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THE DETERMINATION OF X-RAY MASS ABSORPTION COEFFICIENTS FOR COLUMBIUM FROM .200 TO .500 ANGSTROM UNITS

Thesis for the Degree of M. S.
MICHIGAN STATE COLLEGE
Newman Pettitt
1939

THESIS

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THE DETERMINATION
OF X-RAY MASS ABSORPTION COEFFICIENTS FOR
COLUMBIUM FROM .200 TO .500
ANGSTROM UNITS

BY

NEWMAN PETTITT

Submitted in partial fulfilment of the requirements
for the degree of Master of Science in the
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Department of Physics,
June, 1939.

The writer wishes to express his gratitude to Dr. J. C. Clark under whom he worked and to Professor C. W. Chapman who made this research possible.

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INTRODUCTION

The very first experiments performed with X-rays showed a reduction in their intensity as they traversed matter. That this absorption depends upon the thickness of the absorbing medium through which the X-rays are made to pass is also well known.[1] Quantitatively, the phenomena may be expressed by the relationship

$$\frac{dI}{I} = -\mu \rho \, dx \qquad (1)$$

where $\frac{dI}{I}$ represents the fraction of the intensity I of the beam of X-rays absorbed as they traverse a thickness dx of the material of density ρ. The proportionality factor μ_m has been defined as the "mass absorption coefficient" of the absorbing material, and experiments[2] have shown this coefficient to be a function of both the atomic number of the absorber and the wave-length of the X-ray radiation being absorbed.

Studies of phenomena involving the uses of X-rays generally, in some way or another, necessitate a knowledge of the percentage of X-rays absorbed. It has therefore been the purpose of many experiments[3] to determine as accurately as possible the value of the mass absorption coefficients "μ_m" for all the elements and for X-rays extending over a great range of wave-lengths. The experiments herein reported were performed to determine the mass

1. Compton and Allison--X-Rays in Theory and Experiment--
   Sec. 4 Chap. I.
2. F. K. Richtmeyer--Phys. Rev. 18, 13, 1921.
3. Compton and Allison--X-Rays in Theory and Experiment--
   Table I page 800.

absorption coefficient for the element Columbium throughout a wave length range hitherto not measured, specifically, .200 to .500 A.

It is seen from the equation defining the mass absorption coefficient that measurements must be made of the intensity of the X-ray beam before and after absorption has taken place. Since it is practically impossible to make these intensity measurements simultaneously, it becomes necessary to have accurate control over the source of X-rays used. This necessitates having an accurately controllable source of electrical power for the X-ray tube. Also, in order to study the absorption as a function of wave length of the X-rays used, it is necessary to have suitable analyzing apparatus, such as an X-ray spectrometer. At the time these experiments were proposed the above apparatus was not available in the laboratory, and a considerable portion of the total time spent in these experiments has been to assist in constructing and assembling this rather elaborate apparatus.

The first part of this thesis, therefore, will be a description of the apparatus, and the second part a report of the measurements of the mass absorption coefficient of Columbium over the wave length range already stated.

THE DETERMINATION OF X-RAY MASS ABSORPTION COEFFICIENTS FOR COLUMBIUM FROM .200 TO .500 ANGSTROM UNITS

PART ONE

APPARATUS

1) General Description

The measurement of X-ray intensities may be made most easily by either of two methods, first the photographic and second the ionization produced in various gases. For these experiments the second method was used. This method involves the measurement of the ionization current produced by the partial absorption of the X-ray beam as it passes through a suitable gas within an ionization chamber. In these experiments, however, measurements were made over a range of wave lengths, thus requiring a device to select from all of the wave lengths given off by the X-ray source an increment of wave lengths very small in comparison with the entire range covered. Apparatus suitable for this purpose is shown schematically in figure 1. In this figure the source of X-rays was a 400 watt standard air-cooled General Electric tube with a tungsten target and Coolidge type filament. Power for operating this tube was obtained from a high voltage generator to be described in detail later. The X-ray tube was mounted in a lead walled chamber with wall thickness of 1/8 inch, which

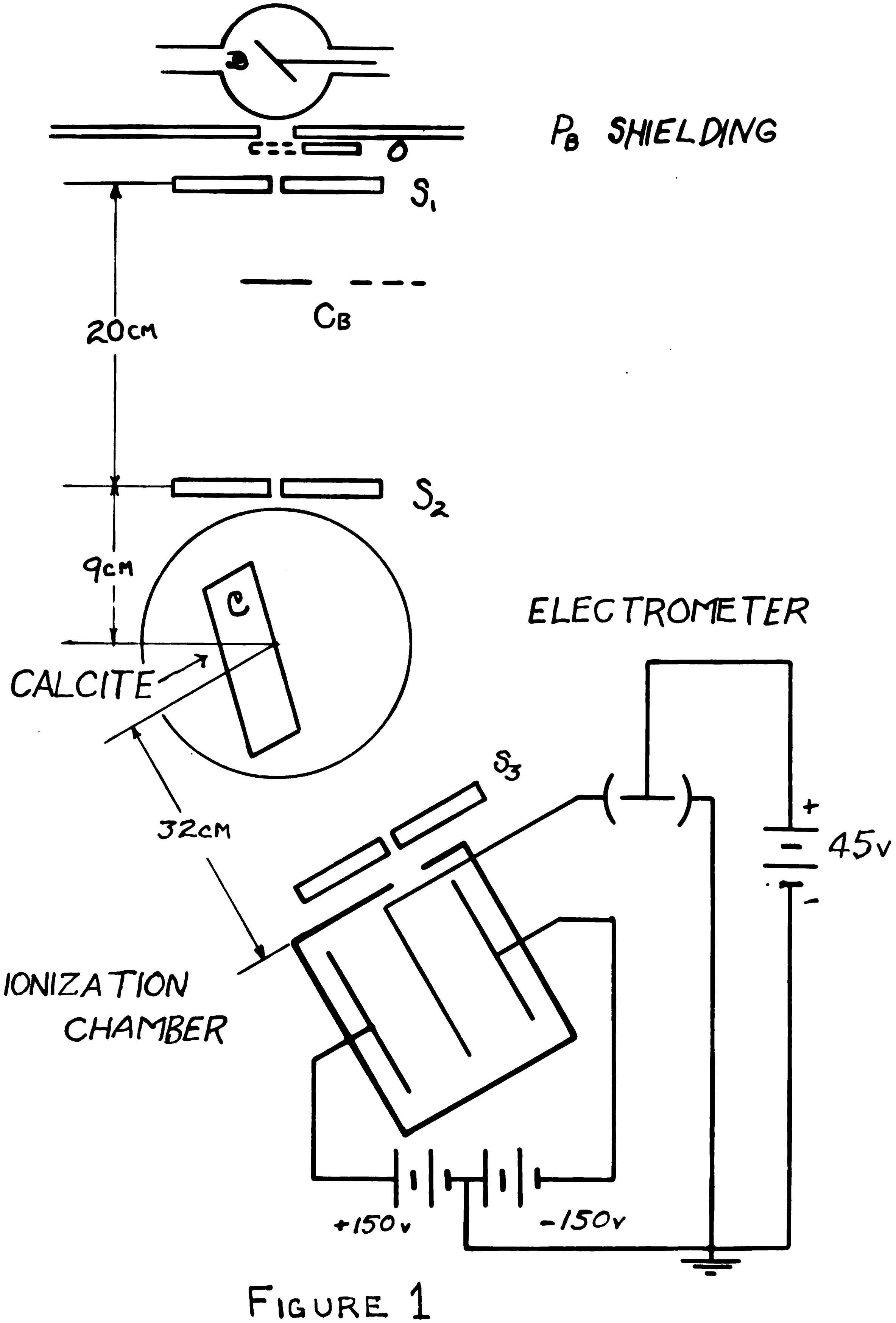

P_B SHIELDING
S_1
C_B
20cm
S_2
9cm
C
CALCITE
32cm
S_3
ELECTROMETER
+
45v
-
IONIZATION CHAMBER
+150v
-150v

FIGURE 1

is sufficiently thick to prevent any X-rays from escaping. A small rectangular opening in this chamber allowed a beam of X-rays to strike the collimating lead slits S_1 and S_2 only when the electromagnetically controlled lead shutter (C) was in the "open" position. Between the two slits S_1 and S_2 the thin sheet of columbium was inserted into the path of the X-ray beam, as shown on the diagram. The X-rays then strike the calcite crystal, where they experience diffraction, and the energy of various wave lengths is sent out in different directions according to the well known Bragg relation

$$n\lambda = 2\, d_{hkl} \sin\theta \qquad (2)$$

The movable ionization chamber is then adjusted to receive the portion of the diffracted beam desired and the intensity of this beam thereby measured by the Compton type quadrant electrometer connected to the ionization chamber.

The above description covers a general view of the apparatus. Since this apparatus can be used for many experiments other than the one herein reported it will be the purpose of the following sections of this thesis to present a detailed description of its construction and operation.

2) High Voltage Power Supply

The total X-ray output from a thick target X-ray tube varies directly with the space current and with the tube voltage squared. It is thus obvious that for a constant source of X-rays both the tube voltage and current must be accurately controlled, and if possible the voltage more accurately than the current. Various high voltage circuits have been reported[4,5,6] as suitable for X-ray research purposes. The apparatus assembled for this work is the voltage-doubler circuit shown schematically in figure 2a. Although neither the positive or negative terminal of this circuit is at ground potential is has the advantage of doubling the transformer voltage and providing full wave rectification and almost complete filtering provided the condensers are of sufficient capacity.

Under a very heavy load the voltage output assumes the wave form shown in figure 2b. Upon calculation the neutral point is found to vary as shown in figure 2b.

The total ripple voltage between the terminals is shown in figure 2c. It will be noted that the frequency of the ripple is just twice the frequency of the transformer voltage, an effect which helps greatly to reduce the final ripple voltage as current from this circuit is further filtered by large inductances.

4. X-ray Technology, Terrill & Ulrey, Chap. IV
5. D. L. Webster, Proc. Nat. Acad. Sci. 6 26 and 239, (1920)
6. D. L. Webster, & A. E. Hennings, PR. 21 301 (1923)

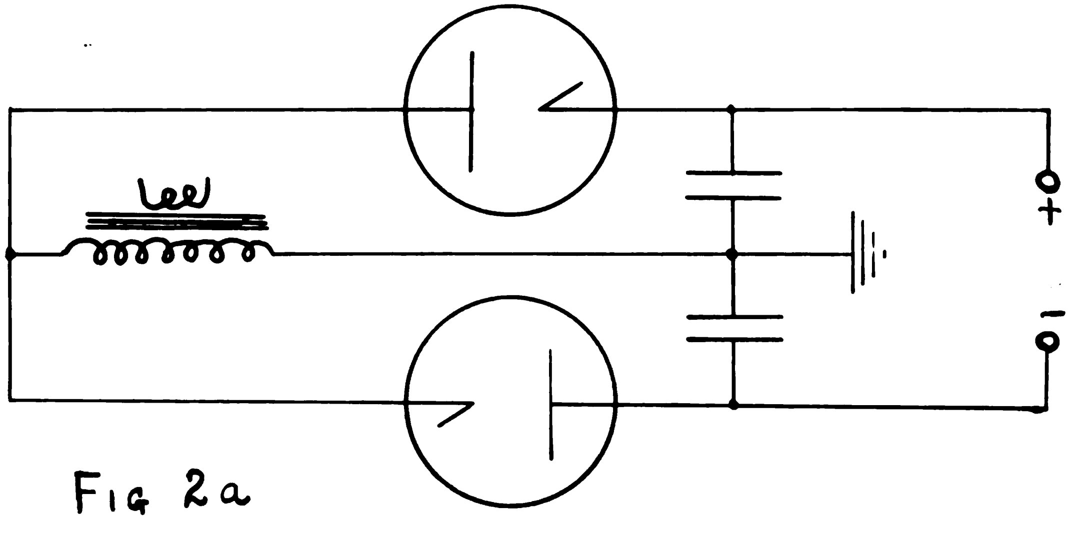


Fig 2a

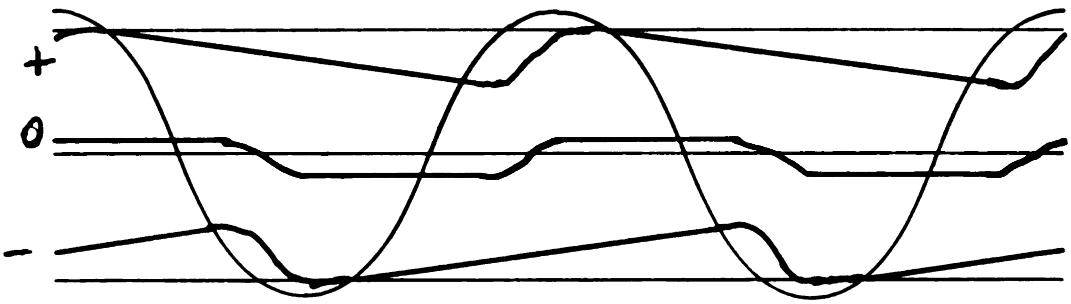


Fig 2b

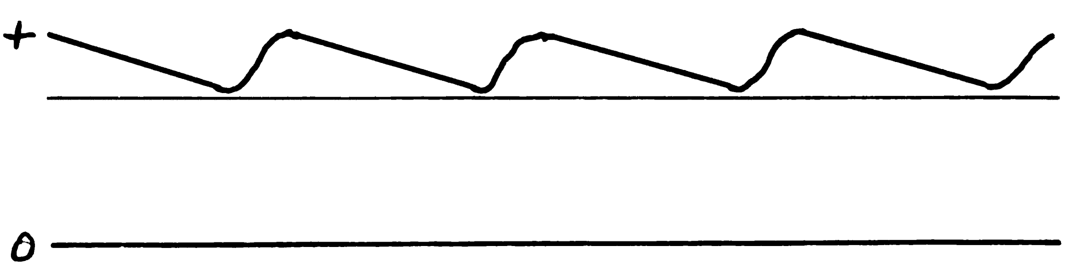
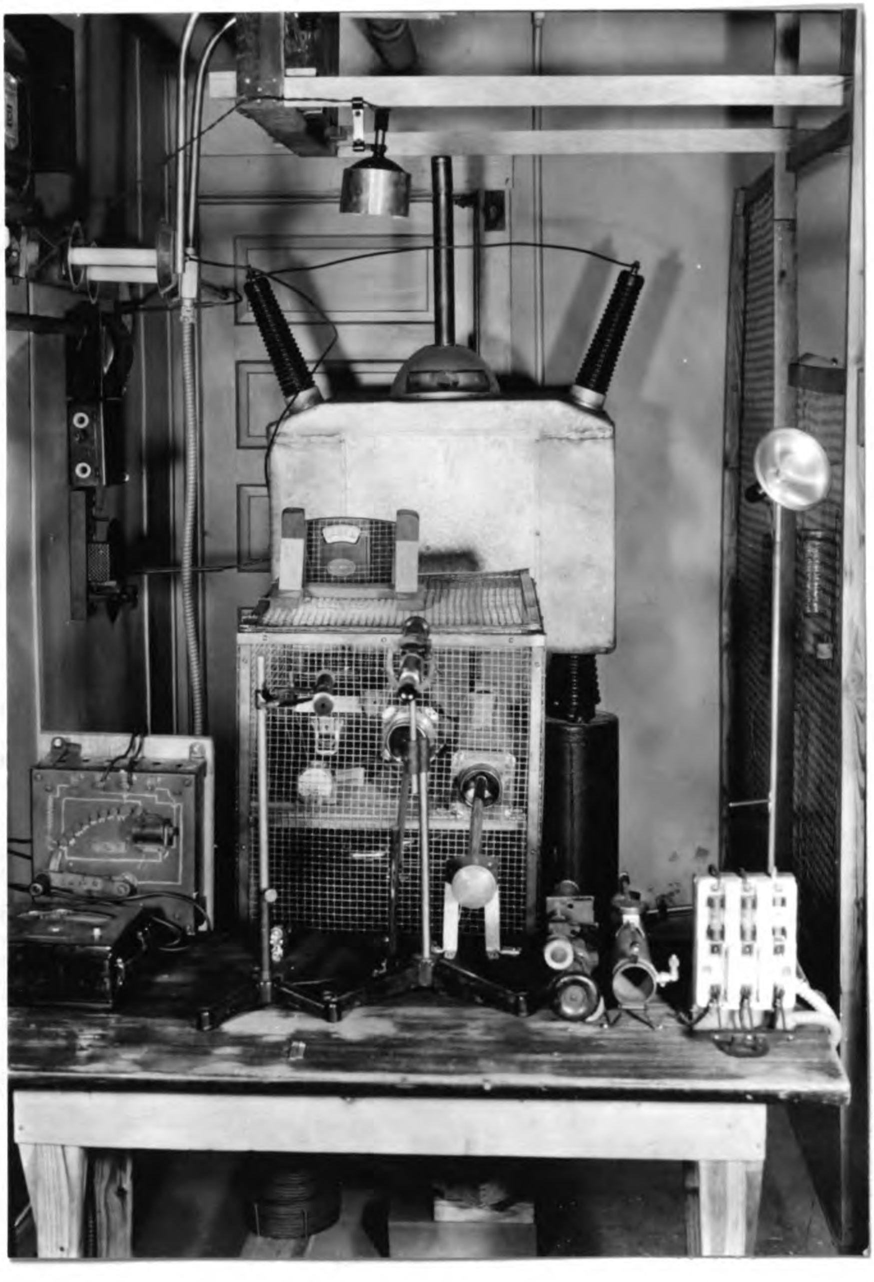
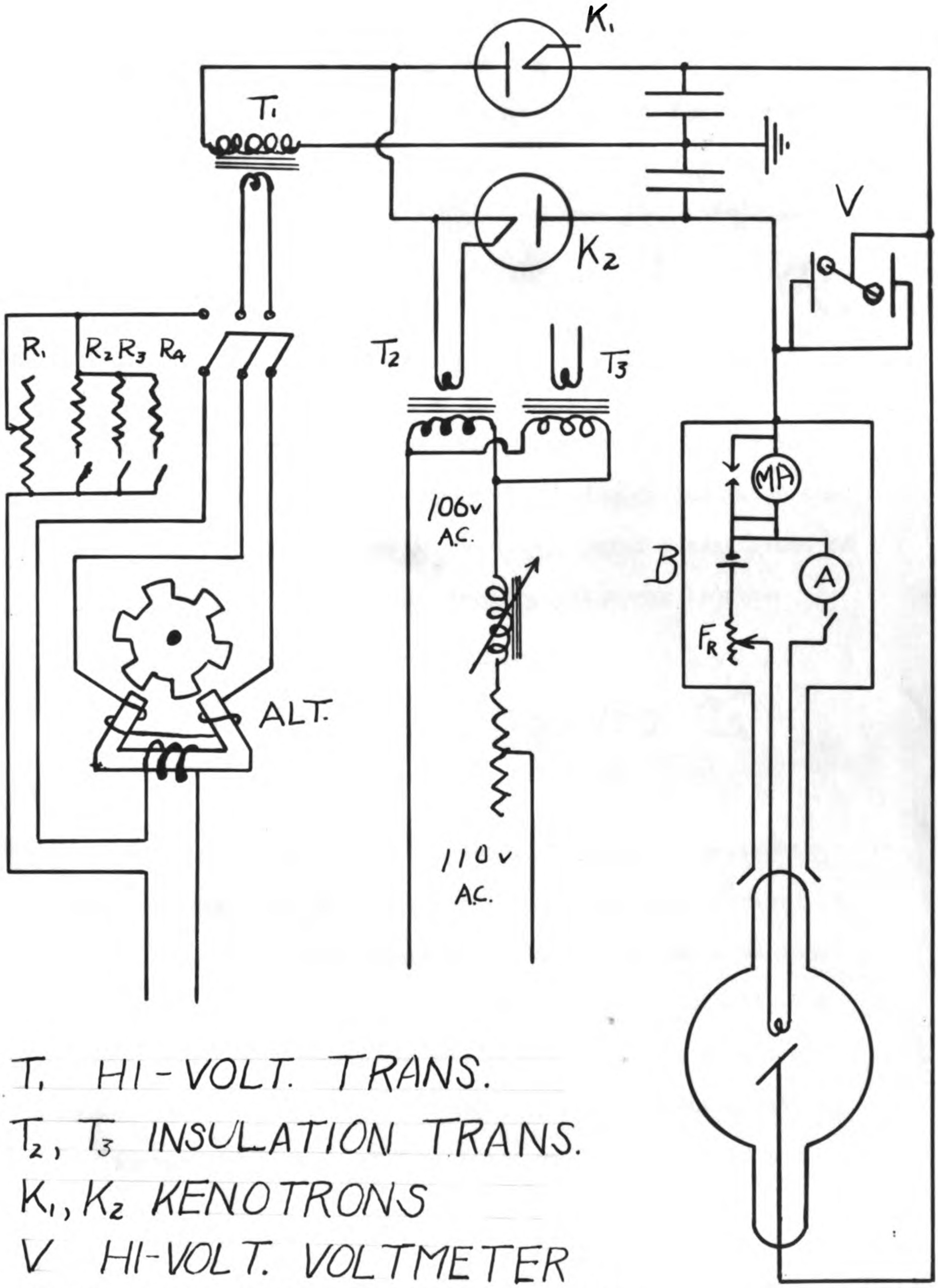


Fig 2c

Complete details of the power supply circuit, with controls, are shown in figure 3. Low voltage (250 volts, maximum) power was supplied to the primary of the high voltage transformer from a five hundred cycle inductor type alternator. Control of the high voltage was secured by varying the field current of the alternator by means of the resistances R_1 R_2 R_3 R_4. The direct current which flows in this circuit does not exceed 1.5 amperes, and hence the controlling resistances need not be large from a standpoint of heat dissipation. Since filtering of the rectified high voltage alternating current is more complete at higher frequencies, the 500 cycle source is preferred to the usual 60 cycle sources. On the other hand eddy current losses in the core of the transformer increase at the higher frequencies and hence cause the core to become heated. It was found however that for the 60 cycle transformer used in this circuit the heating was not excessive.

The air insulated plate glass condensers used in the high voltage circuit consist of fourteen sheets of double strength windowglass selected to be free from air bubbles. Each sheet has an area of nine square feet, four square feet of which are coated on each side with first "aqua dag", and then tinfoil. The six inch border around each sheet of tinfoil provides insulation for about 100 kilovolts. The battery of fourteen plates were divided into two groups of seven each, the seven plates in each group being connected parallel and the two groups connected in series across the positive and negative high voltage source terminals. The middle of these two groups is connected





T_1 HI-VOLT. TRANS.

T_2, T_3 INSULATION TRANS.

K_1, K_2 KENOTRONS

V HI-VOLT. VOLTMETER

ALT. 500 CYCLE ALTERNATOR

FIGURE 3.

to the ground as shown in the diagram. Each group of seven plates in parallel has a total capacity of .0565 microfarad. For this type of circuit the ripple voltage may be approximately calculated, assuming no further filtering by inductances or other capacities, by the expression

$$\Delta V = \frac{i}{c}\,\Delta t \tag{3}$$

where i is the current being drawn from the circuit, C is the capacity and Δt is the interval of time during which the condensers furnish charge to the line. For the conditions of this circuit the ripple voltage per milliampere is thus approximately

$$\frac{\Delta V}{i} = \frac{10^{-3}}{.565 \times 10^{-7} \times 10^{-3}} = 17.7 \ \frac{\text{volts}}{\text{ma}} \tag{4}$$

Since the X-ray tube voltage used during these experiments was not less than 25 KV and the tube current not greater than 5 ma, it is seen that the ripple voltage was less than one percent of the tube voltage at all times. Actually the ripple voltage is less than the value calculated by the expression due to considerable capacity of the electrostatic voltmeter and large size conductors used to transport the high voltage from the high voltage power plant to the X-ray tube. Two type KR-3 General Electric Kenotrons, drawing 12 amps at 13 volts on the filament with a capacity of 100 ma at 120,000 volts continuously were used for rectifier tubes.

3) High Voltage Voltmeter- Description of Voltmeter

a) The high voltage was measured and held constant during all measurements by means of an electrostatic voltmeter shown in the diagram of figure 4. This instrument[7] consists of two cylindrical electrodes mounted on a yoke and supported by means of a bifilar suspension between two large flat electrodes. The entire instrument is encased in a metal box to effect electrostatic shielding. The instrument was designed to withstand a peak voltage of 120 kilovolts, so far as electrical insulation is concerned. The sensitivity of the instrument however depends largely on the bifilar suspension characteristics, and at present the instrument gives a full scale deflection at approximately 60 KV.

b) Calibration of High Voltage Voltmeter

This electrostatic type of high voltage voltmeter is not an absolute instrument, and must therefore be calibrated.

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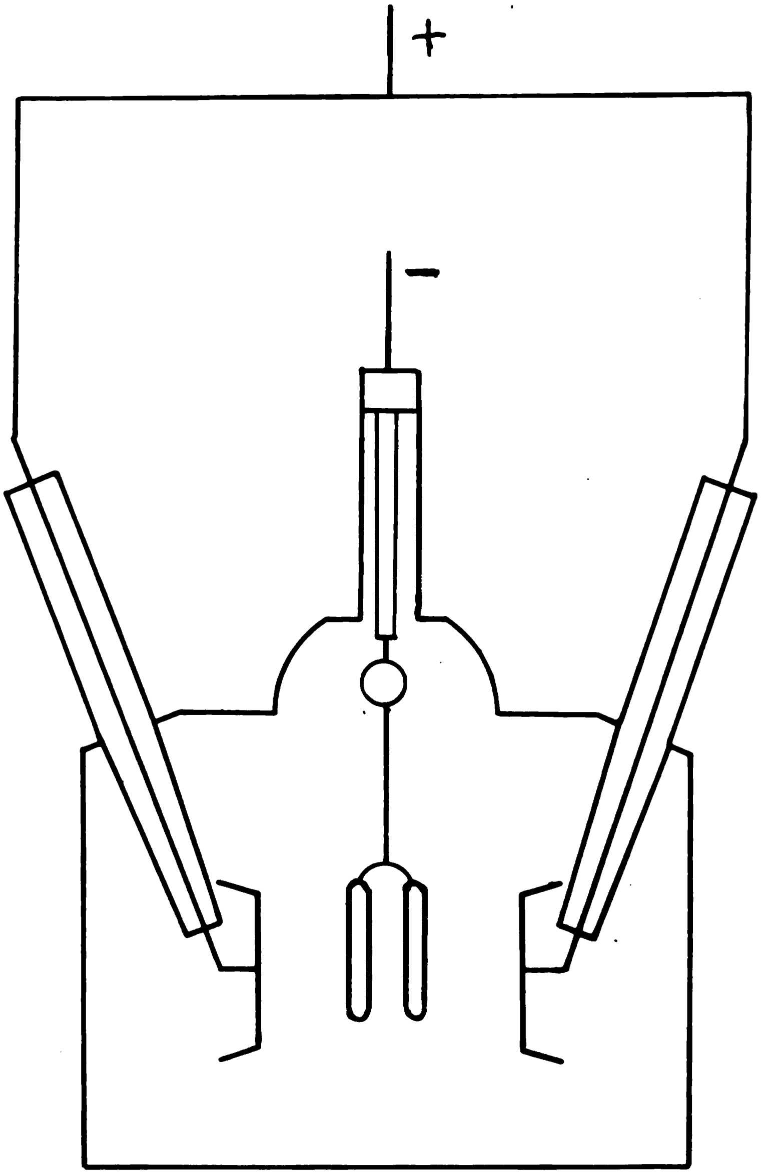
7. H. Clark Rev. Sci. Inst. 1 , 618, 1930

ELECTROSTATIC VOLTMETER



SCALE $\frac{1}{10}$

FIGURE 4

Two ways in general are used: 1) by means of a potentiometer to measure the current which flows through a very high resistance connected across the high voltage terminals, 2) by means of the shortest wave length of X-rays produced by a given high voltage on the X-ray tube. The latter of the two methods was used here. From the well established relationship

$$Ve = h\nu_0 \tag{5}$$

where h is Planck's constant (6.547×10^{-27} erg sec) and ν_0 is the highest X-ray frequency produced by cathode rays of energy Ve electron volts bombarding the target of the x-ray tube. By means of the Bragg spectrometer, yet to be described, the short wave length limit λ_0 corresponding to a given voltmeter setting was determined for several voltmeter scale points. Since

$$\lambda_0 = \frac{c}{\nu_0} \tag{6}$$

where c is the velocity of light, the relationship between λ_0 and V becomes

$$V(KV) = \frac{12.354}{\lambda_0(AU)} \tag{7}$$

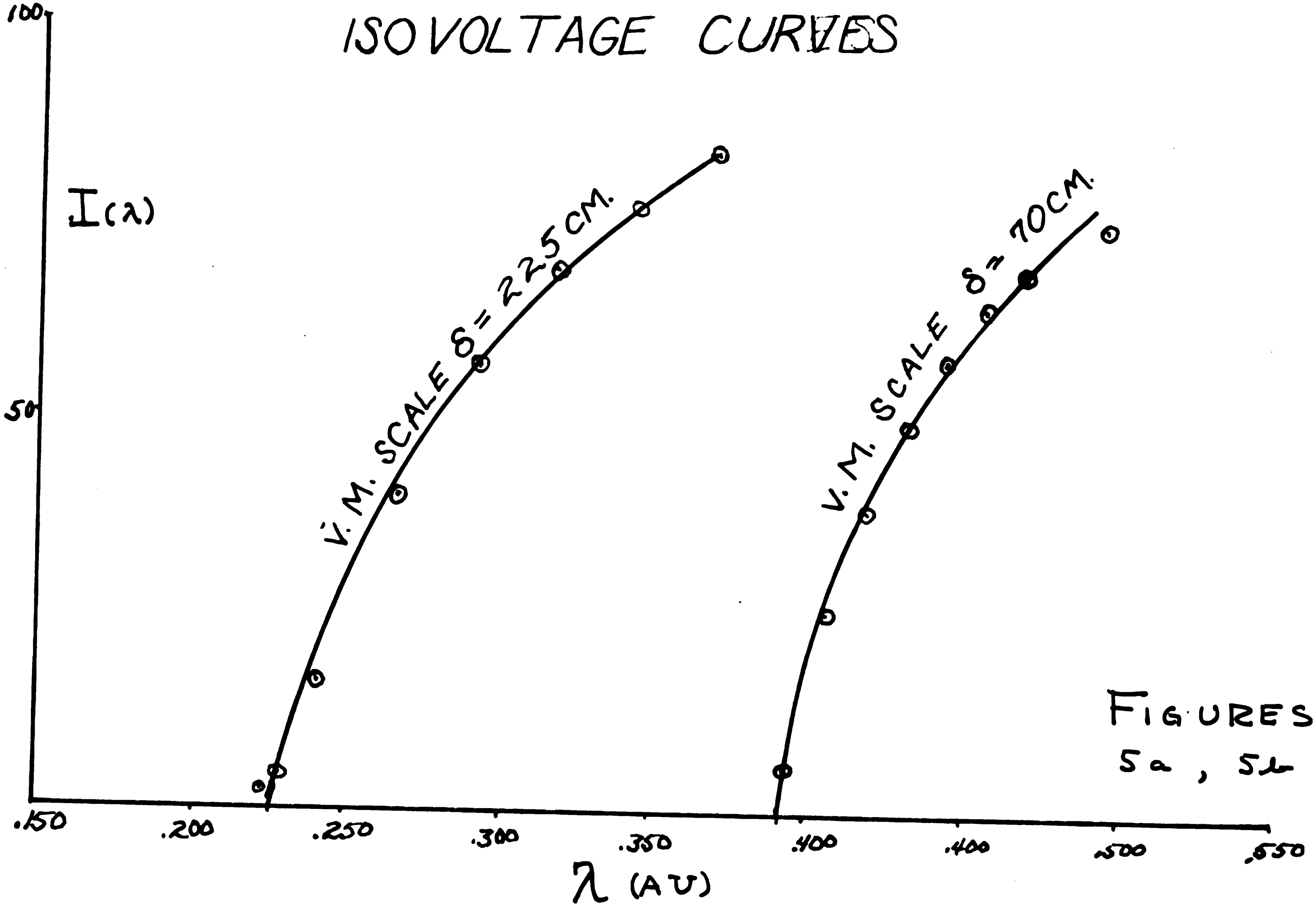
Two typical curves of wave length (λ) versus intensity $I(\lambda)$ where the tube voltage and current was kept constant during the observations are shown in figure 5a and 5b. To determine such curves have been made to determine the voltmeter calibration, and the resultant calibration curve is shown in figure 6.

4) Apparatus and Circuit for Controlling and Measuring X-ray Tube Current

As already stated the intensity of the emitted X-ray beam of any wave length is directly proportional to the space current in the tube. For these measurements the X-ray beam must be as constant as possible, and hence it is necessary to be able to accurately control and measure the space current. The disadvantage of simply putting a milliammeter in one of the high voltage leads is that corona losses from the high voltage conductors are measured along with the space current. These corona losses are variable and since they have no effect on the X-rays produced, it becomes necessary to electrostatically shield the part of the negative lead circuit in which the X-ray tube current milliammeter is placed.

Such an arrangement of apparatus and the circuit used is shown in figure 3. Here B is box electrostatically shielded and containing the X-ray tube filament battery(12 volts), filament controlling resistance F , and ammeter A, as well as the milliammeter which measures the X-ray tube current.

ISOVOLTAGE CURVES



FIGURES 5a, 5b

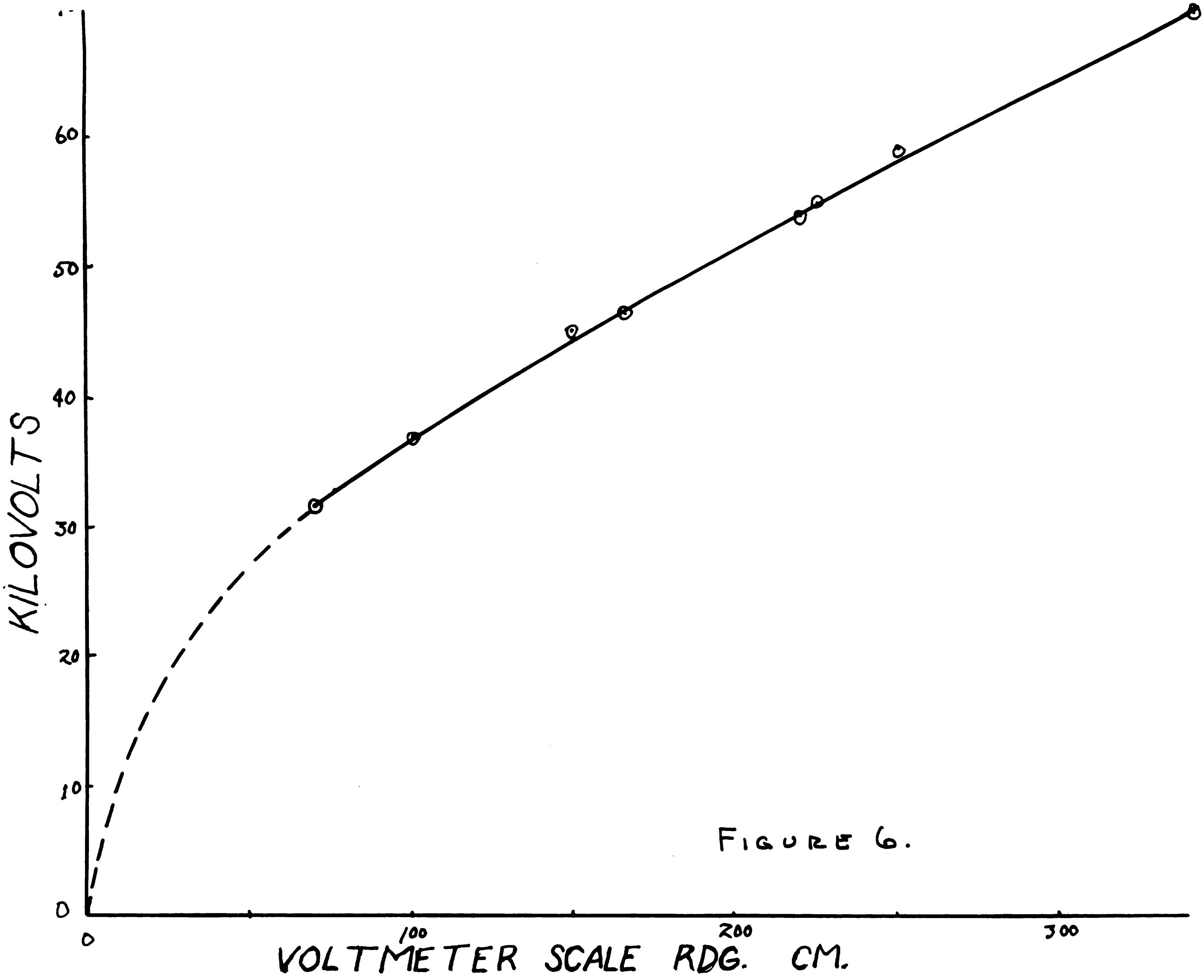

KILOVOLTS
0
10
20
30
40
50
60
0
100
200
300
VOLTMETER SCALE RDG. CM.

FIGURE 6.

This box B, as well as the electrostatic shielding around the X-ray tube filament leads, is connected to the negative side of the high voltage generator. The entire filament circuit is insulated from this shielding, 100 volts insulation being sufficient. Thus it is seen that the connecting link between the negative side of the high voltage generator and negative terminal of the X-ray tube is the Milliammeter(MA figure 3). The milliammeter therefore measures only the X-ray tube current.

5) Bragg Spectrometer

a) General Description

The Bragg X-ray spectrometer may be compared directly with an ordinary optical spectrometer using a ruled line grating. The slits S, S_2 shown in figure 1 collimate the X-ray beam striking the space grating (C), and the diffracted beam is detected by means of the ionization produced in an ionization chamber. The ionization current is measured by the deflections produced on a Compton type electrometer also shown in figure 1

When a narrow beam of X-rays of wave length λ strike a crystal of some substance such as calcite, at an angle θ as shown below in figure 7, constructive interference[8] takes place

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8. Wychoff---"Structure of Crystals" page 91

when the relation

$$n\lambda = 2d_{hkl}\sin\theta \qquad (8)$$

is satisfied.

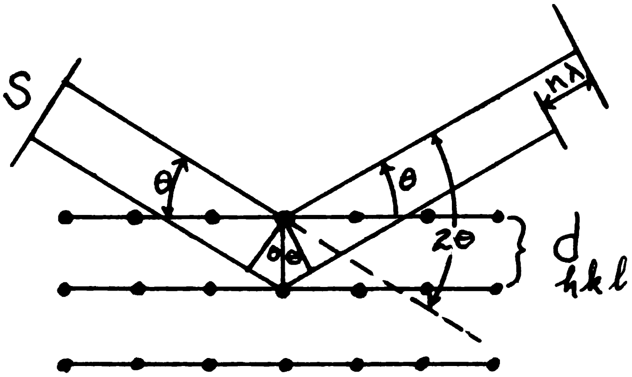

FIG. 7

In this expression n is the order of reflection and d_{hkl} is the distance between seccessive layers of atoms in the crystal lattices. If the direction of the incident beam is kept unchanged as shown in figure 1 by keeping the position of the slits S_1 S_2 fixed, it is seen that it is necessary to rotate the crystal about the point where the beam strikes the crystal in order to get selective wave length reflection from the crystal. Also the angle between the incident and emergent beam is 2θ , and making a change $\Delta\theta$ by crystal rotation means that the ionization chamber must simultaneously be rotated through an angle $2\Delta\theta$ in order to receive the diffracted radiation.

[9] Compton and Allison, page 631

In the apparatus used here the slit widths were made as nearly as possible equal to .3 mm. The distance between the two slits S S was made equal to 20 cm. The crystal used was calcite and the X-rays were diffracted from the 100 face. The crystal lattice $d_{(100)}$ for calcite has been accurately determined by various investigators[9] to be d_{100} 3.02904 A. All measurements used in this work were made in the first order reflection n=1, equation (3), and particular care was taken in fact that no second order reflections of short wave lengths were measured along with wave lengths of the 1st order reflection.

b) Sine Screw for Rotating Crystal[10]

Figure 8 shows details of the so called sine screw on the spectrometer. A Browne & Sharpe micrometer screw is rigidly mounted in a position such that its axis of rotation is perpendicular to some line drawn thru the axis of rotation of the crystal. The flat end of the screw makes contact with a small steel ball which is rigidly fastened to an arm on the spectrometer table. The distance between the axis of rotation of the crystal and the ball is the radius vector r of the angle θ. S, the traverse of the screw, is equal to r sin θ. As previously stated the Bragg equation is

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

hence $\lambda \propto S$, and by mounting the screw in just the right position and adjusting r it is possible to make the screw read directly in ten-thousandths of an A unit.

[10] W. W. Nicholas, =J. O. S. A. 14 61, 1927.

SINE SCREW

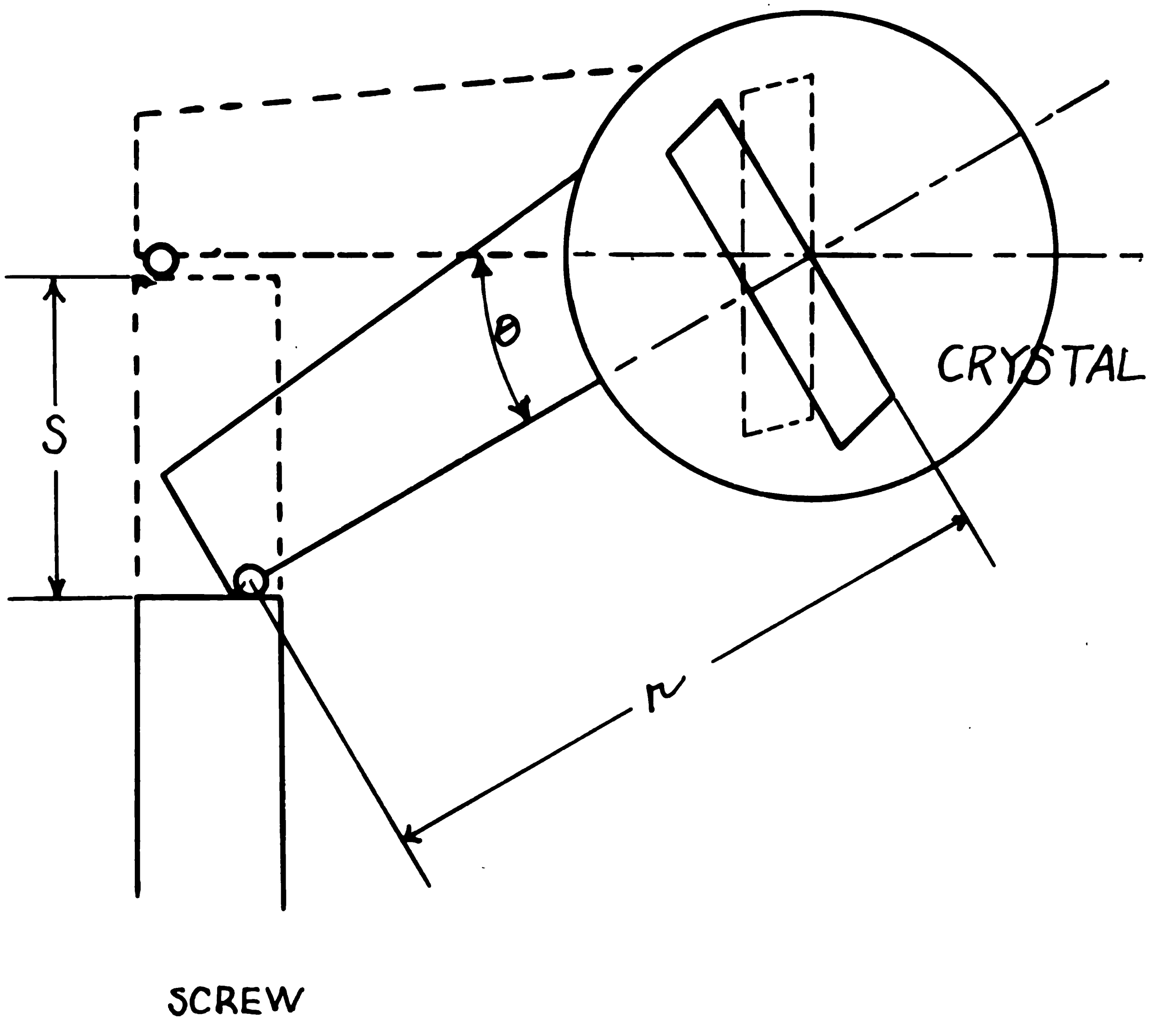

FIGURE 8

The sine screw on the spectrometer used in these experiments was not adjusted so that the calibrations of the micrometer head corresponded exactly to the wave length of X-rays as reflected from the crystal. The instrument was designed so that each division of the screw would correspond to .5 X units, or .0005 A. However, the adjustment of r had not been accurately accomplished, and also the zero setting of the screw had not been accurately made to coincide with the zero position of the crystal at the time these experiments were performed. There did exist a linear relationship between screw setting S and wave length λ, given by

$$\lambda(XU) = .511S - 40.7 \qquad (9)$$

as shown by the calibration curve of figure 10.

Calibration of the spectrometer could be accomplished by calculation. Very accurate measurements on r and θ would be necessary, in addition to knowledge of the grating space of calcite. Another method of calibration would be to use X-rays of a known wavelength. The K lines of different elements could be used if a number of X-ray tubes were available having targets made of these different elements. Such tubes were not available.

The phenomenon of critical absorption was used for calibration. If X-rays are allowed to pass through a film of some element, the amount of absorption gradually decreases with decreasing wave length until at some critical wave length it suddenly increases many times and then gradually decreases again with further decrease in λ.

The explanation of this phenomenon is that at the critical wave length the frequency is such that the product $h\nu$ is equal to the energy necessary to eject one of the K electrons from the atom of the absorbing medium. A similar effect occurs for the L, M, N, etc. electrons, but at frequencies far removed from those we are herewith concerned. It is thus seen that the critical wave length at which the absorption greatly changes is characteristic of the absorbing material, differing approximately .033 A from element to element in the wave length region here used. These critical absorption wave lengths are accurately recorded in the literature, and were used as known wave length standards for calibrating the sine screw of the Bragg spectrometer used in these experiments. Measurements were made of intensity $I(\lambda)$ versus sine screw settings with 5 absorbing films in the path of X-rays.

11. Compton and Allison, page 792, Table I

The films used, together with the wave lengths of their K critical absorption limits are shown in Table I.

TABLE I

Elements used to calibrate spectrometer

Atomic Number	Element	K_{limit} (A)
40	Zr	.687
41	Cb	.652
42	Mo	.618
47	Ag	.484
50	Sn	.424

The wave lengths here used lie in the region throughout which the spectrometer was used in the principal experiment. Figure 9 shows two typical absorption curves near the K limits, and from which the calibration points were obtained. Figure 10 shows the complete calibration curve obtained, and from which the equation (9) was obtained.

c) The Ionization Chamber

As it is hard to measure directly the intensity of an X-ray beam, some effect which is proportional to the intensity is usually measured. In these experiments measurements were made upon the amount of ionization produced when the beam traverses a gas in an ionization chamber.

Methyl bromide put in the chamber at 69 centimeters pres-

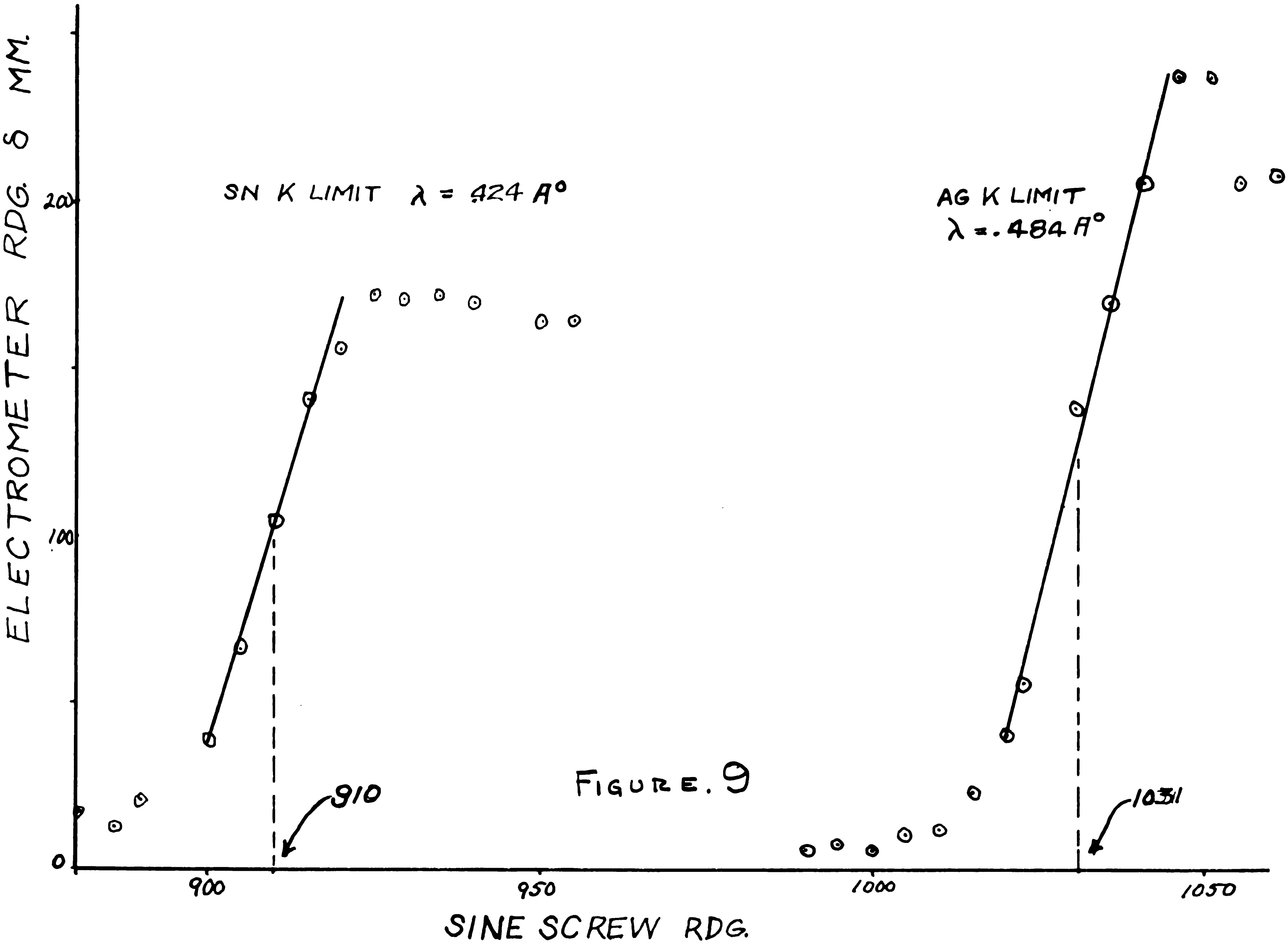

FIGURE. 9

SN K LIMIT λ = .424 A°
AG K LIMIT
λ = .484 A°
910
1031
ELECTROMETER RDG. δ MM.
0
100
200
900
950
1000
1050
SINE SCREW RDG.

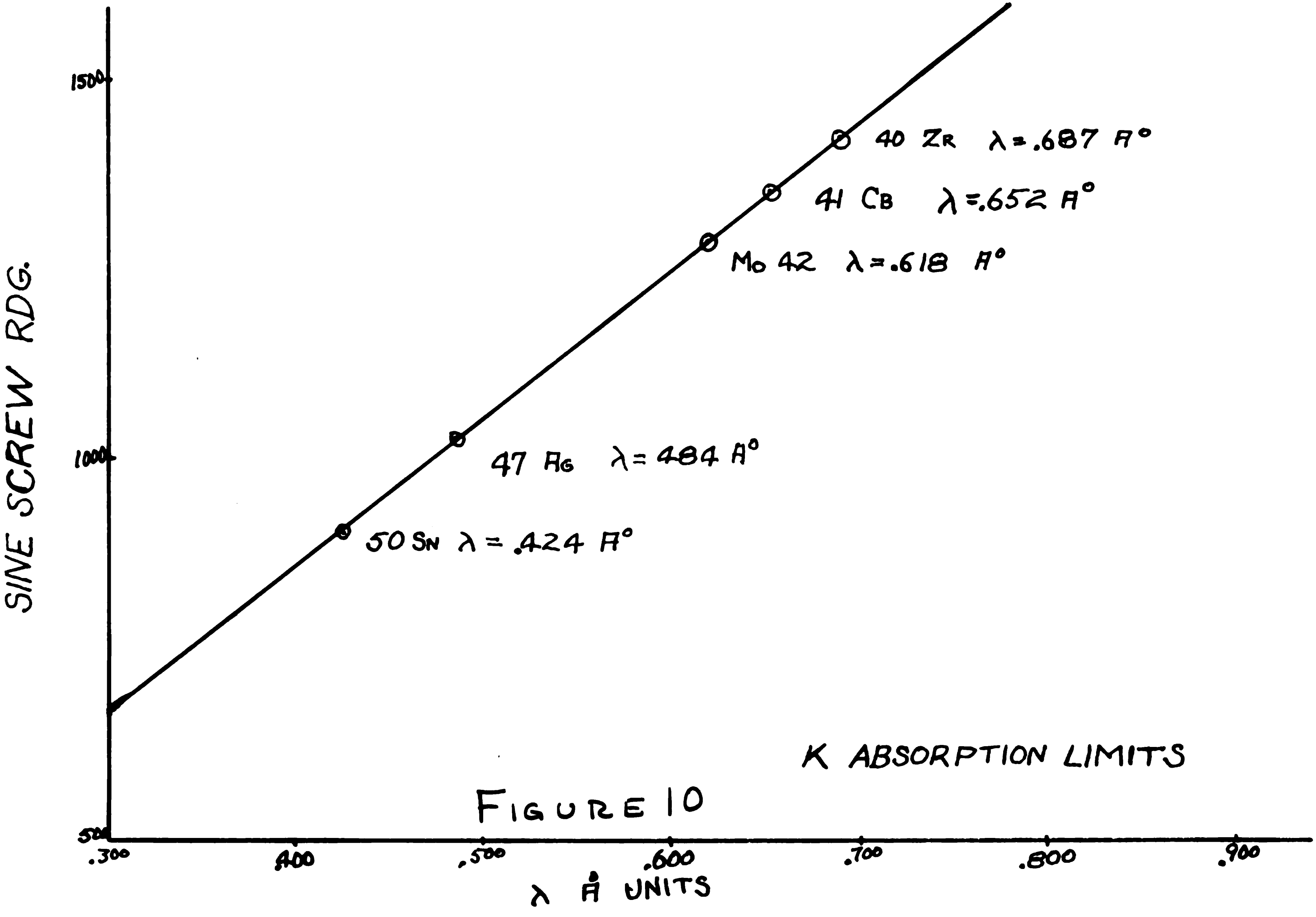
40 ZR λ=.687 A°
41 CB λ=.652 A°
Mo 42 λ=.618 A°
47 AG λ=.484 A°
50 SN λ=.424 A°
K ABSORPTION LIMITS
SINE SCREW RDG.
1500
1000
500
.300
.400
.500
.600
.700
.800
.900
λ Å UNITS

FIGURE 10

sure and at 20°C was the absorbing medium used. As the absorption of x-rays is directly proportional to the atomic number to the fourth power of the absorbing material, methyl bromide is used in the chamber in preference to some lighter materials.

To eliminate errors produced by spurious radiations (cosmic rays or radio active substances) a double chamber was used, Figure 11. In general such radiations will enter both halves of the chamber. All ions formed are swept to the plates by the electrostatic field, the one hundred and fifty volts between plates being sufficient to remove all ions before recombination occurs.[12] From one half of the chamber positive ions are drawn to the center plate and from the other half negative ions which in general tend to neutralize each other, thus leaving no resulting charge on the center plate. In making measurements X-rays were admitted to only one half the chamber through window W, forming ions in one half of the chamber only. As no oppositely charged ions came from the other half, the center plate took on a charge which was transmitted to the ungrounded electrometer quadrant, causing a needle deflection. The charge was removed from the quadrant and plate by closing

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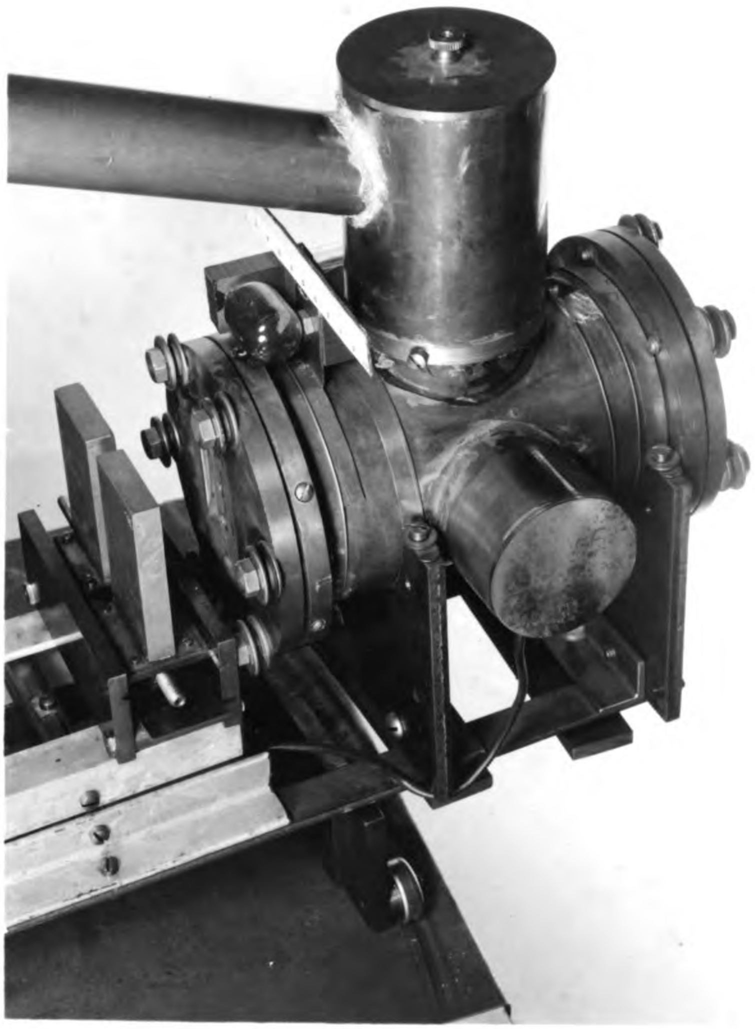
[12] D. L. Webster and R. M. Yeatman --- J.O.S.A. 17,254,1928



C. Rowe

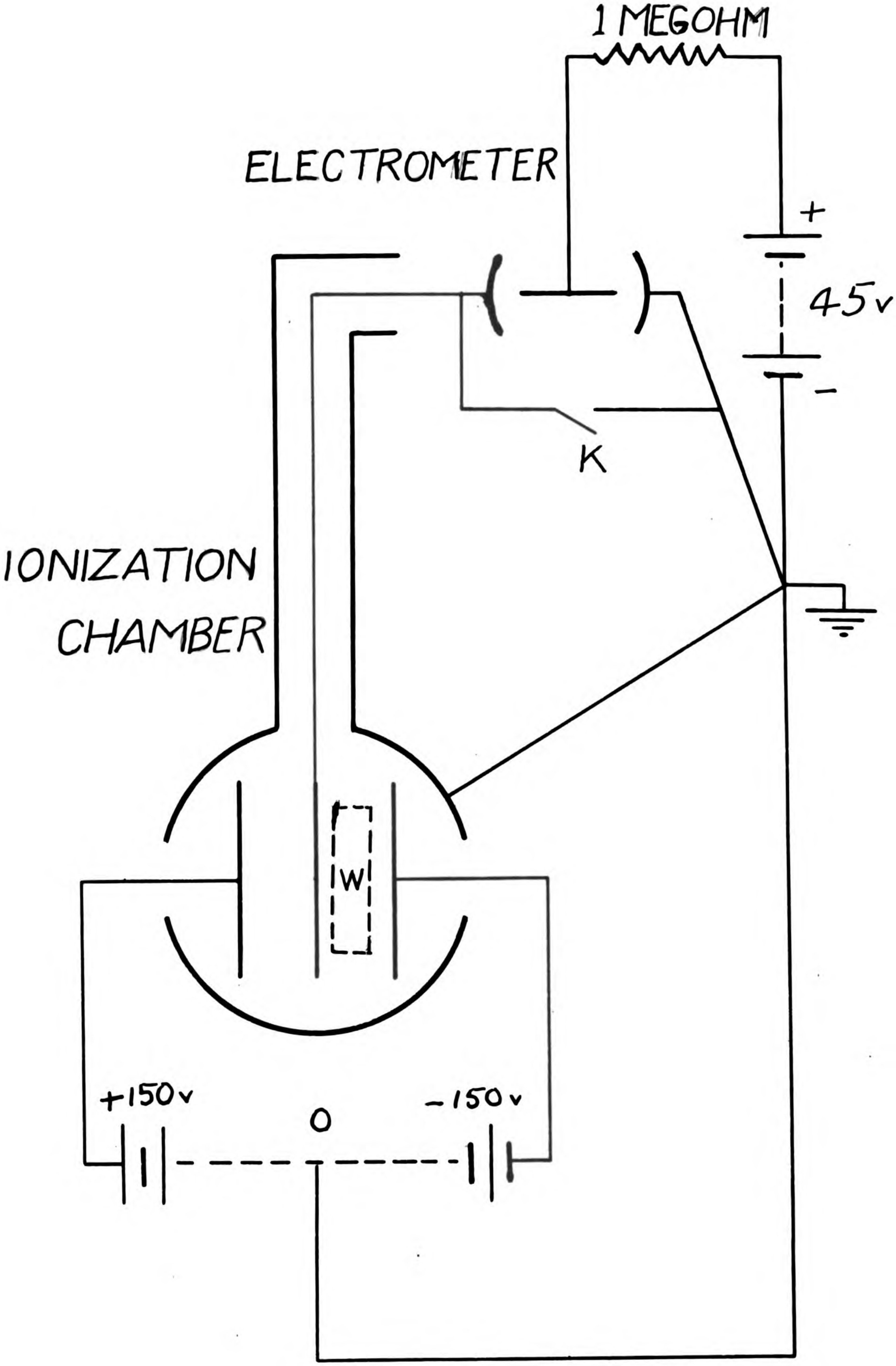

1 MEGOHM
ELECTROMETER
+
45v
−
K
IONIZATION
CHAMBER
W
+150v
0
−150v

Figure 11.

grounding key K.

The insulation of the center plate of the ionization chamber and of the ungrounded electrometer quadrant is sufficiently good so that no leakage of charge was observable over a period of several minutes. Thus as all measurements made used an exposure of less than one minute, no correction was needed for the time of exposure.

It is obvious that the charge accumulated on the center plate is directly proportional to the number of ion pairs formed, which is in turn directly proportional to the intensity of the X-ray beam and to the time of exposure to the beam.

d) The Electrometer

The quadrant electrometer used to measure the charge produced in the ionization chamber was of the so-called Compton type.[13] The instrument was made in the physics department instrument shop. The insulation throughout was of a good grade of amber. The suspension for the movable needle of the instrument was a very small quartz fiber made conducting by evaporating upon it, in a vacuum, gold which had previously been electroplated upon a tungsten wire. Fastened to the movable needle is a small light-weight plane mirror which reflects

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13. L.T. Pockman--- Rev. Sci. Inst. 7, 238, 1936

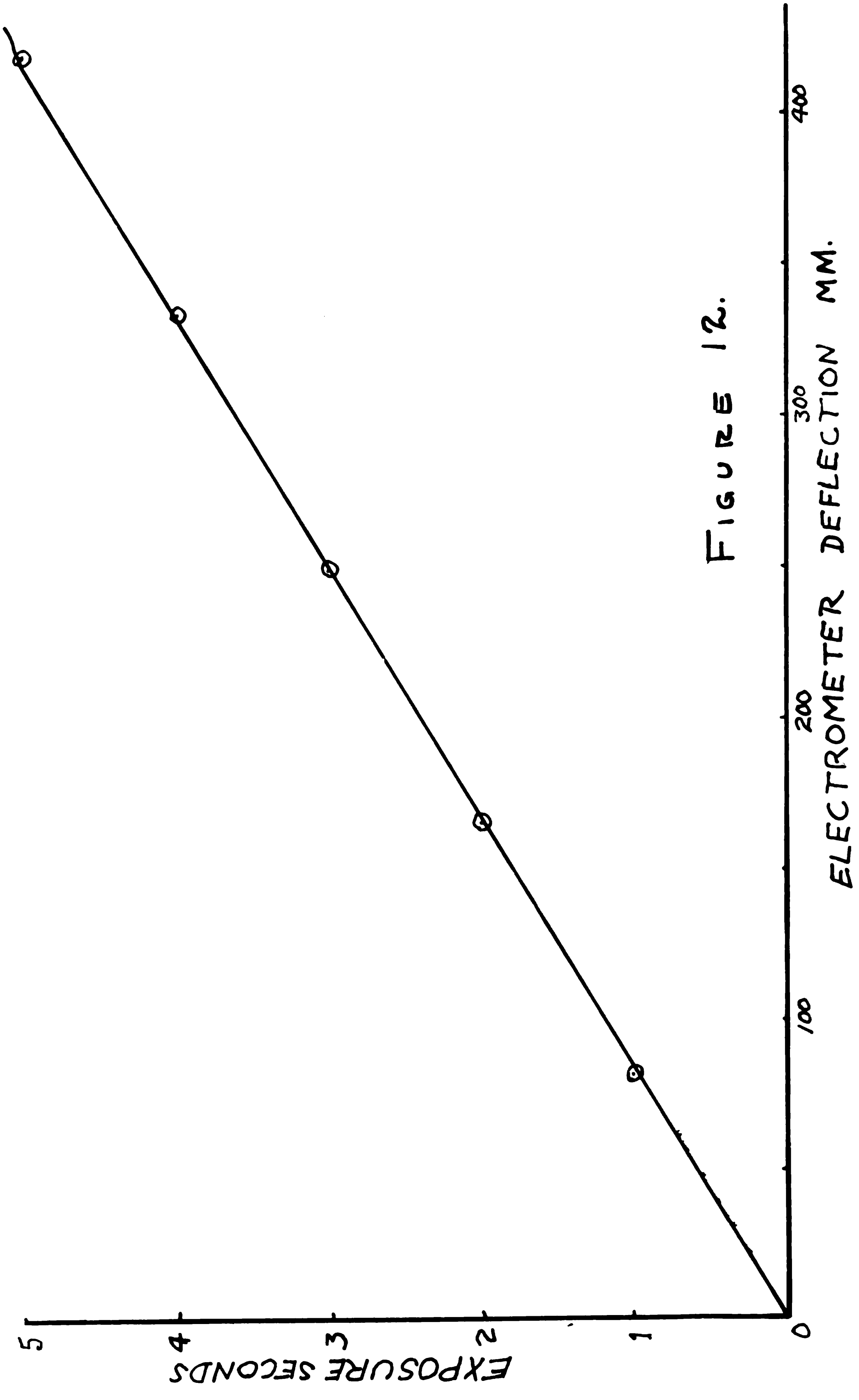
light received from a portion of an illuminated scale into a reading telescope. The scale mirror distance is approximately 183 cm. By properly adjusting the position of the needle in the quadrants of the electrometer, the deflection of the needle as observed in the telescope may be made linear over a reasonable range (300 mm) of scale length.

As already mentioned, the charge placed on the electrometer is directly proportional to the number of ion pairs formed; that is, directly proportional to the time of exposure, assuming a constant X-ray source. On the other hand, if the time of exposure is kept constant, the number of ion pairs formed is found to be directly proportional to the intensity of the X-ray beam.

This fact provides a means of calibrating the electrometer deflections in terms of intensities of the X-ray beam entering the ionization chamber.

e) Calibration of the Electrometer

The electrometer was calibrated by allowing a beam of constant wave length and intensity to pass into the ionization chamber for time intervals of 1, 2, 3, 4, 5, and 6 sec.



EXPOSURE SECONDS
0
1
2
3
4
5
ELECTROMETER DEFLECTION MM.
100
200
300
400

FIGURE 12.

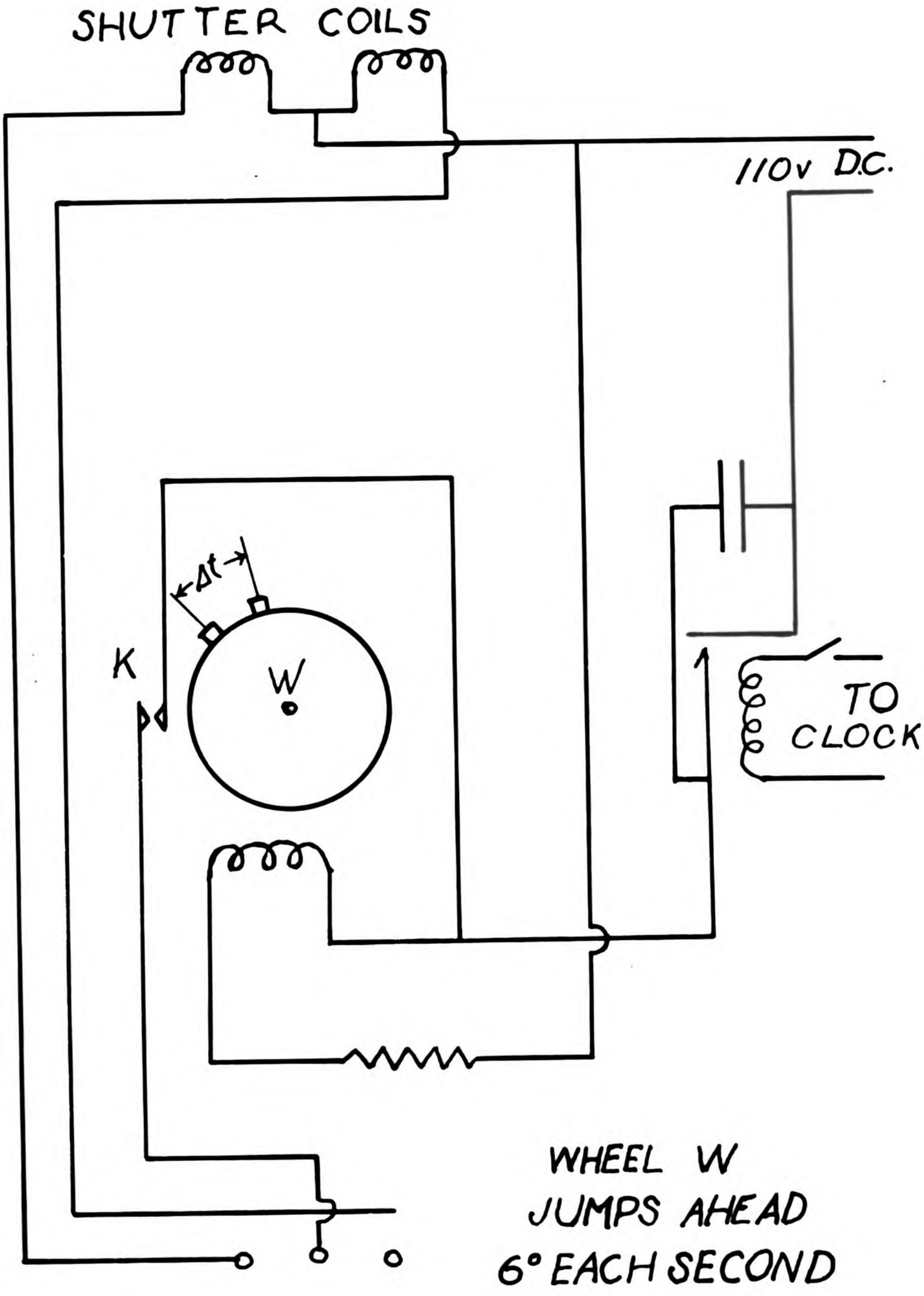

SHUTTER COILS
110v D.C.
Δt
K
W
TO CLOCK
WHEEL W JUMPS AHEAD 6° EACH SECOND

FIGURE 13

PART II

DETERMINATION OF THE MASS ABSORPTION COEFFICIENT AS A FUNCTION OF WAVE LENGTH FOR COLUMBIUM

1) Theory of the Experiment

A monochromatic beam of X-rays of intensity I traversing a very thin sheet of material of thickness dx experiences a decrease in intensity dI, as given by the expression-

$$\frac{dI}{I} = -\mu_m \rho \, dx \qquad (10)$$

where ρ and μ_m are the density and mass absorption coefficient, respectively, of the absorbing material. Integrating this expression gives, assuming μ_m is independent of the thickness x,

$$\log_e I = -\mu_m + \text{constant} \qquad (11)$$

If I_0 is taken as the intensity where $x = 0$, then the constant becomes $\log_e I_0$ and

$$\log_e \frac{I}{I_0} = -\mu_m \rho X \qquad (12)$$

This is often written as

$$I = I_0 e^{-\mu_m \rho X} \qquad (13)$$

So long as the thickness of the absorbing medium is small and the beam of X-rays sensibly parallel, that is, not highly divergent, the above equation (13) exactly satisfies experimental tests. If the above conditions are not fulfilled, additional corrections must be made for the effect of scattered and fluorescent X-rays which increase the intensity at the middle of the beam. Precautions were taken to eliminate the necessity of making any such corrections during these experiments. Solving for μ_m from (12), we have-

$$\mu_m = \frac{\log_e \frac{I_0}{I}}{\rho x} \qquad (14)$$

And as already pointed out, the electrometer deflections δ are directly proportional to the intensities of the X-ray beam entering the ionization chamber, giving-

$$\mu_m = \frac{\log_e \frac{\delta_0}{\delta}}{\rho x} \qquad (15)$$

Equation (15) was then the working equation for all computations made for μ_m. Keeping the voltage and current constant for the X-ray tube, and with the spectrometer adjusted to measure a given wave length of x-rays, electrmeter deflections were taken with and without the absorber in the path of the X-ray beam. Such measurements gave the ratio $\frac{\delta_0}{\delta}$.

In calculating the denominator of the above equation(15), it is seen that both ρ and x for the absorber must be measured. Since the thickness was approximately .01 cm., an accurate determination of this value would have been difficult to obtain. It was determined, however, that the specimen had been rolled to a very uniform thickness, from measurements made with a high grade micrometer caliper. The specimen was approximately 2.5 cm. square, so the area was used together with the mass of the entire specimen, giving,

$$\rho x = \frac{\text{mass}}{\text{area}} \qquad (16)$$

The above description outlines the essential manipulations involved in determining μ_m at any wave length, and this procedure was , of course, followed for all of the values of λ over the range of the measurements. It has been shown by various investigators[14] that μ_m may be expressed as a function of the wave length by

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[14]
S.J.M.Allen, Phys. Rev. 24 1, 1924
F.K. Richtmeyer Phys. Rev. 30 755, 1927
Compton and Allison page 520, 1935
(These authors give references to other authors)

$$\mu_m = C\lambda^n \tag{17}$$

where C is a constant for any given material for wave lengths between any two critical absorption limits or for wave lengths shorter than the K critical absorption limit, and where the value of n is some value generally between 2.5 and 3.0. It should be stated that all authors reporting on this kind of work do not obtain the result that C should be a constant, especially over a large wave length interval. In this thesis, therefore, the results will be compared with the equation (17) by plotting a curve of log μ_m against log λ. The slope of this curve will furnish a value of n and the intercept along the μ_m axis a value for C throughout the range of wave lengths herein reported.

It has become customary to consider the absorption of X-rays as being due to two processes, that is

$$\mu_m = \tau_m + \sigma_m \tag{18}$$

In this expression τ_m is referred to as the true, or photoelectric absorption, a process wherein the total energy of the X-ray quantum is used up in ejecting a photoelectron and giving it kinetic energy after ejection. The latter factor is considered to be a scattering factor, to account for the scattering of part of the absorbed X-rays. This includes the scattering both with and without a change in wave length. Classical Theories given by Compton,[15] de Broglie,[16] and Kramers[17] as well as wave mechanics theories by Wentzel[18] and Oppenheimer[19] give the factor τ_m as a function of the wave length cubed in all cases, although the absolute values of τ_m for any element vary considerably when calculated from the different theories.[20] Experimental results are not consistant in their agreement with the λ^3 law. F. K. Richtmeyer[20] concludes from experiment on tin that the agreement does hold, but S. J. M. Allen,[21] J. Read,[22] and others furnish results not at all in such agreement. The principal difficulty comes in separating the scattering term from the photo-electricterm. To this author's knowledge there have been no experimental determinations reported for the scattering factor σ for any of the heavier elements. It is taken to

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[15] A. H. Compton, Nat. Res. Council Bulletin 20 37, 1922.

[16] L. de Broglie, Jour. dPhys. et Rad. 3 33, 1922.

[17] Kramers, Phil. Mag. 46 836, 1923.

[18] Wentzel, Zeit. f. Phys. 38 518, 1926.

[19] Oppenheimer, Zeit. f. Phys. 41 268, 1927.

[20] F. K. Richtmeyer, Phys. Rev. 30 759, 1927.

[21] S. J. M. Allen, Phys. Rev. 24 1, 1924.

[22] J. Read, Proc. Roy. Soc. 152A 402, 1935.

be a small value, and in some cases considered independent of the wave length. Compton and Allison in their book, X-rays in Theory and Practice state on Page 535, "It is seen, therefore, that the form $\sigma(Z,\lambda)$ is a complex matter from the theoretical standpoint. Experimentally it is difficult to obtain good values of the term from ordinary absorption measurements, because it is usually small in comparison to the photo-electric term. . . . . In general, it may be said that $\sigma(Z,\lambda)$ increases more slowly with both λ and Z than does the photo-electric term."

In order to arrive at a conclusion about the scattering term the data obtained in this work was plotted as shown in figure 14, that is, μ_m versus λ^3. Then the intercept along the μ_m axis would be a measure of σ_m provided the relation

$$\mu_m = A\lambda^3 + \sigma_m \qquad (19)$$

holds. This is making the assumption that τ_m is a function of λ^3 and that σ_m is independent of λ, neither of which assumptions may be valid.

2) Measurements and Data.

a) Determination of the product ρx.

As shown in equation 16, measurements were made on the mass and area of the columbium absorber. The mass was determined to be 0.5771 ± .0001 gm., and the area of sheet of columbium 6.474 ± .001 cm^2. This gives

$$\rho x = .08914 \text{ gm./cm}^2 \qquad (20)$$

b) Determination of μ_m.

From equation 15, μ_m is determined by measurements of electrometer deflections δ and δ_0, with and without the absorbing film in the X-ray path. In Table II is shown the data from

TABLE II

WAVE LENGTH A°	ABSORBER	EXPOSURE SEC.	δ	MEAN δ	δ FOR 45 SEC	δ_0 / δ
.419	air	2	167			
.419	air	2	166	166.5	3746.2	
	Cb	25	147			
			148	147.5	265.5	14.1
.394	Cb	15	133			
			134	133.5	400.5	
	air	2	165			
			166	165.5	3723.7	9.30
.368	air	2	166			
			165	165.5	3723.7	
	Cb	10	133			
			132.5	132.8	597.6	6.23
.343	Cb	10	168			
			169	168.5	758.2	
	air	2	152			
			153	152.5	3431.2	4.53
.317	air	2	136			
			137	136.5	3071.2	
	Cb	10	188.5			
			188.	188.3	847.3	3.63
.291	Cb	10	200			
			199	199.5	897.7	
	air	3	169			
			167	168.	2520.0	2.81
.266	air	5	198.5			
			198	198.3	1784.7	
	Cb	10	178.5			
			177	177.7	799.6	2.23
.240	Cb	10	88			
			87	87.5	393.7	
	air	5	81			
			80	80.5	724.5	1.87
.522	air	2	156			
			158	157.	3532.5	
	Cb	60	72			
			77	74.5	55.9	63.2
.470	Cb	60	177			
			175	176.	132.0	
	air	2	185			
			187	186.	4185.0	31.7
.419	air	2	199			
			200	199.5	4488.7	
	Cb	30	203			
			203	203.	304.5	14.7
.368	Cb	15	199			
			199	199.	597.0	
	air	2	179			
			180	179.5	4038.8	6.77
		2				

TABLE II
cont.

.343	air	2	156			
			160	158.	3555.0	
	Cb	10	175			
			175	175.	787.	4.52
.317	Cb	10	179			
			180	179.5	810.	
	air	2	123			
			127	125	2812.5	3.47
.291	Cb	5	170			
			169	169.5	1525.5	
	air	2	174			
			173	173.5	3904.2	2.56
.266	air	2	148			
			150	149.	3352.5	2.05
	Cb	5	182			
			182	182.	1638.0	2.05
.253	Cb	5	182			
			182	182.	1638.0	
	air	2	140			
			141	140.5	3161.7	1.93
.240	air	2	123			
			123	123.	2767.5	
	Cb	5	175			
			174	174.5	1570.5	1.76
.228	Cb	5	156			
			160	158.	1422.	
	air	3	157			
			155	156.	2340.	1.65
.215	air	3	124			
			123	123.5	1852.2	
	Cb	5	134			
			136	135.	1215.	1.52
.202	Cb	5	96			
			98	97.	873.	
	air	5	143			
			141	142.	1278.	1.46

Table II
cont.

.573	Cb	120	27	27	10.125	
	air	5	163			
			162	162.5	1467.	145.
.547	air	5	172			
			173	172.5	1552.5	
	Cb	120	37.5	37.5	14.063	110.
.522	Cb	120	57.	57.	21.375	
	air	5	184			
			184	184	1656.	77.5
.496	air	5	185			
			185	185	1665.	
	Cb	120	87.	87	32.65	51.0
.470	Cb	120	123.	123	46.125	
	air	5	170	170		
			170	170	1530.	55.2

which the ratio $\frac{\delta_0}{\delta}$ is computed. This data is tabulated for the entire experiment although it was collected during several runs covering a period of as many weeks. The data so collected overlaps considerably and rather than complicate the data the date of observation has been omitted. In column six is shown δ(45sec) a calculation made to correct for the air and columbium exposure times. As pointed out the electrometer was linear over a range of approximately 300 mm, and using exposure times small for no absorber and large for the absorber, all deflections were kept within the linear range of the electrometer and yet large enough for 1% accuracy in reading.

Table III is the data from table II carried through the computations for μ_m.

TABLE III

$\frac{\delta_0}{\delta}$	μ_m	λ	λ^3
1.46	4.246	.202	.0082
1.52	4.697	.215	.0099
1.65	5.618	.228	.0118
1.76	6.341	.240	.0138
1.84	6.841	.240	.0138
1.93	7.376	.253	.0162
2.05	8.052	.266	.0188
2.23	8.997	.266	.0188
2.56	10.55	.291	.0246
2.81	11.59	.291	.0246
3.63	14.46	.317	.0316
3.47	13.96	.317	.0316
4.53	16.95	.343	.0404
4.52	16.92	.343	.0404
6.23	20.53	.368	.0500
6.77	21.45	.368	.-500
9.30	25.01	.394	.0616
14.11	29.68	.419	.0736
14.74	30.15	.419	.0736
30.70	38.77	.470	.1038
33.17	39.29	.470	.1038
51.03	44.10	.496	.1220
63.19	46.51	.522	.1422
77.47	48.80	.522	.1422
1104	52.73	.547	.1637
144.9	55.83	.573	.1881
163.1	57.15	.598	.2138
155.6	56.65	.624	.2425
158.54	21.07	.674	.3061
6.0[illegible]	20.27	.700	.3430
6.92	21.70	.726	.3826

PART THREE

CONCLUSIONS

From the data of Table III are plotted two curves, one of $\log \mu_m$ versus $\log \lambda$ figure 15, and the other μ_m versus λ^3 figure 14. From figure 15 the constants C and n of equation 17, which states

$$\mu_m = c\lambda^n$$

The intercept along $\log \mu_m$ axis gives c = .805 and the slope of this curve makes n = 2.56. Thus we may write, for the wave length range of .200 to .500 A, that the mass absorption coeffecient for columbium is

$$\mu_m = .80\lambda^{2.56}. \qquad (21)$$

From the second curve, that is μ_m versus λ^3, little can be deduced regarding the value of defined by equation 18, and discussed in the same paragraph on pages 36 and 37.

Comparison with existing data on the absorption coeffieient of columbium is interesting. The only references to the subject which the writer has been able to locate in any source is that given by Compton and Allison, X-rays in Theory and Practice, Table I, page 800. They give no reference to this work but state on page 799 that the table I was compiled by S. J. M. Allen, an author who has contributed much to this subject. The mass absorption coefficients at λ=.631 A and .098 A are (87.0) and (0.75), and carry the notation that theywere extrapolated, apparently by use of the $\mu_m \propto Z^4$ relationship, to an extimated accuracy of one percent. The writer therefore draws the conclusion that no previous determinations have therefore been experimentally determined. By extending the straight line curve of figure 15 to include λ= .531 A a value of μ_m = 86.7 is ob-

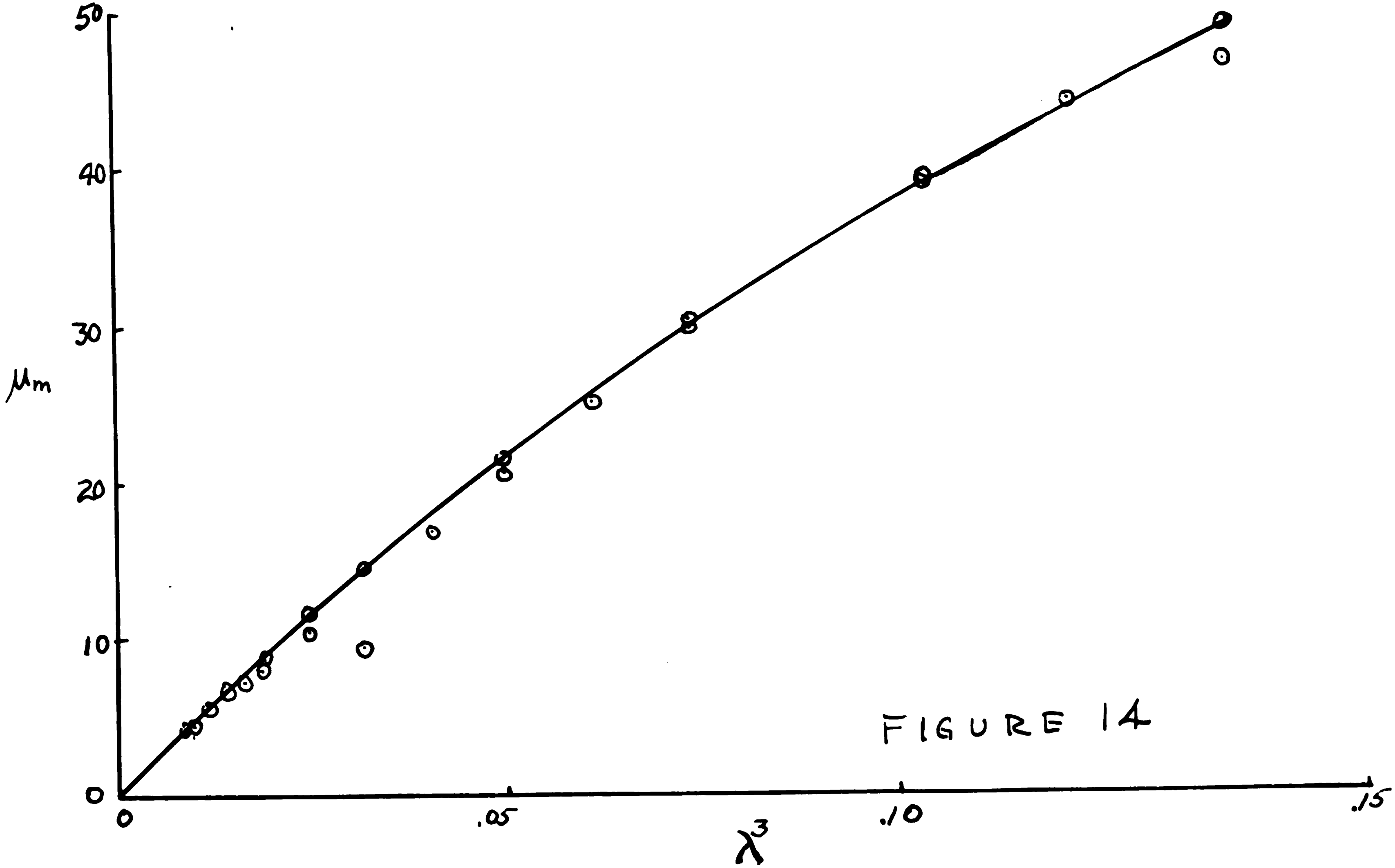

FIGURE 14

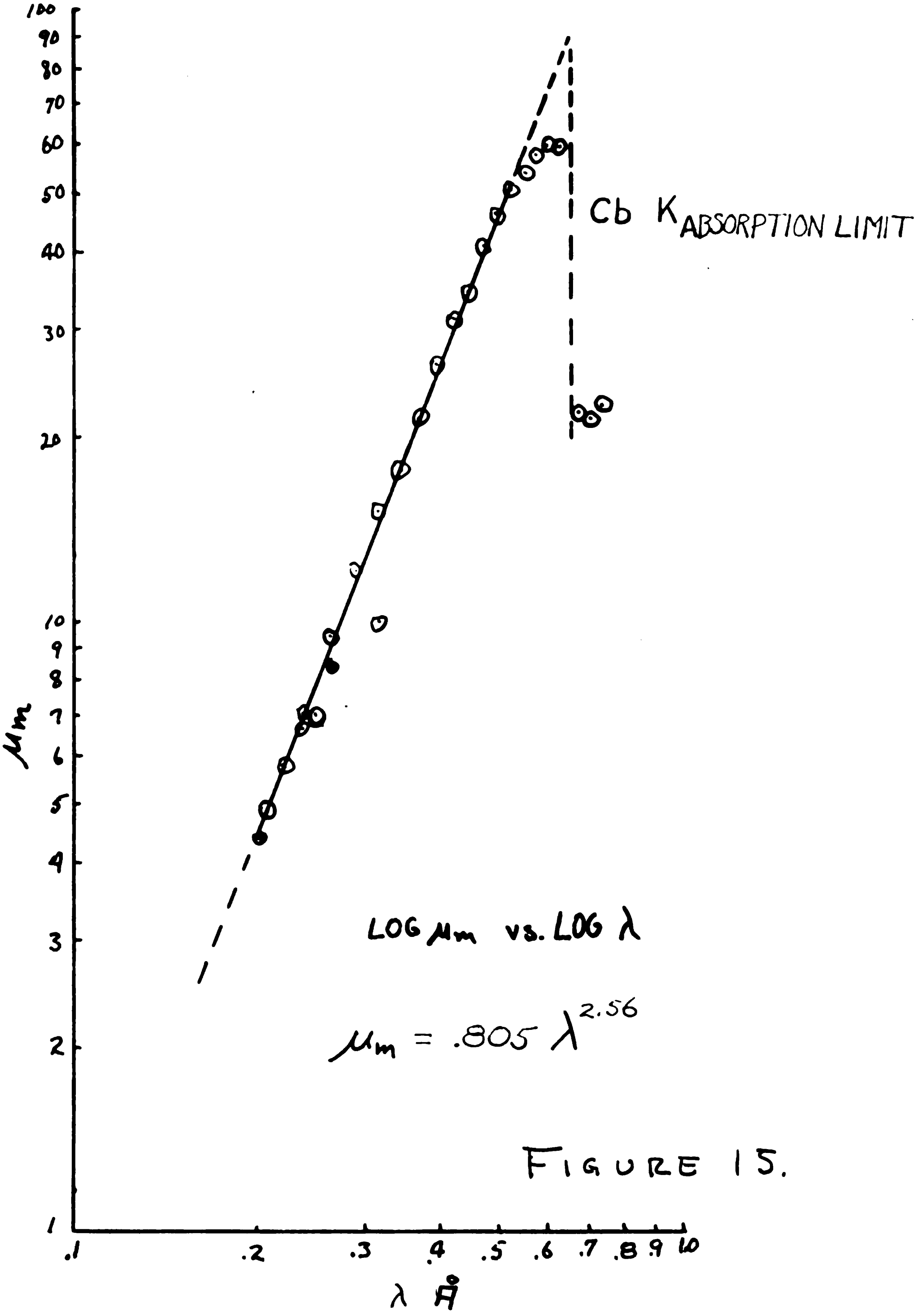
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
μm
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
λ Å
Cb K ABSORPTION LIMIT
LOG μm vs. LOG λ
$\mu_m = .805\,\lambda^{2.56}$

FIGURE 15.

tained. Likeweise extropolating the curve to λ = .093 A gives μ_m a value of .75, the same exactly as that given by Compton and Allison.

Mention should be made of the difficulty in obtaining values of μ_m near an absorption limit. As shown in figure 15 for wave lengths greater than .530 A there is a decrease in value of μ_m, due undoubtedly to wavelengths greater that the K electron critical absorption wave length being measured in the ionization chamber along with the shorter wave lengths. This difficulty can undoubtedly only be remedied by the use of a double crystal spectrometer in place of the single crystal instrument used here.

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