment was shown in the immediate reaction to Kulenkampff's work by Sommerfeld. The most important experimental data so far has been taken by Kulenkampff (2) and his associate Böhm (7) using thin foils of magnesium and aluminum as targets. In addition, Duane (8) made some measurements using a jet of mercury vapor as his target, Nicholas (9) used thin gold foils, and more recently, Thordarson (10), Corrigan and Cassen (11) and Van Atta (12) used thicker targets with considerably higher cathode ray accelerating voltage. In all the work done by these men, the curves obtained from their data have been relative, so that comparison with theory has been carried out by adjustment with one point on the curve and finding how the others compare with respect to it. No attempts have been made to obtain absolute intensities, so that the theories could be checked directly. It is therefore the purpose of the research described in this paper, to obtain some absolute measurements of intensity of x-rays in the continuous spectrum from thin targets, and to compare the measured data with theoretical values.

Since the experimental results of Nicholas and Duane have been superceded by much better data, taken by Kulenkampff and Böhm (loc. cit.), only the later two will be considered here. The general procedure in all

these experiments has been to obtain azimuthal intensity distribution curves as functions of x-ray tube voltage and wave length. Kulenkampff's method of obtaining isochromats was to measure intensities with various thicknesses of absorbing filters, and from the variation obtain the intensity due to a given wave length interval, and to estimate the mean wave length for this interval. Böhm used practically the same method for rays near the low wave length limit, but for a measurement at longer wave lengths, applied a method due to Ross.(13) A copper filter of appropriate thickness is transparent to rays near the low wave length limit for copper. An aluminum filter can be made to have the same transparency for the region of the short wave limit, but will absorb strongly in the neighborhood of the copper K-limit. The difference in the transmitted intensities for the two filters gave Böhm a measure of the intensity in a range just above the copper K-limit.

Neither of the methods used by Böhm gives a well defined narrow wavelength band, the difficulty being that the intensity distribution of the measured x-ray, as a function of wave length is not uniform. A means of obtaining a narrower and more uniform interval, due to Ross (13), and more completely discussed by Kirkpatrick (14), was used for the measurements herewith reported. This method will be described later in this report.

II. EXPERIMENTAL APPARATUS

A. The X-Ray Tube

In order to find experimentally the intensity of x-rays as a function of cathode ray energy, direction of emission, and wave length, certain experimental conditions must be satisfied. In the first place, the cathode rays must be incident on the target with a definite direction and energy. Second, the change of direction and retardation of the cathode rays in the target before the emission process takes place must be minimized. Third, provision must be made for measurement of intensity at various angles with respect to the direction of the cathode ray beam. These were satisfied by Kulenkampff (2) and Böhm (7) by collimation of cathode rays with circular apertures, the use of very thin aluminum or magnesium targets, and an ionization chamber (or geiger counter) that could be rotated about an axis through the x-ray target.

The tube used in the research herein reported satisfies the same conditions in a somewhat different manner. The target is kept thin, like those of Böhm, but the collimation of cathode rays is accomplished by surrounding the hot cathode with a small steel disk to provide a uniform field between the cathode and target. The variation of azimuthal angle is made by rotating the entire x-ray tube support on a solidly mounted base.

The tube is shown in horizontal cross section in Fig. I. Electrons are given off by the cathode C, and those which are not stopped by the thin target T are collected by the anode A. The target and anode are the only parts of the entire x-ray tube at positive potential, while the cathode and chamber wall are negative. Thus the cathode filament itself need only be insulated from the metal chamber wall for 12 volts, while the entire tube must be insulated from ground for the full tube voltage. The tube itself is a steel cylinder of which the entire top plate can be removed. The inside dimensions are a depth of 2.5 inches and a diameter of 8 inches. The target is not placed in the center of the cylinder, but removed one inch in the direction of the cathode filament. On the center of the bottom plate is attached a 2 inch pyrex tube, leading to an oil diffusion pump for evacuation. The leads for the target and anode, which are 3/8 inch and 1/4 inch brass rods, enter through holes in the removable top plate through pyrex tubes of smaller dimensions. These leads are shown in a vertical cross section of the tube in Fig. 2. The anode consists of an aluminum cup 1 1/2 inches long and one inch wide, outside dimensions. The target and its brass rod support are attached to a brass plate at the top of the pyrex tube insulator, so they can be easily removed. The targets are mounted on rectangular steel wire frames, one inch by 1 1/4 inches, an end of the wire being inserted

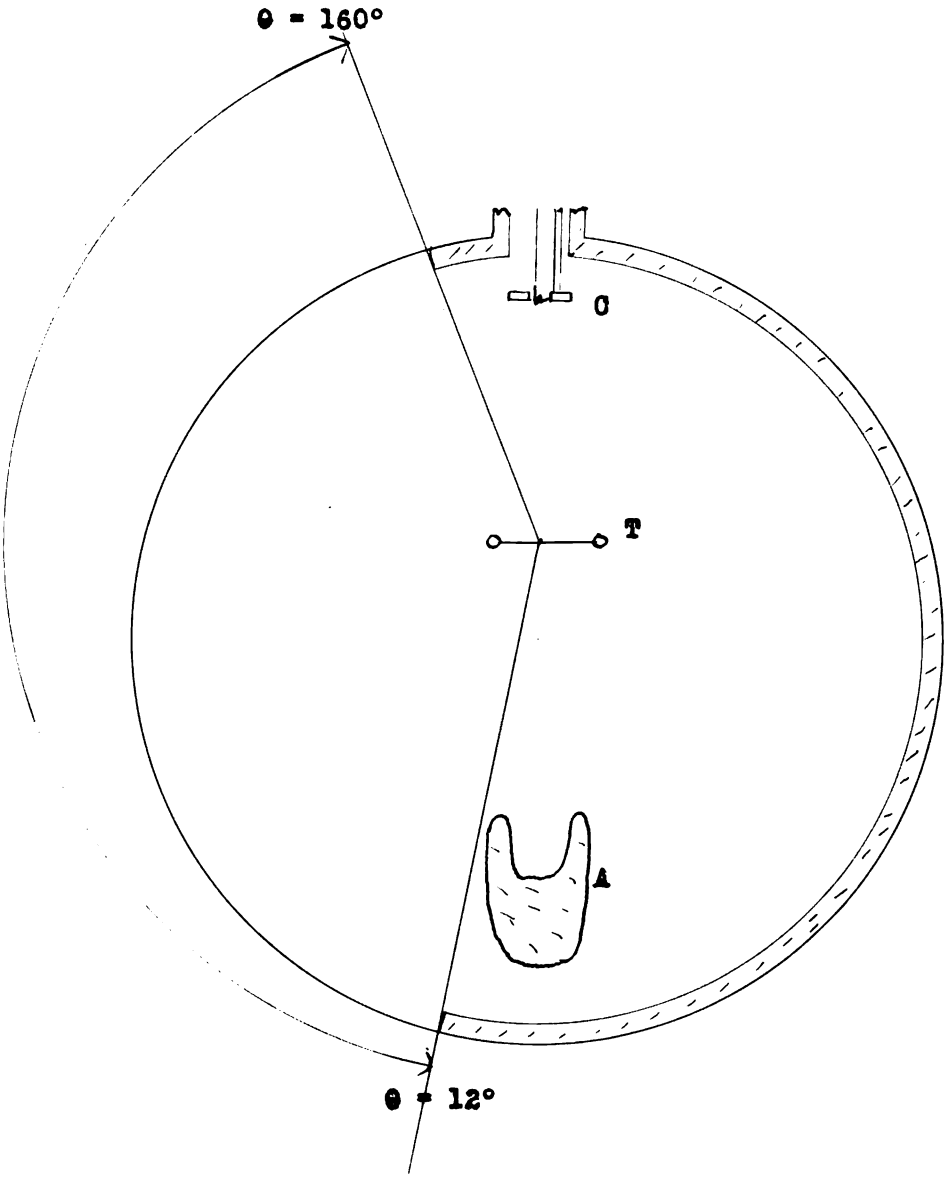

Fig. 1 X-ray Experimental Tube

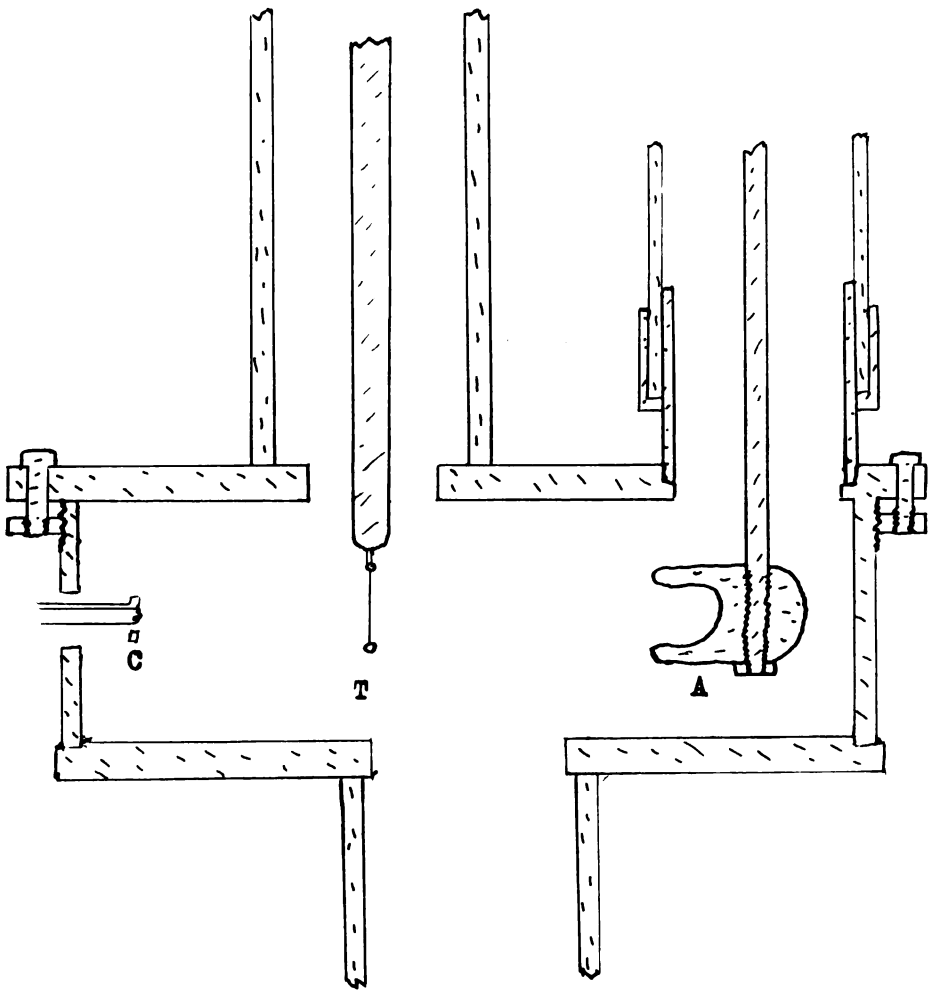

Fig. 2 X-ray Experimental Tube

in a hole in the end of the brass rod support and clamped with a small set screw. The plane of the target can thus be turned at any angle with respect to the cathode ray direction.

The x-rays leave the tube through the window W. This is a horizontal slot in the tube wall, 3/4 inch wide, covered with an aluminum window .0056 cm. thick. Since the absorption coefficient of aluminum is low, this thickness does not seriously diminish the intensity of the beam for the wave lengths used.

The x-ray tube is mounted firmly by means of 8 inch porcelain insulators on a steel frame which can be easily rotated about an axis through the aluminum foil target. This steel frame also supports the diffusion pump used to evacuate the chamber. Outside views of the x-ray tube, showing its general appearance and mounting or insulators are shown in the photographs in Fig. 3a and Fig. 3b.

B. The High Voltage Power Supply

One important requirement for obtaining reliable data in this work is that there must be a supply of constant high voltage, which can be accurately measured, and a means of controlling and measuring accurately the space current in the x-ray tube. The high voltage was obtained from a voltage doubler circuit, which uses two 120 kilovolt Kenotron rectifiers supplied by a 500 cycle 250 volt transformer.

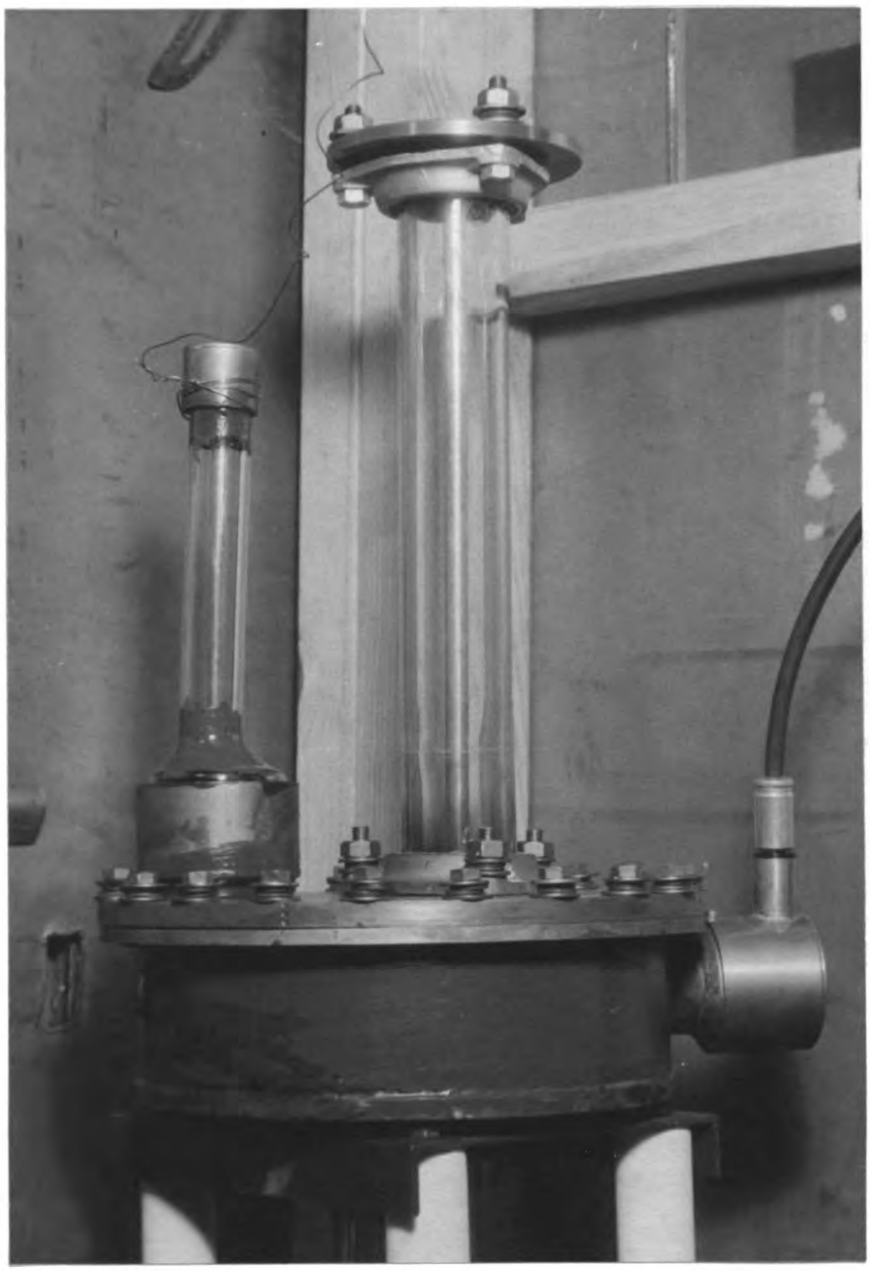

Fig. 3a X-ray Experimental Tube

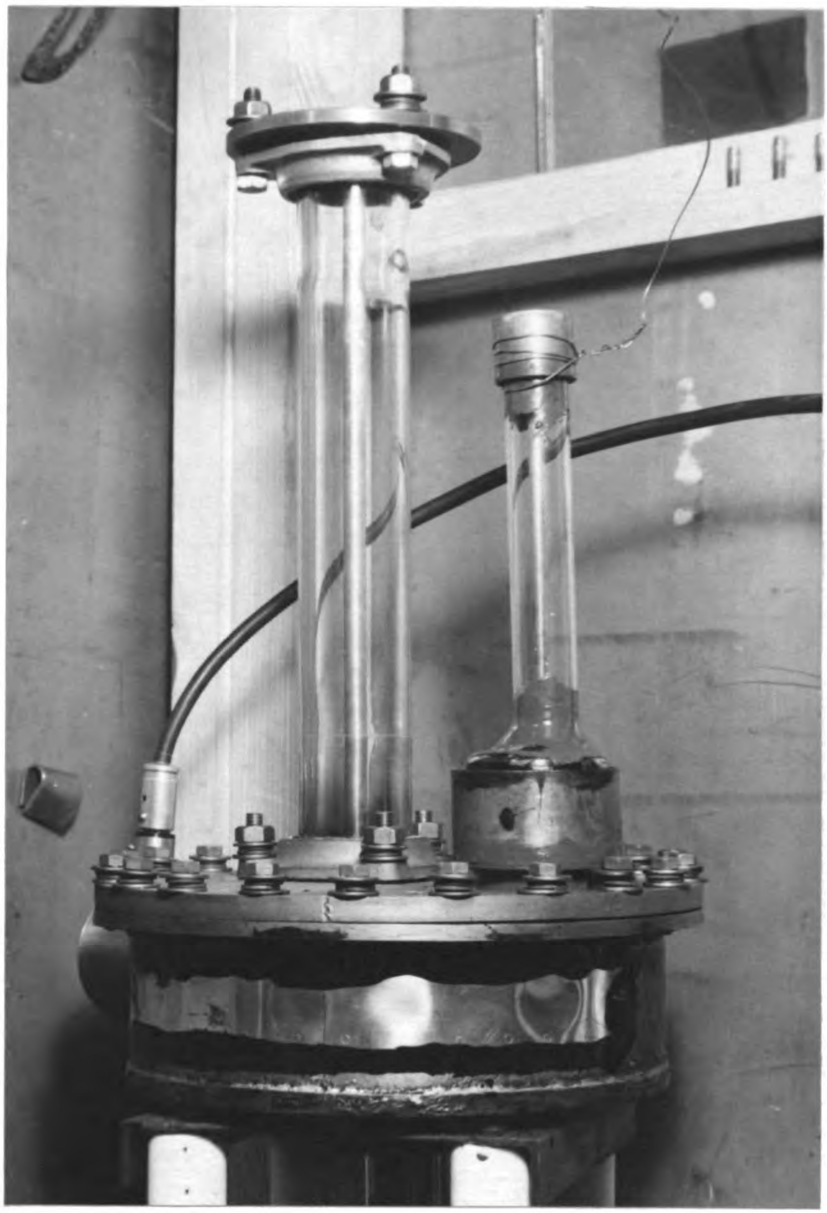

Fig. 3b X-ray Experimental Tube

The 500 cycle generator is driven by a D.C. motor from a 115 volt storage battery, supplemented by a D.C. generator. The capacity of the condensers used in the voltage doubler circuit are of such value that the simple voltage amounts to only 20 volts per milliampere. The high voltage is regulated by a rheostat in series with the field coils of the 500 cycle generator.

The voltage measurement was made with an electrostatic voltmeter shown in Fig. 4. This uses a bi-filar suspension to eliminate inconstancy due to changing torsion constants, and the scale is about 340 cm. from the mirror on the suspension. This allows a sensitivity of about 20 volts /mm. in the neighborhood of 31 kilovolts. The voltmeter is calibrated with a Bragg spectrometer and Coolidge x-ray tube by finding the low wave length limit corresponding to be given voltmeter scale reading.

It would be impossible to measure accurately the small currents used here by merely inserting a meter in either lead of the circuit, since this meter would also record corona currents, which are usually much greater than the tube currents being used. To eliminate this trouble, the entire cathode filament system, including the leads, the 12 volt source, and the current controls are enclosed in an electrostatic shield at negative potential, the cathode system being insulated from the shield for at least 12 volts.

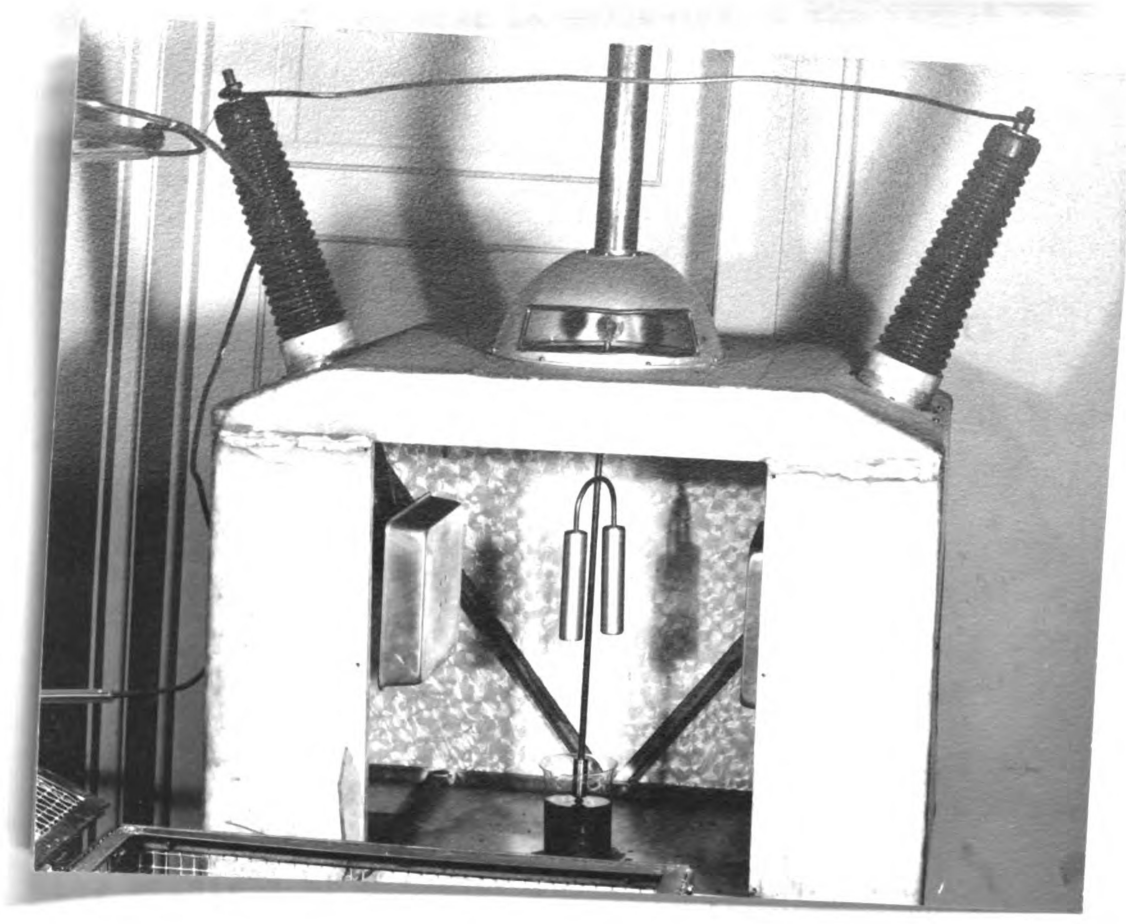

Fig. 4 Electrostatic Voltmeter

The microammeter is inserted between the cathode current source and the shield, and thus measures only the actual space current leaving the cathode in the tube. This current cannot go to the tube walls, since they are at negative potential, so must be collected at the target and anode. The microammeter used is made by the Sensitive Research Instrument Corporation, model S, number 12489, and was used with a sensitivity of 10^{-7} amperes / scale division, so that the current of 10^{-6} amperes used in this work could be measured quite accurately.

C. Measurement of Intensity

Since the purpose of this research is to measure the absolute value of emission intensity, a known fraction of the x-ray beam had to be measured. For this purpose, a standard ionization chamber was designed and built, and is shown in two cross sectional diagrams in Fig. 5 as well as in a photograph in Fig. 6. The chamber consists of a brass cylinder with mica windows at the ends and collector plates of thin aluminum sheet, the chamber being filled with $C H_3 Br$ gas at about 68 cm. pressure. Since the x-ray tube could be rotated, the ionization chamber was permanently mounted. The x-ray beam entered through the mica window and produced ions inside the chamber. In order to eliminate the end effects of irregularity of field, the ion collector was divided into three parts. The central part was connected to the electrometer and the two end portions were

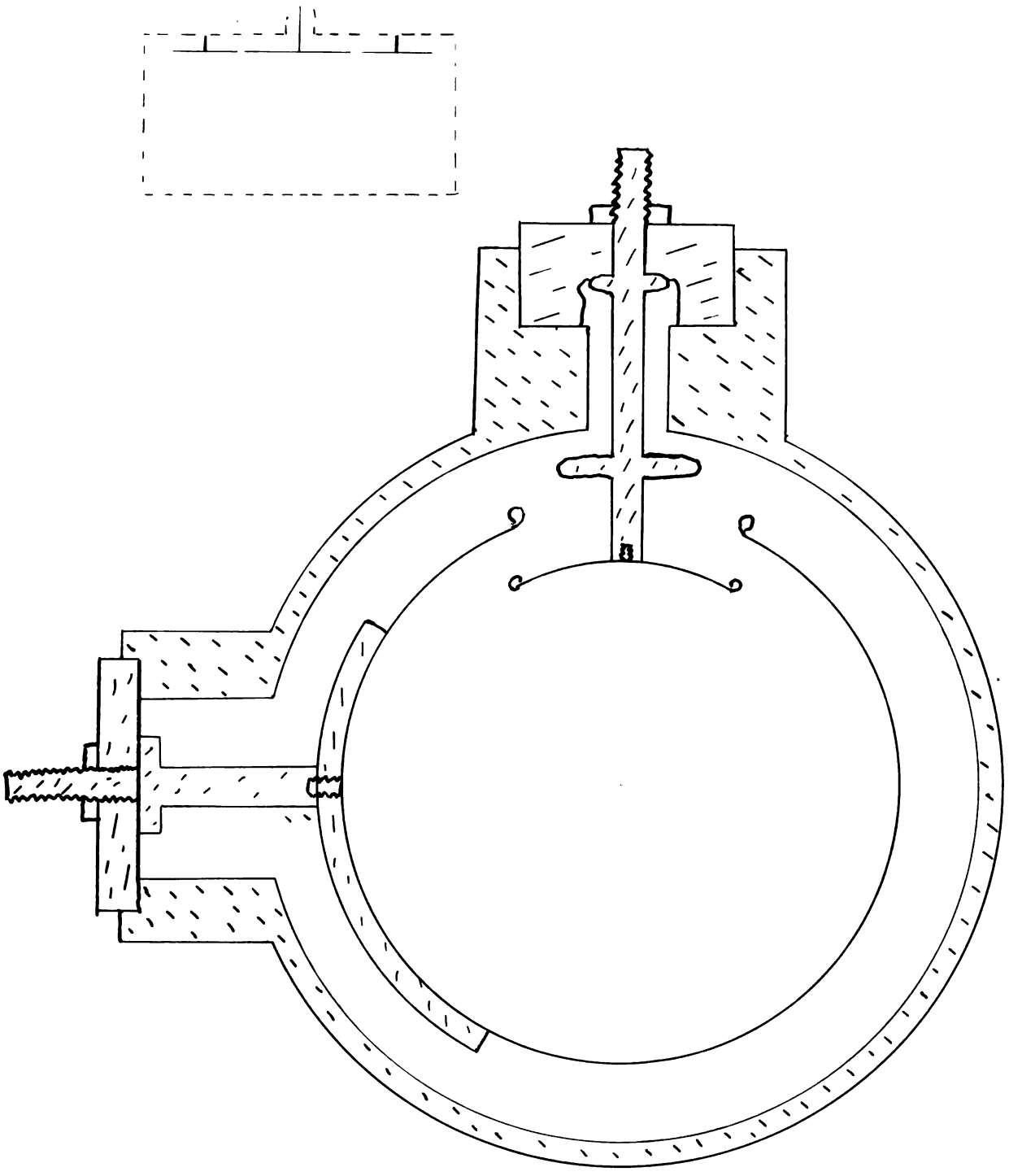

Fig. 5 Standard Ionisation Chamber

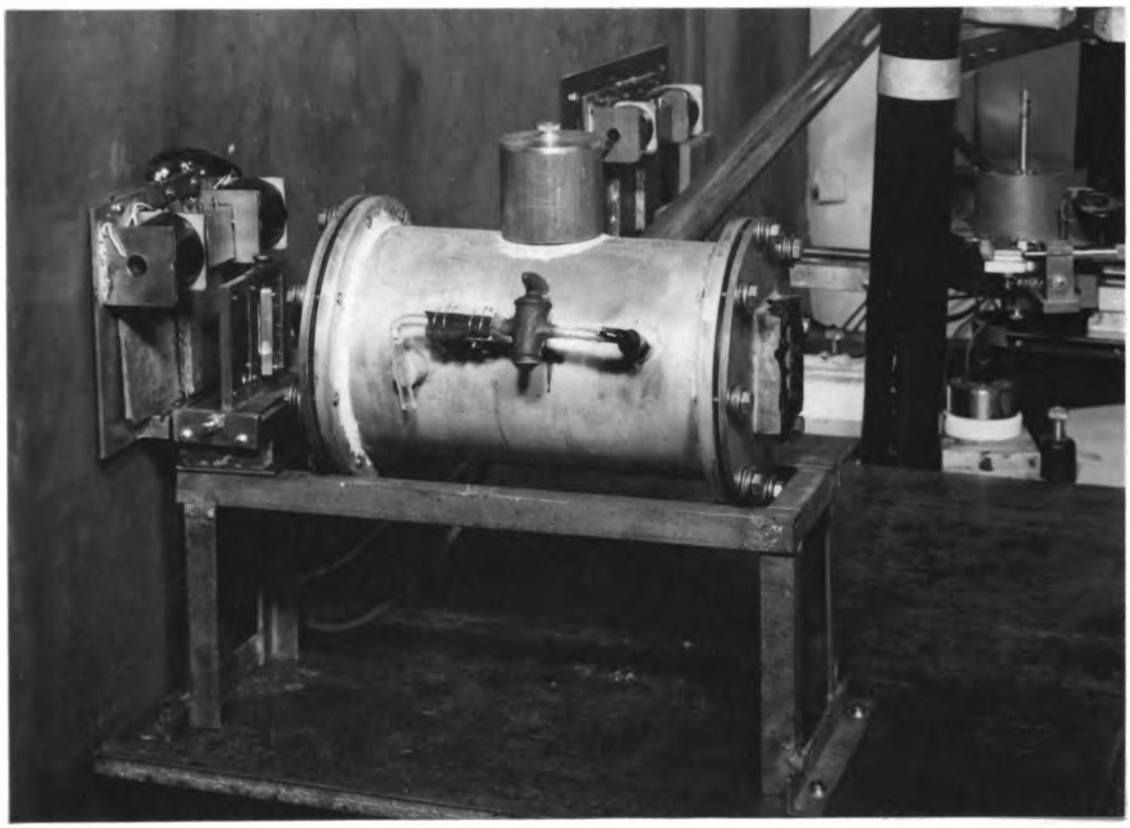

Fig. 6 Ionization Chamber

attached directly to the grounded (negative) chamber. The positive plate is much larger and nearly surrounds the collector electrode, to shield the x-ray beam path from the negatively charged chamber wall. The positive and negative collector supports are inserted through glass and amber insulation, respectively.

It is also desirable to measure only the intensity in a narrow wave length band, so that the distribution curves obtained will be isochromats, or curves of constant wave length. It has already been pointed out that the absorption methods used by Kulenkampff and Böhm do not give a narrow wave length band of uniform intensity. A better method, described by Kirkpatrick (14), uses two absorbing filters of adjacent alements in the atomic table, whose thicknesses can be chosen such that the absorption will be the same for both, except in the narrow interval between their respective K-absorption limits. By the proper choice of filter elements, one can obtain either a narrow or a wide wave length interval, over which the difference in transmitted intensities is quite uniform.

The actual measurement of intensity is made by observing the deflection of a Compton electrometer, which deflection is a function of the total charge collected from a known region in the ionization chamber during a given time interval. In order to have comparable readings, this exposure time interval must be known.

The exposure was controlled by a magnetic shutter, shown in the photograph in Fig. 6, operated through a relay system by a photoelectric cell in a pendulum clock.

D. Arrangement of Apparatus

The general arrangement of apparatus is shown in Fig. 7. The x-ray beam passes from the target through the aluminum window W of the tube and an aperture in the lead house in which the x-ray tube is located. The aperture in the lead house is opened and closed by the magnetic shutter S. The balanced Ross filters F and a defining aperture A are between the shutter and the ionization chamber. This defining aperture has an area of .86 square centimeters, and is of such size and shape that the balanced filters and other apertures and windows are large enough to pass all possible rays from the focal spot on the target through the defining aperture. The aperture A is immediately in front of the ionization chamber window and 34 cm. from the target of the x-ray tube.

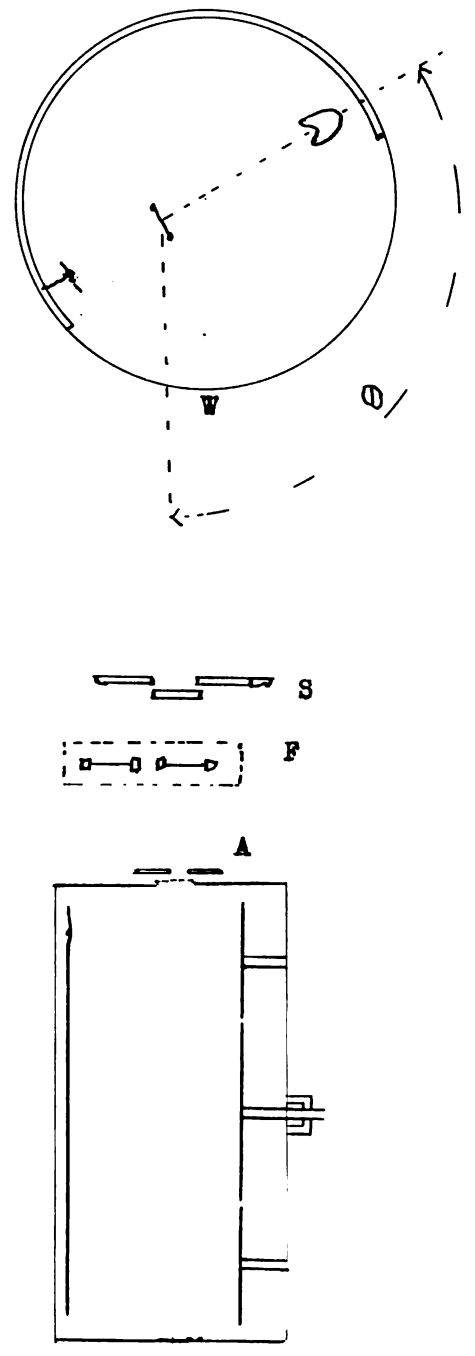

Fig. 7 General Arrangement of Apparatus

III. BALANCING OF ROSS FILTERS

In his discussion of Ross filters, Kirkpatrick (14) shows not only that two such filters should have the same total absorption at all points outside the interval between their K-limits, but also that there is a preferred thickness, with which the maximum intensity difference will be obtained.

This intensity difference is given by

$$I = I_0 (e^{-\mu_L t} - e^{-\mu_S t}) \Delta\lambda$$

$I_0 \Delta\lambda$ being the total unfiltered intensity in the wave length band of $\Delta\lambda$ width, μ_L the absorption coefficient of either element just above its K-limit, μ_S the absorption coefficient of the same element just below its K-limit, and t the thickness of the filter. The value of t that makes I a maximum is found by setting

$$\frac{dI}{dt} = I_0 \Delta\lambda \left[-\mu_L e^{-\mu_L t} + \mu_S e^{-\mu_S t} \right] = 0$$

For this to be true, the quantity in brackets must be zero, so that

$$\mu_L e^{-\mu_L t} = \mu_S e^{-\mu_S t}$$

setting $\frac{\mu_S}{\mu_L} = r$ and taking logarithms,

$$-\mu_L t = \log r - \mu_S t$$

Then $t = \frac{\log r}{\mu_S - \mu_L}$ and, factoring μ_L from the denominator and again substituting r for μ_S/μ_L, one obtains Kirkpatrick's expression:

$$t_{max} = \frac{\log r}{\mu_L (r-1)}$$

In order to have strictly monochromatic measurements, the K-absorption limits defining the wave length interval used should be very close together, but the intensity differences become quite small at the same time. It was decided that the wave length interval of about .021 Angstroms between the silver and cadmium K-limits would be most suitable, and these two elements were used as filters. Using values of μ_a and μ_s for silver, as given in the appendix of Compton and Allison,(17) the optimum thickness for silver is found to be

$$t_{max} = \frac{1.85}{9.8 \times 10.6 \times 5.38} \text{ cm.}$$

= .0033 cm. = .0013 inches, the density ρ of silver being taken as 10.6 gm./cm.3. The thickness of cadmium used must be such that just outside the wave length interval used the absorption is the same for both filters. This means that

$$e^{-\mu_{Ag} t_{Ag}} = e^{-\mu_{Cd} t_{Cd}} \quad \text{or}$$

$$\mu_{Ag} t_{Ag} = \mu_{Cd} t_{Cd}.$$

From this equation,

$$t_{Cd} = \frac{\mu_{Ag} t_{Ag}}{\mu_{Cd}} = \frac{9.8 \times 10.6 \times .0013}{10.66 \times 8.67} = .00147 \text{ in.}$$

Films of the above thicknesses were obtained from Baker & Co., New Jersey and mounted in a brass holder, shown in the photograph in Fig. 6. This was made to hold one

filter perpendicular to the x-ray beam, while the other filter could be rotated about a vertical axis. Then any small inaccuracy in rolling the metal for the thin films could be compensated by changing the effective thickness of one film. When each film was tested roughly with the Bragg spectrometer, it was found that the cadmium was not quite thick enough to balance the silver. By turning the cadmium through a small angle, a balance was obtained for which the absorption of the two films was the same for all wave lengths outside the band of wave lengths under consideration here from the low wave length limit up to about 0.75 Angstroms. For longer wave lengths, the transmitted intensities are quite small and it is not important to have a perfect balance. It can therefore be safely assumed that the difference in transmitted intensities for silver and cadmium is due only to rays in the wave length interval between the K-limits of the two elements.

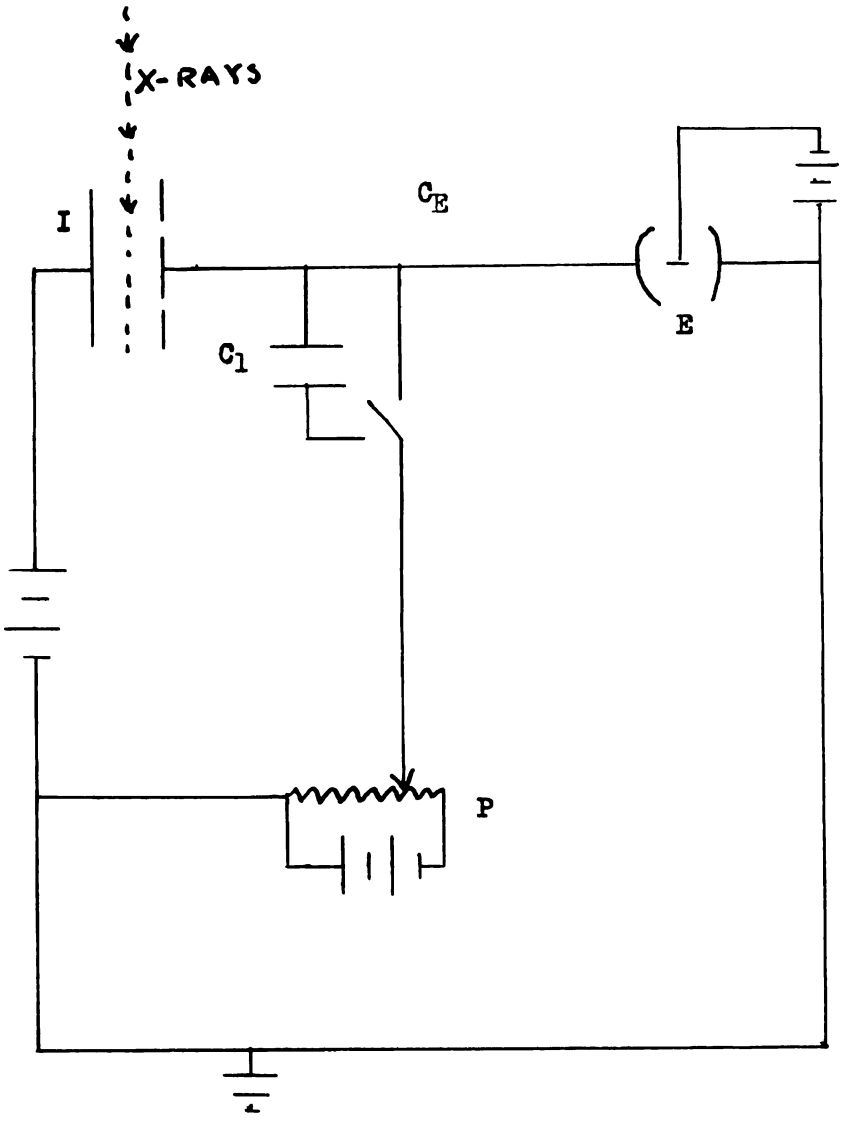

Fig. 8 Electrometer Calibration Circuit

IV. USE OF STANDARD IONIZATION CHAMBER

A. Capacitance of Electrometer circuit

The application of a standard ionization chamber to absolute intensity measurements requires that one know the total charge Q produced in the chamber during the time x-rays are allowed to enter. Assuming that all the ions produced are collected by the elctrometer circuit, the electrometer quadrants are raised to a potential V such that $Q = C_E V$, C_E being the capacitance of the electrometer system and Q the total charge. To find the charge corresponding to a specific electrometer deflection S_1 it is then necessary to measure C_E and the potential v_1 necessary to produce a deflection S_1. This accomplished by the circuit shown in diagram in Fig. 8. Since ballistic electrometer deflections were used for taking data, known voltages V_1 were applied by means of the potentiometer P directly to the electrometer system to produce ballistic deflections in the range in which the instrument was used. Then a standard condenser C_1, specifically a Precision condenser of the General Radio Co., type 222, serial #660, was placed in series with the electrometer system and new voltages V_1 applied to produce the same deflection S_1. In Fig. 9, S is plotted as a function of v_1 and again as a function of V_1. Using a well known relation for condensers in series, then for v_1 and V_1 corresponding to a particular deflec-

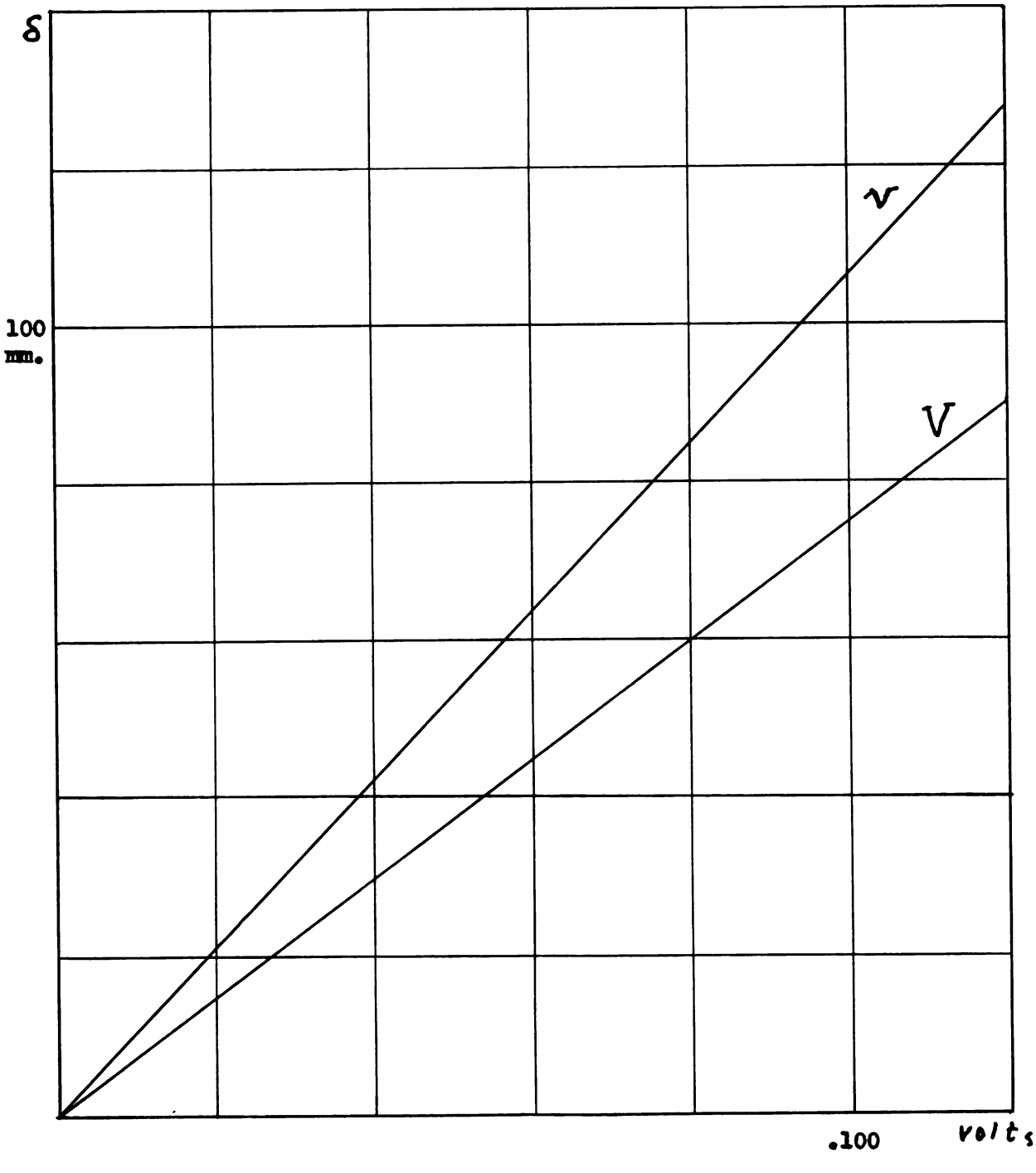

Fig. 9 Electrometer Calibration Curve

tion (or particular charge), $C_E v_1 = C_1(V_1 - v_1)$. The value of C_1 as used was 102 micro-microfarads, and for any deflection in the range utilized, the value of $\frac{V_1 - v_1}{v_1}$ was calculated from points on the graph to be .415. This gives a value of 42.3 micro-microfarads for the capacitance of the electrometer system, which capacitance is constant for the small deflections used here. The total charge collected can then be found by multiplying this by the proper vlaue of v_1 from the graph.

B. Saturation Current Corrections.

So far it has been assumed that all the ions formed reached the collecting plates. Webster and Yeatman (15) have shown that the field intensity between the collector plates of the ionization chamber must be strong enough to sweep out all the ions before recombination occurs. For taking data, eight "B" bateries, supplying 373 volts, were used. As a test for the condition of saturation described by Webster and Yeatman the curves in Fig. 10 were made by chnging the voltage on the ionization chamber, with a constant source of x-rays at least three times as intense as any abtained for the actual data, and constant exposure time. The trend of the curve indicates that the design of the ionization chamber is sufficiently good that practically complete saturation occurs at 373 volts, and that no correction is necessary.

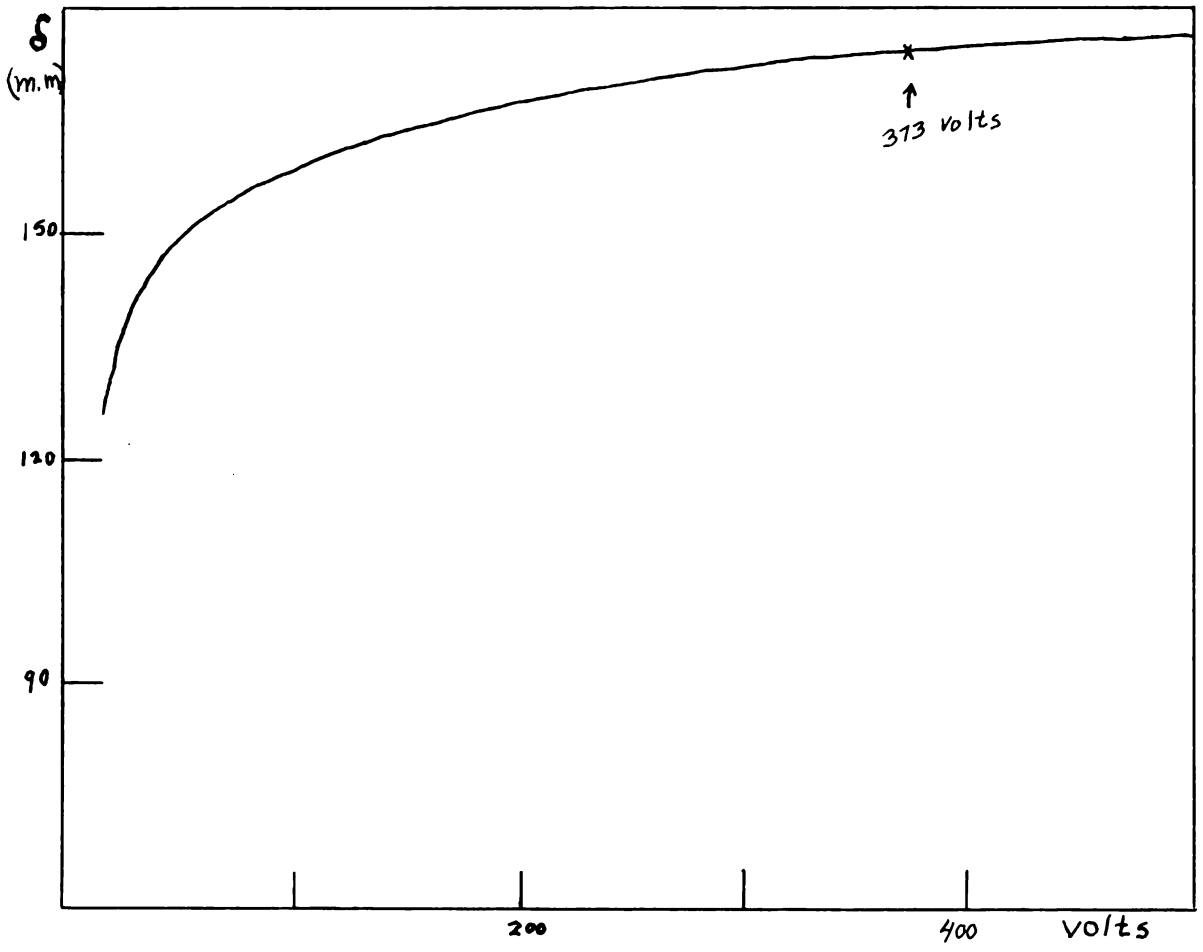

Fig. 10 Voltage Saturation Curve.

C. Fluorscence Correction in the Standard Ionization Chamber

When a beam of x-rays passes through the relatively heavy gas (CH_3 Br) used as the absorber in the ionization chamber utilized in these experiments, two principal kinds of absorption occur. The first of these, and in our case negligible, is that due to scattering of the x-rays by the gas molecules. The second kind of absorption process is that due to the so-called photoelectric absorption. In this case x-rays interact with the highly bound electrons close to the nucleus of the gas atom, which electrons are ejected with energies equal to the difference between the energy of the incident quantum of of x-rays and their atomic binding energy. This difference in energy amounts to 13,100 electron volts for the bromine K-electrons. Photoelectrons of this energy have a range less than 3 millimeters in CH_3 Br at the pressure used here. However, the ejection of the Br. K-electron leaves the atom in an excited state, following which there may be an emission of a quantum of Br K radiation. The minimum amount of gas that this radiation must pass through before it reaches the collecting electrode is 3 centimeters, and in passing through this distance the intensity of this fluorescent radiation is reduced 82%. The actual computations required to arrive at this value are involved, and have already been made for a similar ionization chamber by J.C. Clark (16).

V. ABSORPTION CORRECTIONS

It is necessary to know the fraction of the original intensity of x-rays at the target which is absorbed in the useful part of the ionization chamber. Considering the general arrangement of apparatus shown in Fig. 7, and defining I_0 to be the original intensity at the target, I_1 the intensity penetrating the x-ray tube window, I_2 the intensity emerging from the Ross filter, I_3 the intensity penetrating the mica window of the ionization chamber, I_4 the intensity reaching the front end of the ion collecting electrode, and I_5 the intensity leaving the other end of the same electrode. Then the fraction of the original intensity being absorbed in the useful region of the ionization chamber is given by $\frac{I_4 - I_5}{I_0}$. This must be calculated for the silver filter and the cadmium filter for the mean wave length being used, and the difference will be the fraction of the original intensity in the wave length band being considered. This fraction proportional to the electrometer deflection obtained.

If t_1 is the thickness of the aluminum window of the x-ray tube, t_2 the thickness of the silver or cadmium filter, t_3 the thickness of the mica window of the ionization chamber, l_1 the distance from the mica window to the front end of the collecting electrode, l_2 the length of the collecting electrode, one may write:

$$I_1 = I_0\, e^{-\mu_{Al} t_1}$$
$$I_2 = I_1\, e^{-\mu_F t_2}$$
$$I_3 = I_2\, e^{-\mu_{mica} t_3}$$
$$I_4 = I_3\, e^{-\mu_{Bn} l_1}$$
$$I_5 = I_4\, e^{-\mu_{Bn} l_2}$$

Where μ_p is the linear absorption coefficient for the Ross filter being used. Combining these equations, the fraction of the original intensity reaching the front end of the collecting electrode is given by

$$I_F = e^{-(\mu_{Al} t_1 + \mu_{mica} t_3 + \mu_{Bn} l_1 + \mu_F t_2)}.$$

The fraction of original intensity that passes the far end of the collecting electrode is $I_F\, e^{-\mu_{Bn} l_2}$ The difference between these two fractions, $I_F (1 - e^{-\mu_{Bn} l_2})$ will be the fraction of the original intensity absorbed in the section of ionization chamber containing the collecting electrode.

VI. CHARACTER OF TARGETS USED

A. Scattering and Retardation.

It is already been explained why it is necessary to use thin targets for these measurements. Kulenkampff (2) used targets of commercial aluminum foil about 0.6 microns thick, and calculated the retardation of electrons in foils of this thickness from the Thomson-Whiddington law. He also made measurements of the amount of scattering of the electrons in the same foils, and drew the conclusion that neither retardation nor scattering was enough to influence his data appreciably. Böhm (7) made some measurements with several thicknesses at 31 kilovolts, and found that his experimental results were influenced considerably by changes in thickness from 0.15 microns to 0.6 microns, so he chose to use thicknesses of 0.1 micron or less, made by evaporating magnesium on thin celluloid films. The foils used in the research reported here were made by evaporating aluminum on cellophane, and are approximately the same thickness as those used by Böhm. It is also interesting to note how the energy loss (retardation) compares at 0.1 micron and 0.6 microns. Using the Thomson-Whiddington law

$$V_x^2 = V_o^2 - bx$$

and using values of 9.7×10^{11} for b and 6×10^{-5} cm. for x, Kulenkampff obtained an energy loss of 3.2% at

an energy of 31 kilovolts. If one substitues 1×10^{-5} for x, the energy loss becomes 0.45%, which is a very substantial reduction.

B. Focussing of Cathode Rays

It has been pointed out that the direction of the cathode rays between the filament and target of the x-ray tube should be well defined. For the design of tube used here, this means that the electric field between the target and cathode should be uniform so that no divergence of the cathode rays will occur. The hot filament used was a flat circular coil of tungsten, 5 millimeters in diameter, and upon examination of used targets, the focal spot was plainly distinguishable, being oval, about 5 millimeters high and 8 millimeters long. On some targets which had been used only a short time, the outer portion of the focal spot showed a rough image of the corresponding part of the filament. From these observations, it has been concluded that the targets used, aided by the disk about the cathode filament, produced a very uniform field, so that all the electrons were incident on the target in the same direction. A trial run with a target set at an angle of 45° to the cathode ray beam showed a distorted focal spot being formed, so all actual measurements were made with the cathode rays incident perpendicularly on the target surface.

C. Effect of target backing

One would not expect the cellophane, which was used as a base on which to evaporate aluminum, to contribute an appreciable amount to the x-ray intensity produced by the target. A trial measurement was made to test this assumption, by using a cellophane target without aluminum. A focal spot was formed that coincided almost exactly with those on the aluminum targets, but the intensity of radiation emitted was about 2% of that obtained with aluminum. The difference in intensity when silver and cadmium filters were interchanged was too small to measure.

VII. RESULTS

A. Azimuthal Curves

The data for azimuthal intensity distribution were taken as follows: The x-ray tube was run with a constant voltage of 31,700 volts and a constant current of one microampere, and for an orientation of the tube such that a line from the center of the focal spot through the ionization chamber made an angle θ with the direction of the incident cathode rays, electrometer deflections were recorded for exposure times of 15 seconds, first through the cadmium filter, then through the silver filter. This procedure was repeated at angular intervals of 10° from $\theta = 30^\circ$ to $\theta = 150^\circ$. The data for a typical run are given in table I, and these points plotted in polar coordinates in Fig. 11. An azimuthal distribution curve is drawn through these points, which compares favorably with curves given by Böhm[7]. Points from this and subsequent data show some variation from this curve due to the error in measurement of such small differences. The curve as it is drawn is determined by weighted averages of all the data recorded here, the weighting being determined by the steadiness of tube voltage and current at the time the observation in question was made. The value of θ for the maximum intensity appears at 57° on the curve, while Böhm's maximum value appears at 55°.

Table I

θ	δ cadmium (mm)	δ silver (mm)	difference (mm)
30°	110.2	101.8	8.4
40°	118.0	108.0	10.0
50°	120.1	108.9	11.2
60°	119.6	108.1	11.5
70°	113.0	102.7	10.3
80°	101.0	92.1	8.9
100°	76.1	70.1	6.0
110°	70.8	65.7	5.3
*120°	57.1	55.1	2.0
130°	50.9	47.1	3.8
140°	43.2	41.5	1.7
*150°	37.9	34.9	3.0

*Current not very steady

Table II.

θ	δ cadmium (mm)	δ silver (mm)	difference (mm)
145°	40.1	38.8	1.3
135°	46.1	42.2	3.9
125°	53.2	50.4	2.8
115°	63.9	58.0	5.9
105°	72.1	65.8	6.3
75°	103.8	95.0	8.8
* 65°	111.1	102.0	9.1
* 55°	114.1	106.0	8.1
45°	113.8	105.9	7.9

* voltage not steady

Table 2 lists some deflections observed at angles half way between those used for Table I. It will be noticed that no values of θ are used nearer than 10° to the 90° direction. Observations made edgewise along the target are found to be quite inconsistent, probably partly due to absorption in the wire frame holding the target and to the very much increased apparent thickness of aluminum in this direction. The observations recorded in table 3 were repeated at each angle used to average out errors in measurement.

Table III

θ	δ Cadmium (mm)	δ silver (mm)	difference (mm)	average for θ
30°	106.2	97.5	8.7	
	106.9	98.1	8.8	8.75
40°	111.9	102.6	9.3	
	112.2	102.0	10.4	
	111.9	102.4	9.5	9.66
50°	113.9	104.0	9.9	
	115.0	104.5	10.5	10.2
60°	112.0	101.5	10.5	
	112.1	101.0	12.0	
	113.3	101.1	12.2	11.45
70°	104.9	98.0	6.9	
	104.9	96.8	8.1	7.5
80°	95.4	86.9	8.5	
	98.1	88.1	10.0	
	96.1	88.6	7.5	8.6
100°	75.0	69.0	6.0	
	75.0	68.7	6.3	6.15
110°	65.8	60.5	5.3	
	65.3	61.0	4.3	4.8
120°	56.0	53.0	3.0	
	56.0	52.0	4.0	3.5
130°	50.2	46.3	3.9	
	50.1	46.0	4.1	4.0

B. Absolute values of emission intensity

It has been shown in section V that the fraction of the original intensity in the wave length interval being studied which leaves the target in the solid angle subtended by the lead defining aperture, and which is absorbed in the region of the collecting electrode, is given by

$$\left(1 - e^{-\mu_{Br} l_2}\right)\left(e^{-\left(\mu_{Al} t_1 + \mu_p t_2 + \mu_{mica} t_3 + \mu_{Br} l_1\right)}\right)$$

The μ_F and t_2 apply to the particular Ross filter being used. If one calculates the fraction for each filter and take the difference, one obtains the ratio of the radiation absorbed to produce the difference in deflections observed on the electrometer to the original intensity mentioned above. Calling this ratio R, we have

$$R = .90\left(1 - e^{-\mu_{Br} l_2}\right)\left[e^{-\left(\mu_{Al} t_1 + \mu_{mica} t_3 + \mu_{Br} l_1 + \mu_{Ag} t_{Ag}\right)} - e^{-\left(\mu_{Al} t_1 + \mu_{mica} t_3 + \mu_{Br} l_1 + \mu_{Cd} t_{Cd}\right)}\right]$$

In this equation the constant .90 is that due to the unabsorbed fluorescent radiation produced within the standard ionization chamber a detailed discussion of this absorption correction is given by J.C. Clark.[16]

Since our objective is to find the number of x-ray quanta of mean wave length .474 A° produced, the electrometer deflection differences must be interpreted. A calculation has been carried out for $\theta = 60°$

using an average value of 11.45 millimeters for the deflection difference. In section (IV A), the capacitance of the electrometer system was shown to be 42.3 micro-microfarads. The curve of deflection as a function of applied voltage is a straight line, so a given difference in deflections will represent the same difference in potential at any deflection in the range used. The deflection difference of 11.45 millimeters is found to correspond to a potential difference of .0108 volts. Solving for the charge from the relation $\Delta Q = C \Delta V$ and dividing by the exposure time of 15 seconds, the charge collected per second is 3.05×10^{-14} coulombs /sec.; one uses the relations:

Charge associated with one ion pair (one electron)= 1.6×10^{-19} coulombs.

Energy of one quantum (.474 Angstroms)= 26,130 electron volts.

Energy required to produce ion pair = 25.4 electron volts.

The value of 25.4 electron volts of energy for each ion pair formed is the same as was used recently by J.C Clark (16). Using these relations, one obtains the result that 3.05×10^{-14} coulombs/sec. = 188.5 quanta /sec. equ. (2).

The solid angle subtended by the defining aperture of .86 cm^2. at a distance of 34 cm. from the target is

$\frac{.86}{(34)^2}$ = .00074 spherical radians or .000059 of a sphere.

The number of electrons per second incident on the target with the current of one microampere is

$$\frac{1 \times 10^{-6} \text{ coulombs/sec.}}{1.6 \times 10^{-19} \text{coulombs/electron}} = 6.25 \times 10^{12} \text{ electrons/sec.}$$

To determine the number of atoms present in a square centimeter of target foil, it is necessary to know the thickness of the target or the mass/cm^2. A section of foil was weighed by Prof. E. Leininger with the aid of a micro-balance, and 51.1 cm^2. of foil contained 1.96 milligrams of aluminum. This corresponds to a thickness of 1.4×10^{-5} cm. The number of atoms/cm^2 is given by

$$a = \frac{Nm}{AM},$$

where N is avogadro's number, m the mass of an area A, and M the atomic weight. Then

$$n = \frac{6.06 \times 10^{23} \times 1.96 \times 10^{-3}}{51.1 \times 26.97} = 8.63 \times 10^{17} \frac{\text{atom}}{\text{cm}^2}$$

To evaluate equation (1), it is necessary to know the absorption coefficient of CH_3 Br, designated as in equation (1), was measured with a Bragg spectrometer at the pressure of 68.3 cm. Hg. used and found to be .0782. The other absorption coefficients were obtained from Compton and Allison (17) and are as follows at .474 Angstroms.

$\mu_{al} = 1.70 \times 2.7 = 4.6 \text{ cm}^{-1}$

$\mu_{mica} = 4.658 \text{ cm}^{-1}$

$\mu_{ag} = 58.7 \times 10.6 = 623 \text{ cm}^{-1}$

$\mu_{cd} = 9.34 \times 8.67 = 81.0 \text{ cm}^{-1}$

The thicknesses of absorbers are

$t_1 = .0056$ cm.

$t_{ag} = .0033$ cm.

$t_{cd} = .0037$ cm.

$l_1 = 7.8$ cm.

$l_2 = 10.0$ cm.

$t_3 = .0043$ cm.

Then

$\mu_{al}\, t_1 = .0256$

$\mu_{mica}\, t_3 = .020$

$\mu_{ag}\, t_{ag} = 2.057$

$\mu_{cd}\, t_{cd} = .300$

$\mu_{Br}\, l_1 = .610$

$\mu_{Br}\, l_2 = .782$

Equation (1) then becomes

$$R = .9\,(1-e^{-.782})\,(e^{-.956} - e^{-2.713})$$

$$= .9\,(1 - e^{.457})\,(.385 - .066)$$

$$= .156$$

Then since R is the measured fraction of the total number of quanta emitted in the solid angle used, the

number of quanta per sec. in this solid angle is

$\frac{188.5}{.156}$ = 1208 quanta per seconds

This value, 1208, represents the number of quanta in the wave length band $\Delta\lambda$ =.0215 A° of mean wave length 474. 0A° emitted per second by an aluminum foil target of thickness 1.4 x 10^{-5} cm, in a solid angle of .000744 spherical radians at an angle of 60° with respect to the direction of the incident cathode ray beam.

With the azimuthal distribution curve plotted in Fig. 11, a dotted curve is added which represents Scherzer's theoretical results as plotted by Böhm (7). The azimuthal distribution curve obtained here agrees quite well with the theoretical curve when the two are normalized to be identical at θ = 90°. The agreement is not as good at small and large angles, where the intensity differences measured are small, and the error correspondingly larger.

Owing to the laborious numerical calculations involved in evaluating Scherzer's theory, a direct quantities comparison with this theory has not as yet been carried out for the absolute value of continuous x-ray energy.

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