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I hereby recommend that the thesis prepared under my supervision by Donald K. Berkey

entitled Fluorescent Yield of X-Rays From the K-Shells Of Various Elements

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Approved by:

S. J. M. Allen

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FLUORESCENT YIELD OF X-RAYS FROM THE K-SHELLS OF VARIOUS ELEMENTS

A dissertation presented in partial fulfillment of the requirements for the degree of Doctor of Philosophy, University of Cincinnati, June, 1932.

By

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FLUORESCENT YIELD OF X-RAYS FROM THE K-SHELLS OF VARIOUS ELEMENTS.

1. OBJECT

The purpose of this investigation is to determine how the output of fluorescent X-rays from the K-shells of various elements varies with the atomic number of the elements. In the spring of 1930 Dr. S.J.M. Allen suggested that it might show a decrease for the higher elements above molybdenum.

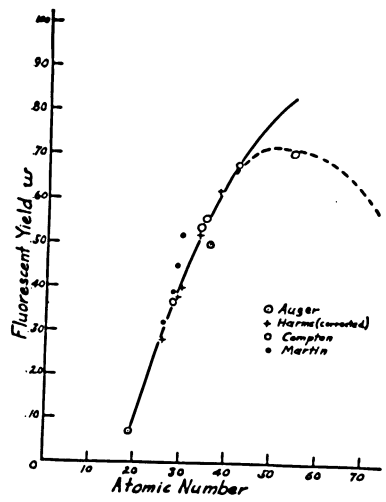

Fig. 1

2. HISTORICAL

DISCOVERY OF THE COMPOUND PHOTOELECTRIC EFFECT

The simple theory of the production of fluorescent X-rays indicates that for every quantum photoelectrically absorbed in, for example, the K-shell of an atom, a K-quantum of fluorescent energy will be emitted. Recent [1] work has thrown considerable doubt on this theory, and the present investigation casts still more. It is found that the fluorescent X-rays are not as intense as this theory predicts, while the photoelectrons are more abundant. Data published by Sadler [2] shows both of these effects. They have also been mentioned by Barkla [3] and by Barkla and Dallas [4]. The discovery of the compound-photoelectric effect by Auger [5] made these effects more understandable. In his Wilson cloud-chamber

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1) The paper of A.H. Compton [Phil.Mag. 8, p.961, (1929)] gives an excellent discussion of this point.

2) C.A. Sadler, Phil.Mag. 17, p.739 (1909); 18, p.107 (1909); 19, p.337 (1910).

3) C.G.Barkla, Phil. Trans. 217, p. 315 (1917)

4) C.G.Barkla and Miss Dallas, Phil.Mag.47, p.1, (1924)

5) P.Auger, Comptes Rendus.180, p.65 (1925); J.de Phys. et Radium, 6, p. 205 (1925).

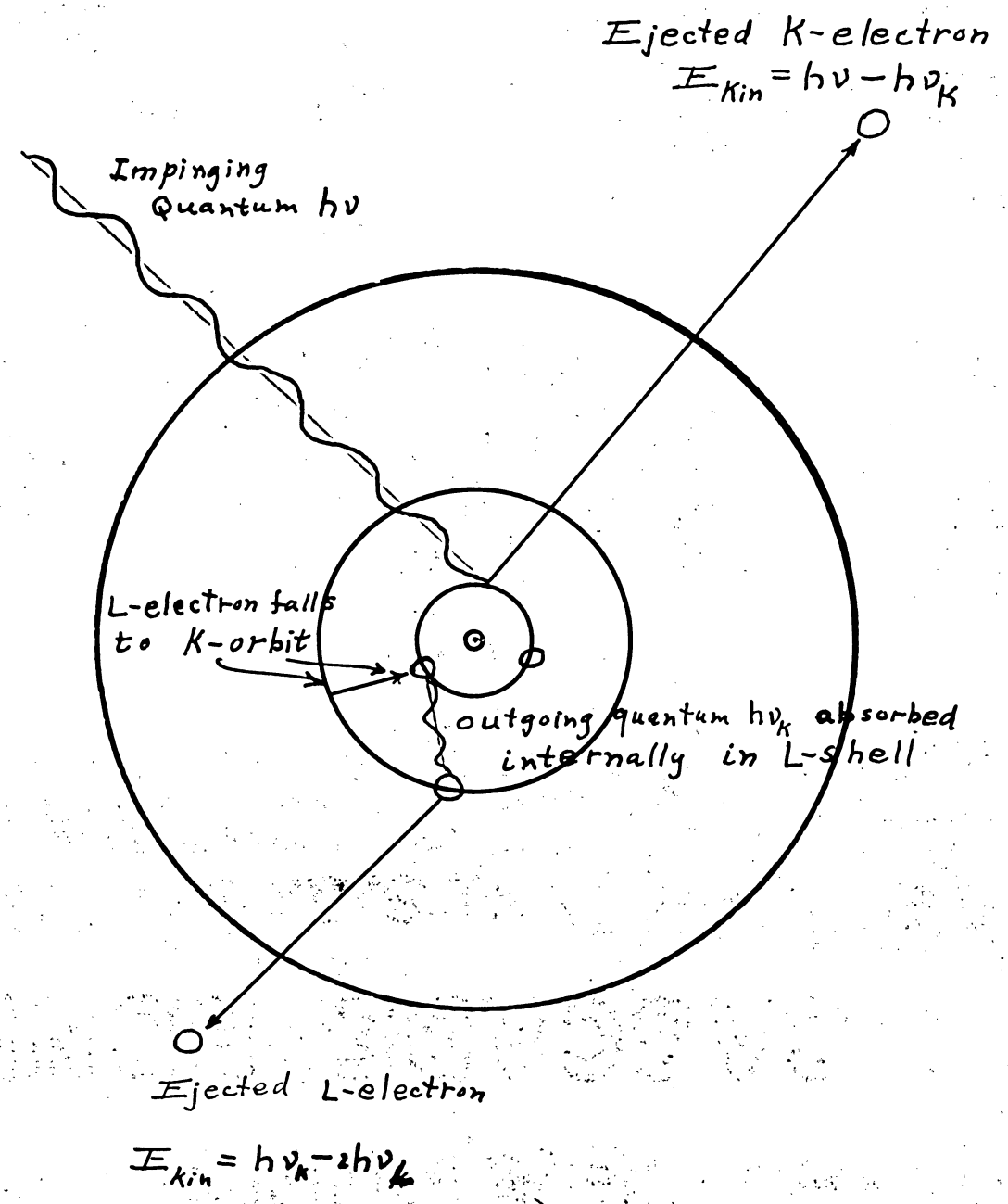

Fig. 2 Atom affected by the Compound Photoelectric Effect.

apparatus he often found more than one electron track proceeding from the same source. By measuring their lengths [6] he found that in addition to the electron of energy, $E_{kin} = h\nu - h\nu_K$ emitted from the atom, there was often found one of energy,

$$E_{kin} = h\nu - 2h\nu_L$$

This was assumed to be an L-shell electron which had absorbed the $h\nu$ (emitted from the K-shell) before it ever left the atom. Thus was explained the excess of photoelectrons and the deficiency of fluorescent K-quanta. This internal photoelectric absorption may also be thought of as a kind of radiationless transfer [7] of energy from an excited atom to an electron. It has been recognized in the region of optical spectra for some time.[8] It has lately become known as the Auger Effect, both in X-ray and optical regions.

The fluorescence yield w has been defined by Auger [6] as the ratio of the number of fluorescent K-quanta that leave an assemblage of atoms to the number of quanta that are photoelectrically absorbed in the K-shells. This is

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6) P. Auger, Ann.de Physique, 6, p. 183, (1926)
7) Klein and Rosseland call this "an event of the second kind."
8) See also the last footnote of Compton's paper, p. 962.

Cliché 3
Atmosphère d'hydrogène à 5 p. 100 d'argon
Rayons X de 45 kilovolts.

Fig. 3

Cliché 8.
Atmosphère d'hydrogène à 2 p. 100 de xénon.
Rayons X de 90 kilovolts.

Fig. 4

the yield from the K-shell. The same definition can apply to the yield of fluorescent X-rays from the L-shell. His results for the K-shell are summarized below:

Element	Voltage	w
19 Argon	70 kv	0.07
36 Krypton	70	.50
	22	.51
54 Xenon	43	.71

These experiments indicate that the fluorescence yield of light elements is small, that it is independent of the wave length of the exciting radiation, and that it increases with increase of atomic number.

FLUORESCENCE MEASUREMENTS OF w

From the fluorescence data of Sadler and Barkla, respectively, Kossel [9] and Bothe [10] have calculated rough values of the fluorescence yield. Kossel obtained:

	24	26	27	29	30
Element	Cr	Fe	CO	Cu	Zu
w	0.23	0.32	0.39	0.42	0.51

He, himself, does not place a great deal of reliance on these results, but at least they are of the correct order

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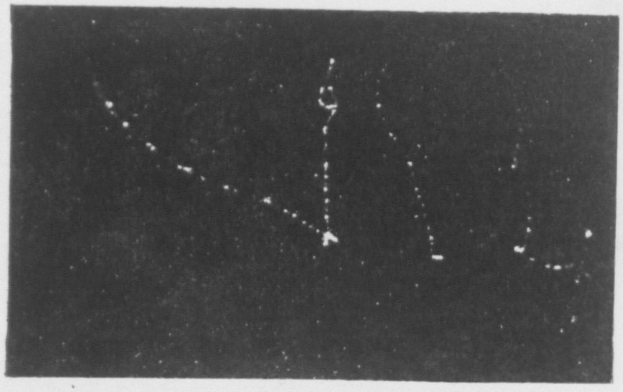
9) W.Kossel, Zeits. f. Phys. 19, p. 333 (1923)
10)W. Bothe, Physik. Zeits. 26, p. 410 (1925)



Cliché 9.
Atmosphère d'hydrogène à 3 p. 100 de krypton.
Rayons X émis sous 60 kilovolts.

Figs

of magnitude to agree with the work of Auger.

Bothe obtained 0.5 for bromine (35) and 0.23 for chromium (24). These fit in with Auger's data somewhat better.

Jauncy and De Foe [11] have made a rough measurement of the fluorescence yield of copper. It turns out to be less than unity.

Since the discovery of the Auger effect, several investigators [1,12,13,14,15] have reported values of the fluorescence yield with varying degrees of success. Balderston measured the ratio of the total number of quanta absorbed to the number of fluorescent K-quanta reëmitted, calling this the "fluorescent transformation coefficient μ." As only about 7/8 of the absorbed quanta are absorbed in the K-shell, we must divide his ratio μ by 7/8 to get w. His results then become:

	26	28	29	30	42	47
Element	Fe	Ni	Cu	Zn	Mo	Ag
w	0.38	0.45	0.50	.57	.95	.86

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11) G.E.M. Jauncy and K.K. De Foe, Proc.Nat.Acad. 11, P.52, (1925)
12) L. Balderston, Phys. Rev. 27, p.695, (1926)
13) M.I. Harms, Ann.d. Phys. 82, p. 87 (1926)
14) L.H. Martin, Roy. Soc. Proc. 115, p.420 (1927)
15) Gordon L. Locher, Phys. Rev. 40, no. 4, May 15, 1932.

His method of calculation, however, is open to considerable criticism as it assumes a linear extrapolation over a large wave length interval. Also he mentions a probable error of ± 13% in the determination of the solid angle subtended by the window of the ionization-chamber.

Not much weight can be assigned to these above-mentioned measurements due to the large errors involved, the lack of modern technique available to the earlier investigators, and the fact that some of the values were deduced from measurements made for other purposes. They do, however, show that the fluorescent yield is less than unity, that it seems to increase with atomic number, and that it is probably nearly independent of the wave length of the exciting radiation.

Harms, Compton, and Martin have recently made fluorescence measurements of w. In addition Locher has made measurements using the Wilson cloud chamber.

The experiments by Harms appear to have been very carefully done, although he has brought an assumption into his calculations that the X-ray energy necessary to produce a pair of ions varies with the wave length. This has been disproved by experiments made by Kulenkampff [16], Kircher and Schmitz [17], Crowther and Bond [18], and Gaertner.[19]

16) H.Kulenkampff, Ann.der Physik 79, p.97 (1926)
17) H.Kircher & W. Schmitz, Zeits.f.Physik 36,p.484,(1926)
18) J.C.Crowther & W.N.Bond,Phil. Mag.6,p.401 (1925)
19) O.Gaertner, Ann.d.Physik 2.1.p.94 (1929)

In particular, Gaertner has shown that the energy necessary to produce a pair of ions in argon does not vary more than ± 4.5% from $\lambda = 1.27$ Å to $\lambda = 0.345$ Å.

This point is vital to any attempt to compare energies of X-ray beams of different wavelength. It is clearly brought out and carefully discussed in the papers previously cited by Compton and Martin. Compton has therefore corrected these results, both for this effect as well as for several minor effects, and given out the values:

	26	29	30	34	38	42
Element	Fe	Cu	Zu	Se	Sr	Mo
w	0.28	0.38	0.40	0.52	0.62	0.73

Harms used filtered radiation, the homogeneity of which is in considerable doubt. Nevertheless, his work appears to be more trustworthy than that of former investigators, and merits considerable attention.

Martin investigated the variation of w (he calls it ϕ) with wavelength of the exciting radiation for the elements iron, nickel, copper and zinc over the range of wavelengths $\lambda = 0.60$ Å to $\lambda = 1.66$ Å.

He found the fluorescent yield to be independent of the wavelength of the exciting radiation. He used filtered

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19) con't.
10.7 p. 825 (1931). These experiments also show that the energy necessary to produce a pair of ions in argon is much less than in other gases commonly used in ionization-chambers. This would indicate that argon possesses a considerable advantage over other gases for ionization measurements of X-ray intensity, as it would give a greater current for the same X-ray intensity.

X-rays and a hemispherical ionization-chamber, in which the rays passed through the collecting electrodes, which were of thin paper coated with india ink. This and other effects necessitated corrections which could not be made with extreme accuracy. Martin says that "the error in the present experiment is in the neighborhood of 5 per cent." In addition to these measurements, he reported values of w for selenium, bromine, and iodine deduced from measurements of Barkla [20] and Beatty [21]. His results are given below:

Element	w	
26 Fe	0.32	Martin's own experiments
28 Ni	.39	
29 Cu	.45	
30 Zu	.52	
34 Se	.68	Deduced from work of Barkla and Beatty
35 Br	.68	
53 I	.88	

Although I place considerable faith in the results of Martin's own work, I assign little weight to the values he reports for Se, Br, and I.

The measurements made by Compton [1] support the conclusions of others that the fluorescent yield is independent of

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20) Barkla and Philpot, Phil. Mag. 25, p.849 (1923)
21) Beatty, Roy.Soc. Proc. A, 85, p. 329 (1911)

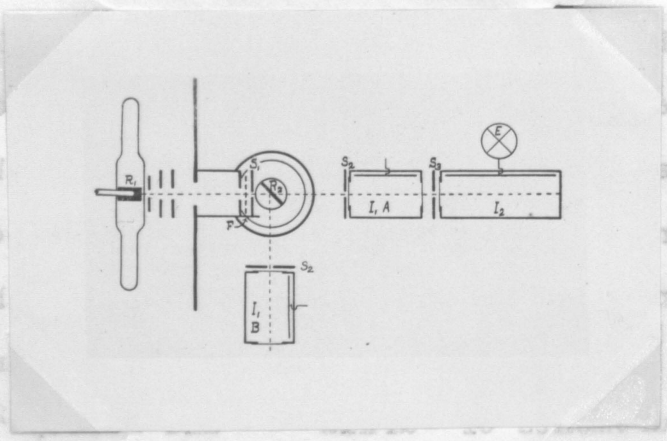

Fig. 6. Schematic Diagram of A.H. Compton's Apparatus

the wavelength of the incident radiation. He allowed the general radiation from a tungsten-target Coolidge tube to fall on a substance R_1. The approximately homogeneous X-rays emitted from R_1 excited the radiator R_2, the substance under investigation. The intensity of the rays from R_1 were compared with those from R_2, appropriate diaphrams being placed at S_1 in the two cases so that the ionization-currents were of the same order of magnitude. The fractions of the two beams absorbed in the front chamber by the methyl bromide vapor were measured by using the second chamber. By an application of the method of successive approximations he also determined the fluorescent yield of bromine. He found:

	28	34	35	42
Element	Ni	Se	Br	Mo
W	0.37	0.54	0.56	0.68

The method used by Compton has provided a model for the present investigation. It will be described in more detail in a later section.

The work of Locher [15] was done by a method similar to that of Auger. He used a Wilson cloud chamber and counted the number of multiple tracks. This number was divided by the number of atoms ionized in their K-shells to give the fluorescence yield w. No details of his work

are available at the time of writing this. His results are:

	8	10	18
Element	O	Ne	A
w	0.082	0.083	0.149

VARIATION OF w WITH Z FOR LIGHT ELEMENTS.

Since the compound photoelectric effect consists in the expulsion of L-shell electrons as well as K-shell electrons from the atom, this effect ought to decrease as one considers those atoms having fewer and fewer L-shell electrons. In fact, this effect ought to disappear entirely for lithium, since it has only one L-shell electron. After it has fallen to the K-shell, setting free a quantum $h\nu_K$ there is no L-shell electron left to cause an "internal absorption" of this $h\nu_K$ in the manner described by Auger. It has been shown that the efficiency of production of fluorescent X-rays is a decreasing function of atomic number from molybdenum down to argon. This means that the compound photoelectric effect is playing a greater and greater part.

But in the neighborhood of neon, the fluorescent yield must begin to increase, i.e., the compound photoelectric effect must begin to be less important. As we run down from neon which has 8 L-shell electrons to

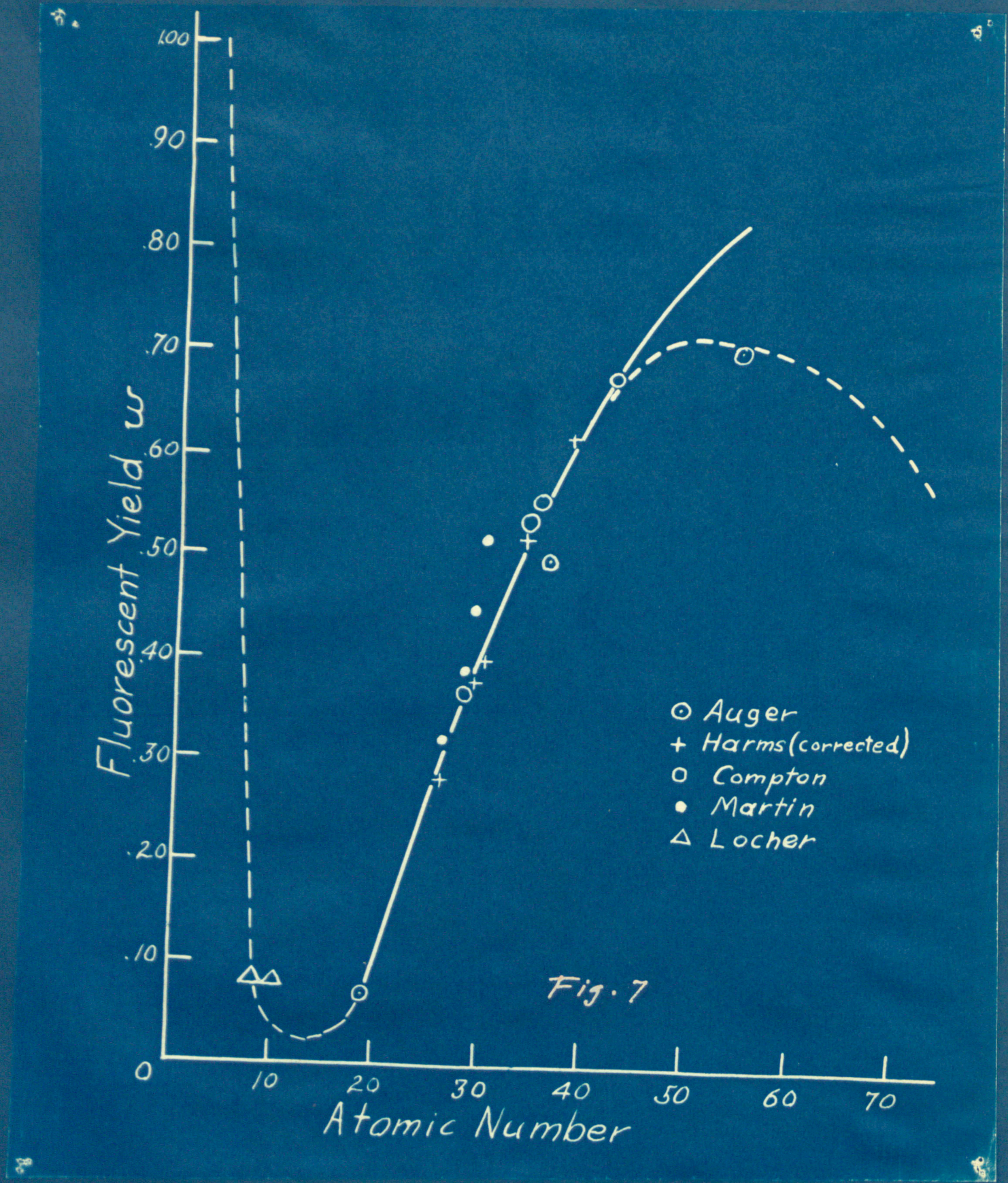
Fluorescent Yield ω
.100
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
10
20
30
40
50
60
70
Atomic Number
⊙ Auger
+ Harms (corrected)
o Compton
• Martin
△ Locher

Fig. 7

lithium which has only one, the fluorescent yield should rise from its minimum value to unity for lithium. This theory, which the author has held for nearly two years, receives some qualitative support from the work of Locher. His values for neon and oxygen are higher than those reported by Auger for argon, although his own value for argon is substantially higher. It is not hard, however, to imagine that there is a minimum in the curve somewhere between argon and neon.

This might not occur, however, if the only electrons taking part in the Auger effect are the 2s electrons. These constitute the first sub-group in the L-shell, a sub-group containing but two electrons and complete down to beryllium (Z = 4). But I think this last is improbable, as the 2s are the most tightly-bound in the L-group. This increase is shown by the dotted line at the left of Figure 7.

3. THEORY

The method of calculating the fluorescence yield from measurements of fluorescence as made in this investigation is originally due to Compton [2]. The following derivation follows his with only minor changes.

Consider the rays from R_1 striking the radiator R_2. Let μ' be the total absorption coefficient for these rays

in R_2, τ' the photoelectric absorption, and σ' the absorption due to scattering. Then

$$\mu' = \sigma' + \tau' \quad - - - - \quad (1)$$

If $\lambda_{R_1} < \lambda_{K_{R_2}}$ as is always the case in these experiments, then most of the photoelectric absorption will be due to the electrons in the K-shell, τ_K' . Let a beam of intensity I^1 and cross-section A^1 traverse a thickness as of the radiator R_2. The number of quanta absorbed by the K-electrons, and therefore the number of atoms ionized in their K-shells will then be

$$dn = I'A' \tau_K' ds * \frac{1}{h\nu'} \quad - - - - - (2)$$

where ν' is the effective frequency of the primary rays. This is readily seen to be so, for the energy removed from the beam in unit time in distance ds is

$$-\Delta E = h\nu' dn = I'A'\tau_K' ds .$$

Now the fluorescent yield w is defined by Auger as

$$w = \frac{n_1}{n} \quad - - - - - - - - - (3)$$

where n is the number of atoms ionized in their K-shells by absorption of incident quanta from the primary beam, and n_1 is the number of fluorescent quanta emitted. Then

$$n_1 = w\, n$$

or

$$dn_1 = w\, dn . \quad - - - - - - (4)$$

The total power in the fluorescent beam will be

$$h\nu'' dn_1 = dP'' \quad - - - - (5)$$

where ν'' is the effective frequency of the fluorescent ray. By substituting (2) in (4) and that in (5) we find

$$dP'' = h\nu'' w I' A' \tau_K' \, ds \times \frac{1}{h\nu'} \cdot - - (6)$$

Putting $P' = I'A'$, the power in the primary beam, we find

$$dP'' = w P' \tau_K' \frac{\nu''}{\nu'} ds \cdot \quad \cdots (7)$$

It has been shown by Barkla and Sadler that the intensity of the fluorescent ray is the same in all directions. Hence the power in the fluorescent ray entering the ionization-chamber through the diaphram S_2 from the infinitesimal layer ds is (uncorrected for absorption)

$$dP'' = \frac{A''}{4\pi r^2} w P' \tau_K' \frac{\nu''}{\nu'} ds, \quad \cdots (8)$$

where A'' is the area of the diaphram S_2 and r is the distance from R_2 to S_2.

Now this experiment is carried out with a thick radiator (effectively infinitely thick) placed at an angle of 45° to the primary beam. The secondary beam is measured at an angle also of 45°, thereby making the path lengths of the primary and fluorescent beams equal. Then denoting the absorption coefficients of the two beams [22] by

22) For absolute accuracy, one should use an absorption coefficient intermediate between μ' and τ', since part of the primary rays scattered in R_2 are reabsorbed before leaving it. But μ' is so nearly equal to τ' that one can neglect this difference.

the power in the fluorescent beam entering the ionization-chamber from the thick radiator R_2 becomes

$$P'' = \left(\frac{A''}{4\pi r^2}\, w\, P'\, \tau_K'\, \frac{\nu''}{\nu'}\right) \int_{s=0}^{s=\infty} e^{-(\mu'+\mu'')s}\, ds \quad \ldots (9)$$

$$= \left(\quad " \quad \right) \left[\frac{e^{-(\mu'+\mu'')s}}{-(\mu'+\mu'')} \right]_0^{\infty}$$

$$= \left(\quad " \quad \right) \left[\frac{1}{-(\mu'+\mu'')\, e^{(\mu'+\mu'')s}} \right]_0^{\infty}$$

$$= \left(\quad " \quad \right) \left[\frac{1}{-\{-(\mu'+\mu'')\} \times 1} \right],$$

since

$$\frac{1}{e^{(\mu'+\mu'')s}} = 0 \quad \text{when} \quad s = \infty, \quad \text{and}$$

$$" \quad = 1 \quad " \quad s = 0.$$

$$\therefore P'' = \frac{A''}{4\pi r^2}\, w\, P' \frac{\tau_K'}{\mu'+\mu''}\, \frac{\nu''}{\nu'} \quad \ldots\ldots\ldots (10)$$

Now $\frac{\nu''}{\nu'} = \frac{\lambda'}{\lambda''}$, so on substituting this in (10) and solving for w we find

$$w = \left(\frac{4\pi r^2}{A''}\right)\left(\frac{\mu'+\mu''}{\tau_K'}\right)\left(\frac{\lambda''}{\lambda'}\right)\left(\frac{P''}{P'}\right). \quad \ldots (11)$$

The value of τ_K' can be found in terms of the K-absorption jump δ of any element. It is

$$\tau_K' = \frac{\delta - 1}{\delta} \times \mu'. \quad \ldots\ldots\ldots (12)$$

For elements of medium atomic weight, $\frac{\delta - 1}{\delta} \doteq 0,85$.

This means that 85% of the photoelectric absorption is caused by K-shell electrons. Compton has used this approximation throughout his work. If he had used exact values, it would have reduced his values by one unit in the second decimal place. In this investigation exact values of $\frac{\delta - 1}{\delta}$ have been used.

In general, not all the energy reaching the ionization-chamber will be spent in producing ionization. Some of it will be scattered to the walls and some will excite fluorescent radiation in the atoms of the gas in the chamber. If this radiation is penetrating enough, some of it will reach the walls and be spent there, rather than in the gas of the chamber. In obtaining P''/P' , we shall assume that the ionization is proportional to the energy spent in producing electrons. This is in accord with the previously mentioned work of Kulenkampff [16], Kircher and Schmitz [17], Crowther and Bond [18], and Gaertner [19].

Compton [1] derives the following equation for the ratio R of the energy spent in producing ionization to the absorbed energy:

$$R = 1 - \frac{\delta - 1}{\delta} \times e^{-\mu'' x} \left(w \frac{\tau}{\mu} \frac{\lambda}{\lambda''} \right)_{\text{Gas in chamber}} - e^{-\mu' x} \frac{\sigma}{\mu} \quad \cdots (13)$$

The second term accounts for the loss of fluorescent energy excited in the gas in the chamber. The third term takes account of scattering. In the present work, argon gas was used in the ionization chamber. This has several advantages. In the first place, it has a high enough atomic number so that the scattering is negligible in comparison with the photoelectric absorption (that is, for the wavelengths used here). In the second place its fluorescent rays are so long that they will be completely absorbed before reaching the walls. The first reason has the effect of making the third term in (13) effectively equal to zero. The second and third reasons act together to make the second term zero. Therefore in this investigation we shall take

$$R = 1$$

Let i' and i'' be the ionization-currents due to the primary and secondary beams, respectively. Let f' and f'' be the fractions of the beams absorbed by the argon in the chamber, and S' and S" be the areas of the diaphrams S_1 used in the two cases. We have then

$$\frac{i''}{i'} = \frac{p'' f'' S'' R'' e^{-(\mu_a'' r + x'')}}{p' f' S' R' e^{-(\mu_a' r + x')}} \qquad \cdots\cdots (14)$$

In (14) μ_a refers to the absorption coefficient of the beam in air, r is the distance from R_2 to the window A" of the ionization-chamber, and x takes account of the absorption in the cellophane window of the chamber. In these

Fig. 8 View of X-ray tube before lowering it into tank.

experiments the cellophane is so thin that the exponential factors in (14) are taken equal to unity. Solving equation (14) for P''/P', we have

$$\frac{P''}{P'} = \frac{i'' f' S'}{i' f'' S''} \quad \ldots\ldots (15)$$

Putting the values of (12) and (15) in eq. 11, we obtain

$$w = \frac{4\pi r^2}{A'' \frac{\delta - 1}{\delta}} \times \frac{\mu' + \mu''}{\mu'} \times \frac{\lambda''}{\lambda'} \times \frac{i''}{i'} \times \frac{f'}{f''} \times \frac{S'}{S''} \quad \ldots\ldots (16)$$

A geometrical constant of the apparatus is

$$M \equiv \frac{4\pi r^2}{A''} \times \frac{S'}{S''} \quad \ldots\ldots (17)$$

After the fractions f' and f'' have been determined, there is a constant for each element under investigation.

$$C_z = \frac{M}{\frac{\delta - 1}{\delta}} \times \frac{\mu' + \mu''}{\mu'} \times \frac{\lambda''}{\lambda'} \times \frac{f'}{f''} \quad \ldots\ldots (18)$$

Then eq. (16) reduces to

$$w = C_z \frac{i''}{i'} \quad \ldots\ldots (19)$$

4. APPARATUS AND METHOD OF OBSERVATION.

The general layout of the apparatus used in this investigation resembles that used by Compton [1] (see Fig. 6). The radiator R1 is placed at an angle of 45° directly above the X-ray tube. Fluorescent rays from R1 pass through holes in a series of baffles and finally through S1, falling

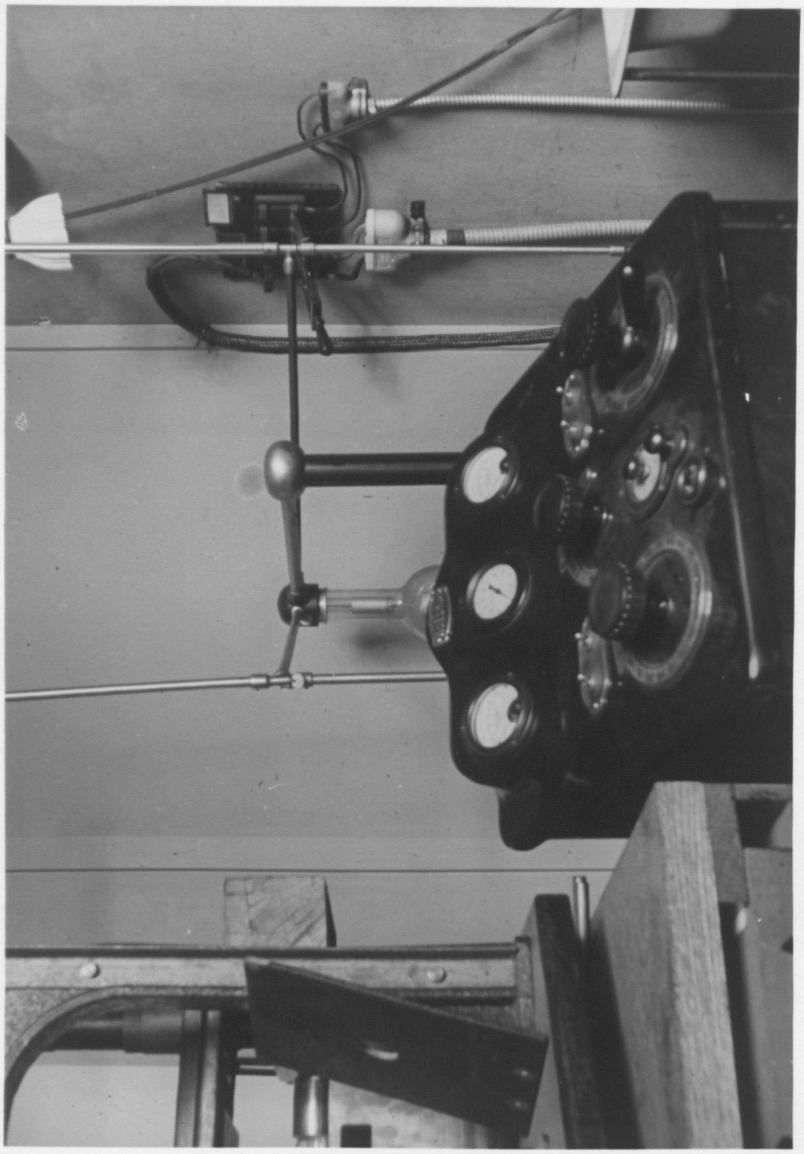

Fig. 9 High Tension Control Apparatus

upon R_2, set at 45° to the beam. The fluorescent radiation from R_2 (the sample under investigation) is measured by the ionization-chamber I_1 in the so-called right-angle position, B, through the diaphram S_2. (In some of the later experiments, S_2 was removed and the beam limited by the aperture of the front window of I_1.) The ionization-current thus measured was compared with that caused by the direct beam, R_2 being then removed and a much smaller diaphram placed in position S_1. The fractions f of the two beams absorbed by I_1 can be experimentally determined by connecting the electrometer to I_2 and making absorption measurements by swinging I_1 in and out of the beam. I_2 is arranged to swing around a common axis with I_1.

The X-ray tube was a Müeller "cross-focus" Metallix, having a tungsten target, metal center section, and Lindemann glass windows. It was immersed in transformer oil contained in a lead tank. A celluloid window was sunk down in the oil bath on the bottom of a glass tube, so that the rays would not have to be filtered through a thick layer of oil. The power was supplied by a motor-generator set run by an induction motor. This minimized fluctuations of the supply voltage. It could be held constant to one-tenth volt by means of a field rheostat. The high tension transformer and control were made by the Kelley-Koett Manufacturing Company. It consisted of a 120 k.v. transformer with a half-

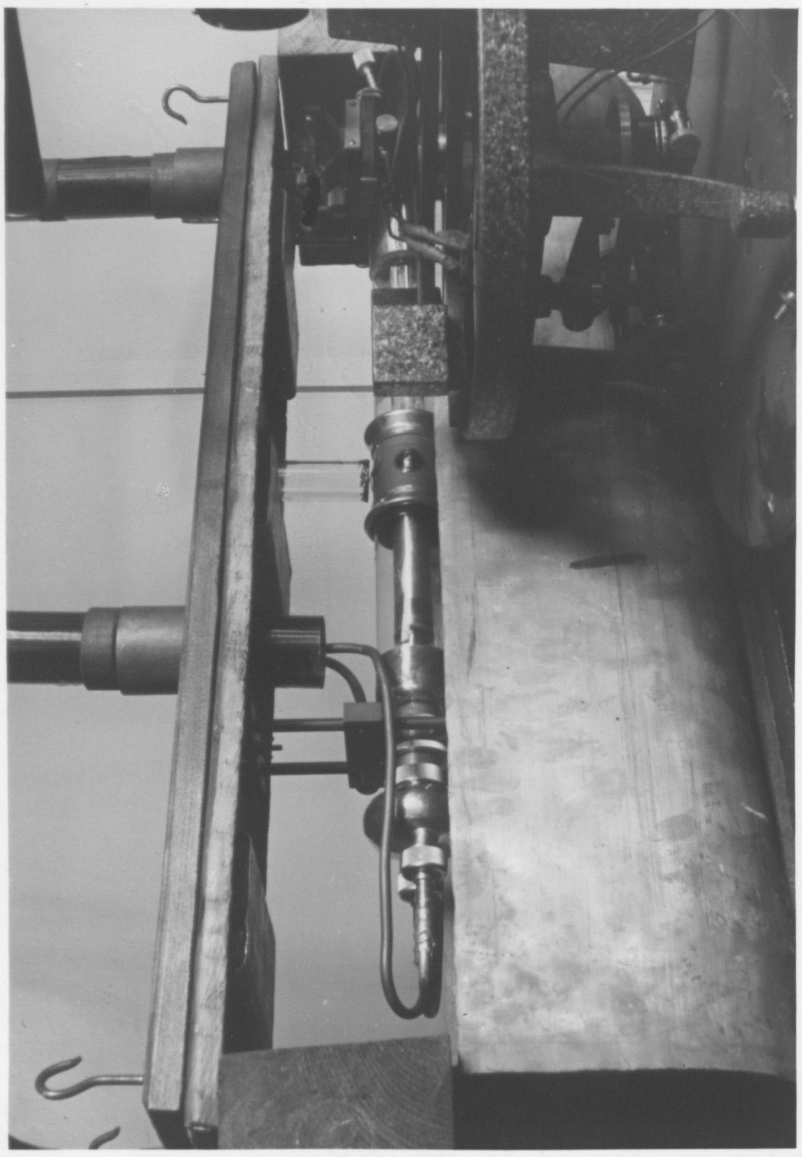

Fig. 10

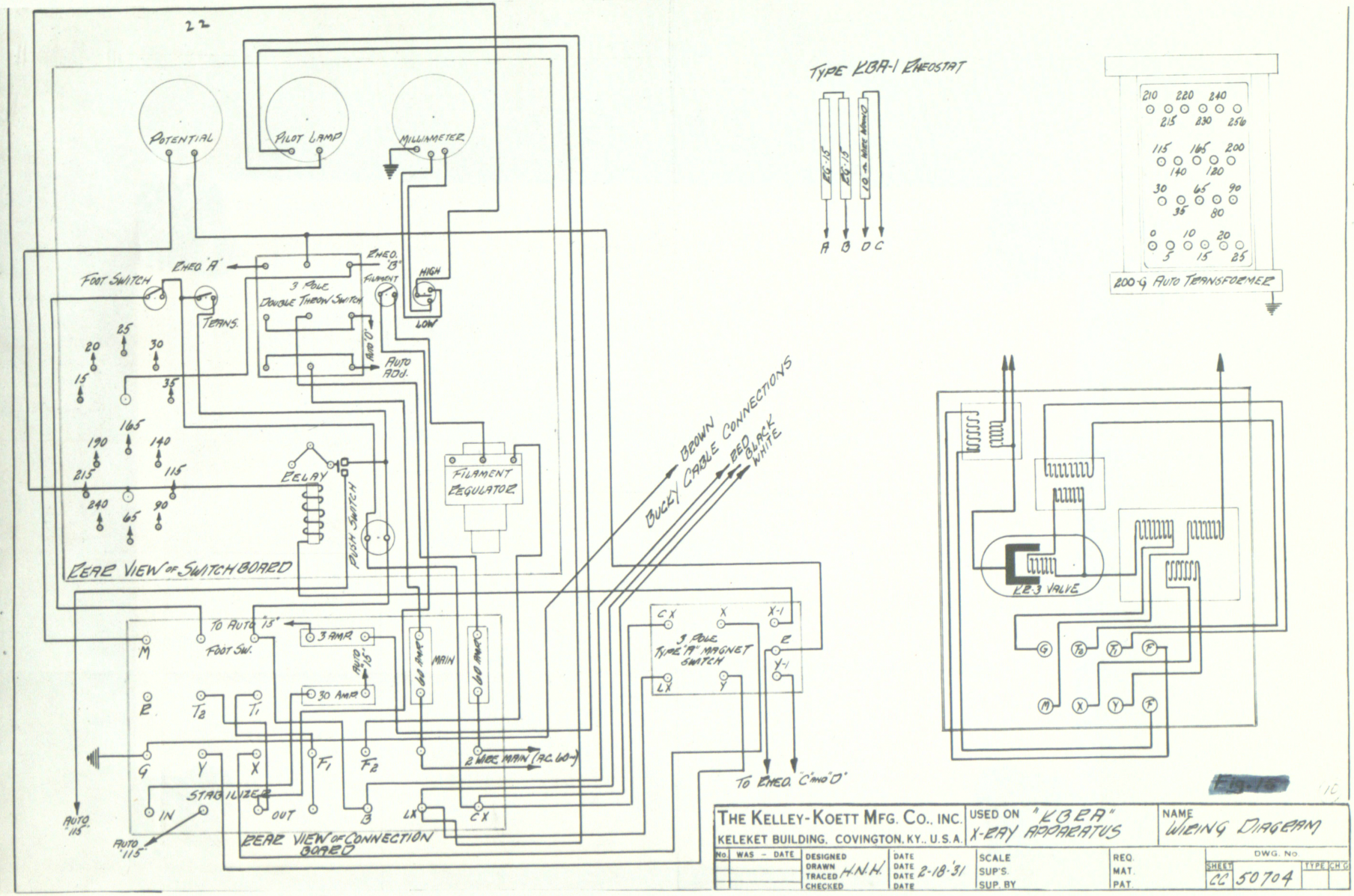

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Fig. 12

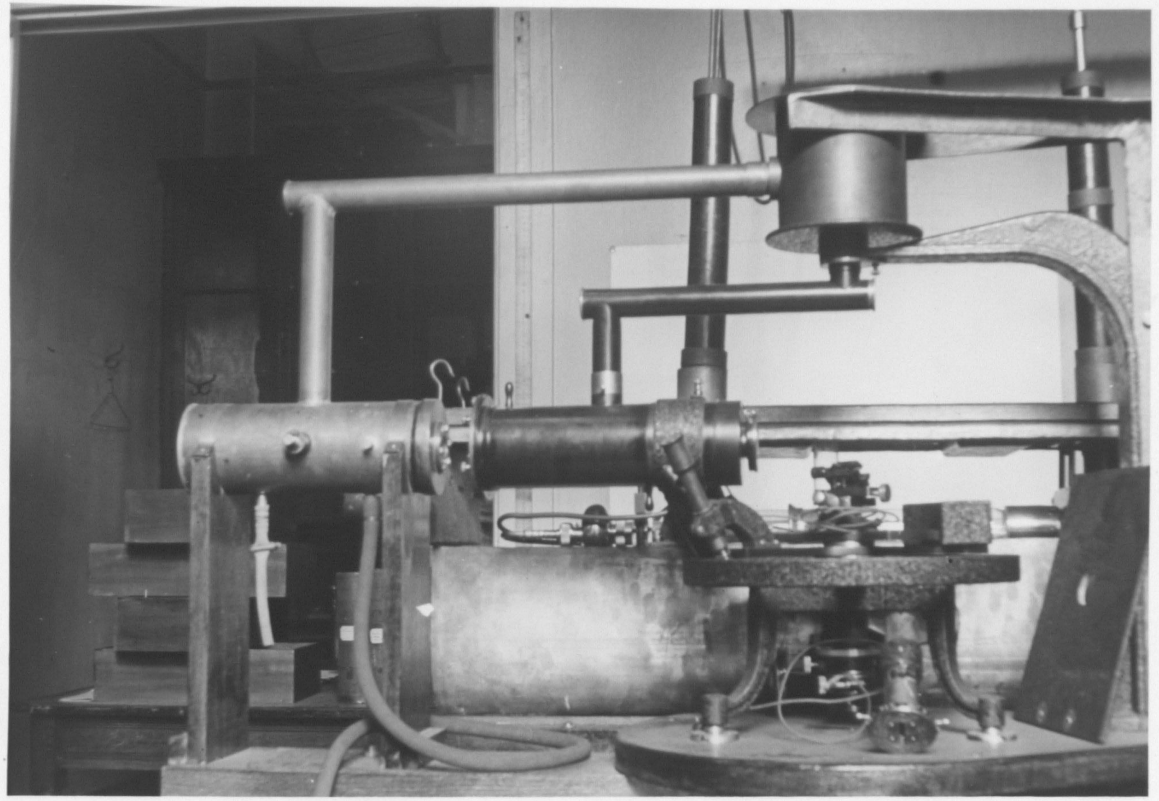
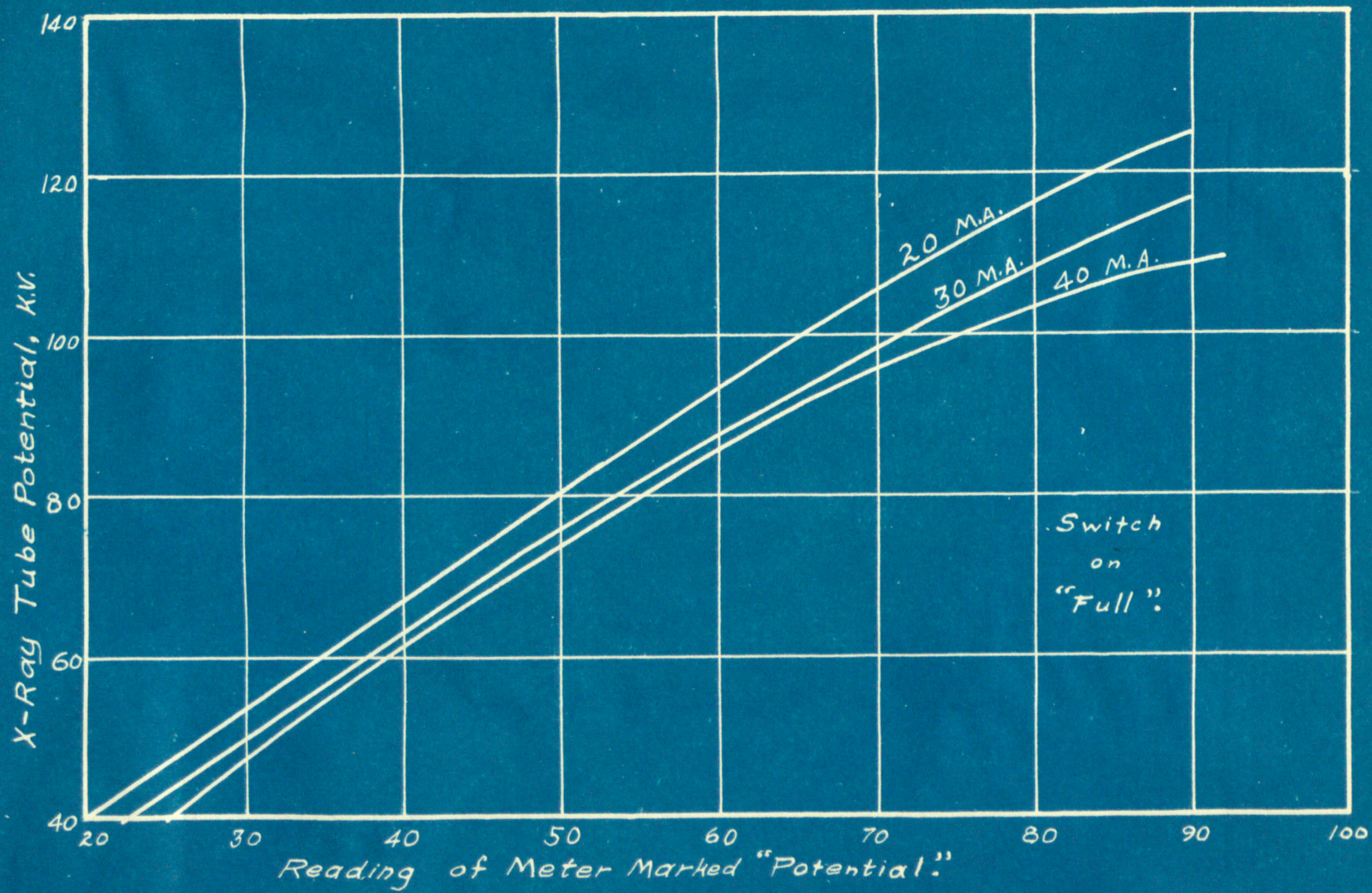


Fig. 11 X-ray Spectrometer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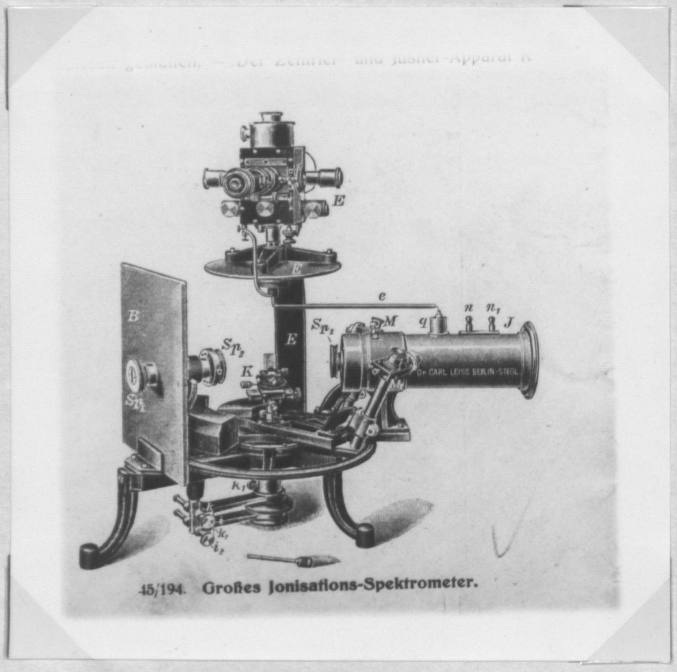
X-Ray Tube Potential, K.V.
20 M.A.
30 M.A.
40 M.A.
Switch
on
"Full".
20
30
40
50
60
70
80
90
100
Reading of Meter Marked "Potential."

Fig. 13



45/194. Großes Ionisations-Spektrometer.

Fig. 14

wave kenotron rectifier. The filaments of both the X-ray tube and kenotron were heated by insulated transformers enclosed in the oil tank with the main transformer. The filament heating current of the X-ray tube was maintained constant by a special inductive stablizer designed and built by Kelley-Koett. The apparatus was calibrated by means of a sphere gap.

The X-ray spectrometer was a large one built by Carl Leiss. The electrometer was of Stryker make. The cooling water for the tube was led in through 36 feet of 2 mm rubber tubing, and out to the drain through an equal amount. This gave 700 cc/minute at 30 lb. per square inch pressure, and allowed very little current leakage.

5. TECHNIQUE OF MEASUREMENT AND EXPERIMENTAL DIFFICULTIES.

In order to avoid the many difficulties inherent in the use of a Compton electrometer, the suggestion was early made that a trial of vacuum tube electrometers be made. This was before the General Electric Company's FP54 Low Grid Current Photron had been put on the market, and the best tube available was the UX-222. This has the lead from the control grid brought out through the top of the tube, a design that reduces leakage and facilitates placing a guard ring in position.

Grid Current vs. Grid Potential Characteristic of UX 222

A— 45 v. on plate & 22 v. on screen grid
B — 9 v. on plate & 4.5 v. on screen grid

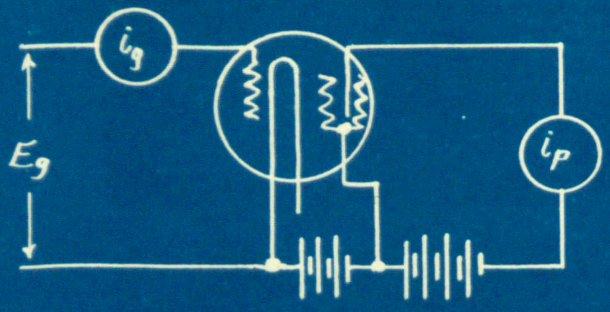


Fig. 15

Accordingly a UX-222 was secured and a test of its grid current made for various values of the grid voltage. Figure 6 shows the arrangement of the circuit and the results of two tests. It will be seen that in order to avoid a grid current of more than 10^{-8} amperes, it would be necessary to operate the tube constantly with a negative bias of two volts or more. A constant bias would be very difficult to arrange, and even then it is not certain that good sensitivity could be obtained. Then too, the expected ionization-currents were only of the order of 10^{-14} amperes, so that the use of a vacuum tube did not appear promising.

About this time the writer learned that even those[23,24] who had built and used vacuum tube amplifiers were not sure they could compete on even terms with a Compton electrometer for ionization measurements. Also they have to be shielded much more carefully as they tend to rectify all sorts of electromagnetic waves and register them. The writer also learned [25] that the particular make of Compton electrometer (Pyroelectric Instrument Company) in use in this laboratory was very unsatisfactory and much harder to use than that made by either Stryker or Cambridge Instrument Company.

23) R.D. Bennett, Rev.Sci.Instr. 1, No. 8 (1930)
24) W.B. Nottingham, Journ. of Franklin Inst., 209, p. 303 (1930)
25) from A.H. Compton

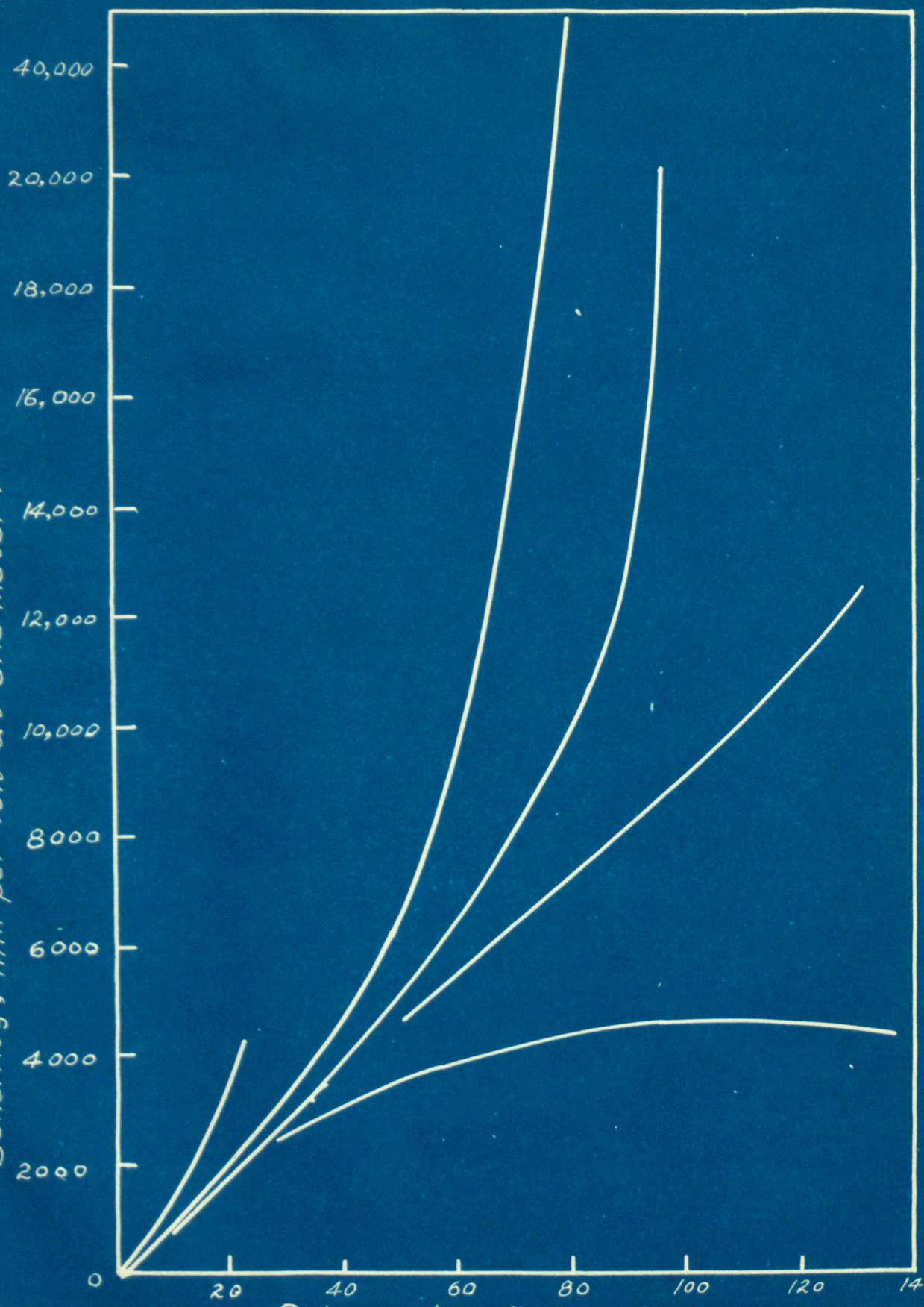

40,000
20,000
18,000
16,000
14,000
12,000
10,000
8000
6000
4000
2000
0
Sensivity, mm per volt at one meter.
20
40
60
80
100
120
140
Potential on Neede, volts.

Fig. 16

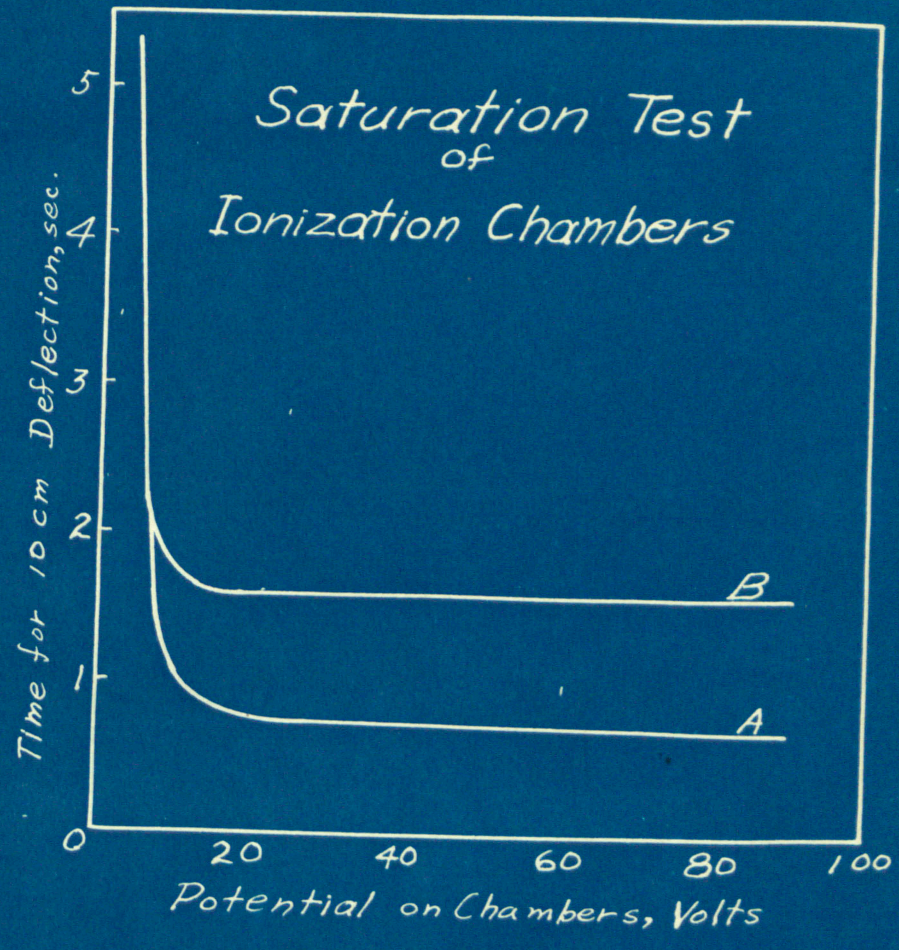

Saturation Test
of
Ionization Chambers
Time for 10 cm Deflection, sec.
0
1
2
3
4
5
B
A
20
40
60
80
100
Potential on Chambers, Volts

Fig. 17

The experiments on vacuum tube amplifiers were therefore laid aside and a Compton electrometer ordered from Stryker. No difficulty was experienced in making this instrument operate at sensitivities up to 15,000 mm per volt, except that it had to be very free of vibrations to work above 5,000. In these measurements it was usually used at from 2,000 to 4,000 mm per volt at a scale distance of 140 cm.

Loose connections in the battery that supplied potential for the needle of the electrometer and the ionization-chambers were a considerable source of trouble. They would cause erratic readings. The effect of substituting new batteries for old ones is shown by the following measurements. Two series of 25 measurements each were made of the time for the electrometer index to move 50 mm when radium was used as a source of radiation. The probable error R of a single observation was then deduced from the statistical fluctuations by means of Peters' approximation formula.

Old"B" Batteries	R = $\pm$ 6.5%
New"B" Batteries	R = $\pm$ 2.2%

These readings were taken in the daytime. At night the fluctuations were much less.

Trouble was also experienced due to a bad grid leak inserted in the battery lead to the ionization-chambers.

This grid leak was finally eliminated, although one was retained in the lead to the electrometer needle.

Several times the linearity of response of the electrometer was tested by applying known small potentials to the quadrants by means of a potentiometer. These tests always showed that the instrument had a linear scale. One of the graphs so obtained is shown in Figure 18. The response of the system electrometer plus ionization-chamber, however, was not uniform. This was determined by dividing the scale up into five centimeter intervals, numbering them consecutively from one to ten, and noting the time taken for the index of the electrometer to traverse each separate interval. The graph (Figure 19) shows that for the higher-numbered intervals, the time for one interval is greater. This is caused by a leaking-away of the charge on the insulated system. This can take place over and through the amber insulators, and also through the agency of stray ions in the air near the conductors. The effect increases for slower rates of charging (smaller currents) as is shown by the lower curve. This suggests that to minimize this effect, slow rates of charging should be avoided. Also the readings should all be taken over the same part of the scale, preferably the first part. These precautions were observed.

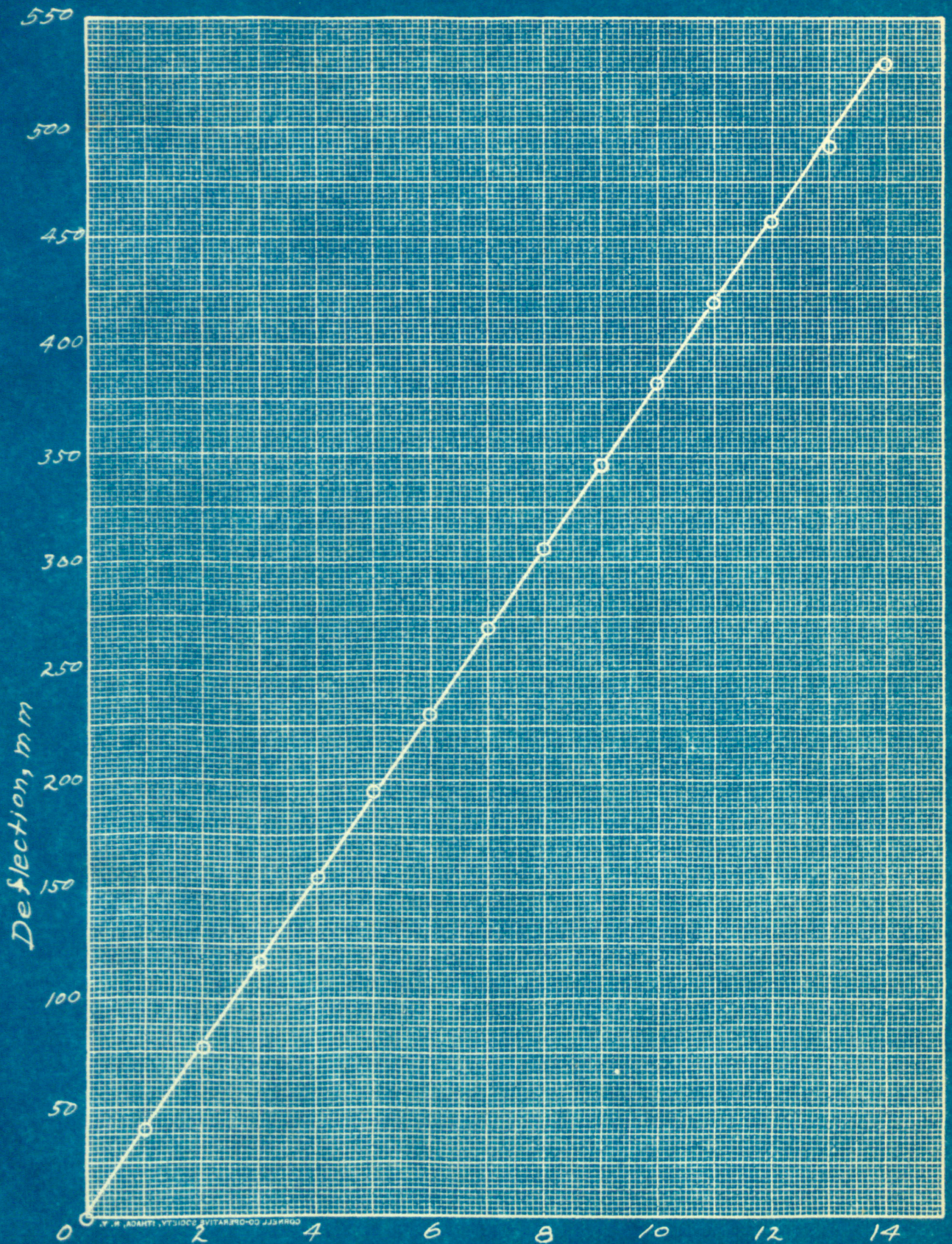

550
500
450
400
350
300
250
200
150
100
50
0
Deflection, mm
2
4
6
8
10
12
14
Potential on Quadrants, Volts x 10⁻²

Fig. 18

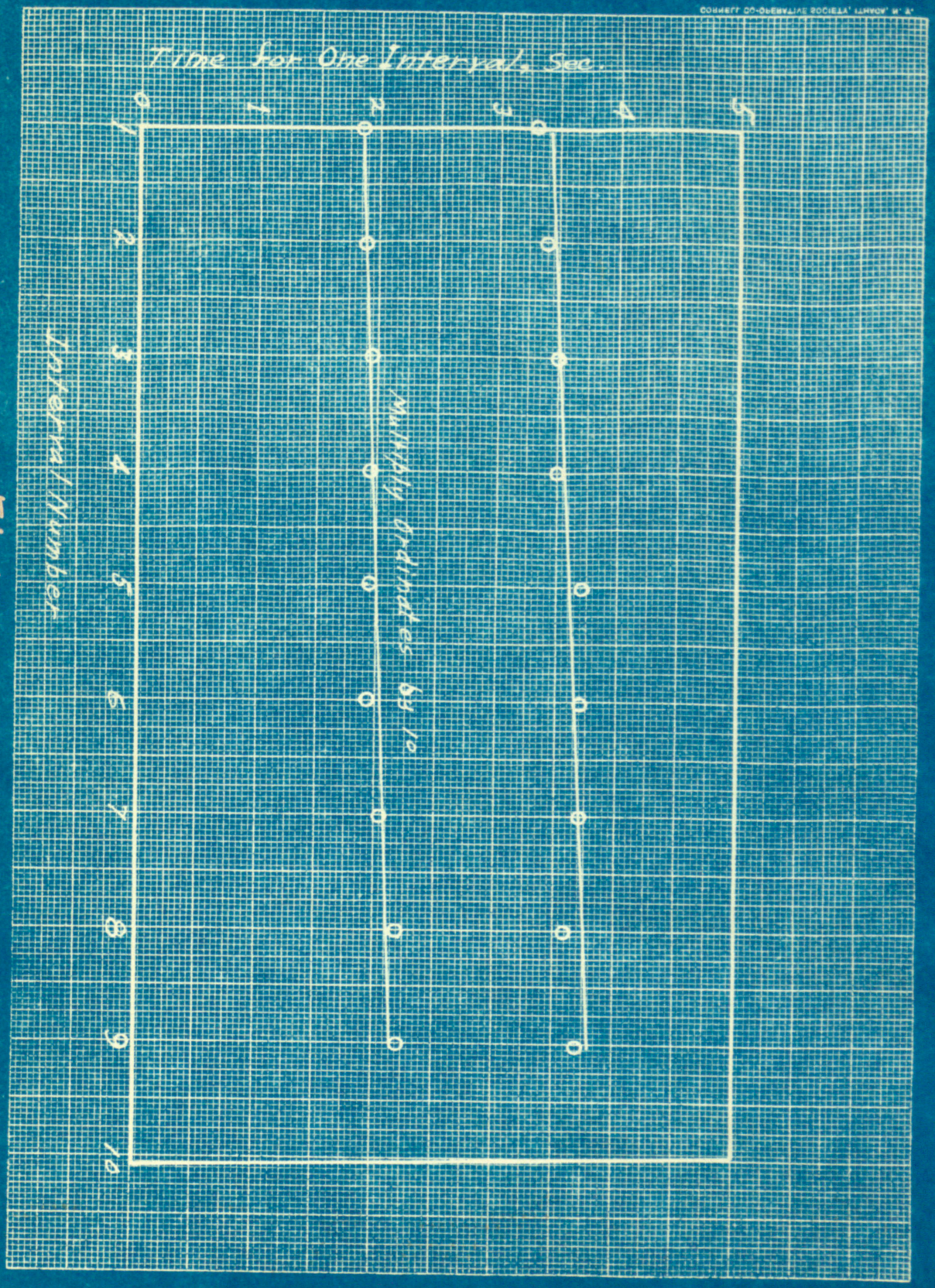

Time for One Interval, Sec.
Temperature Number
Annual Variation of Temperature

Fig. 19

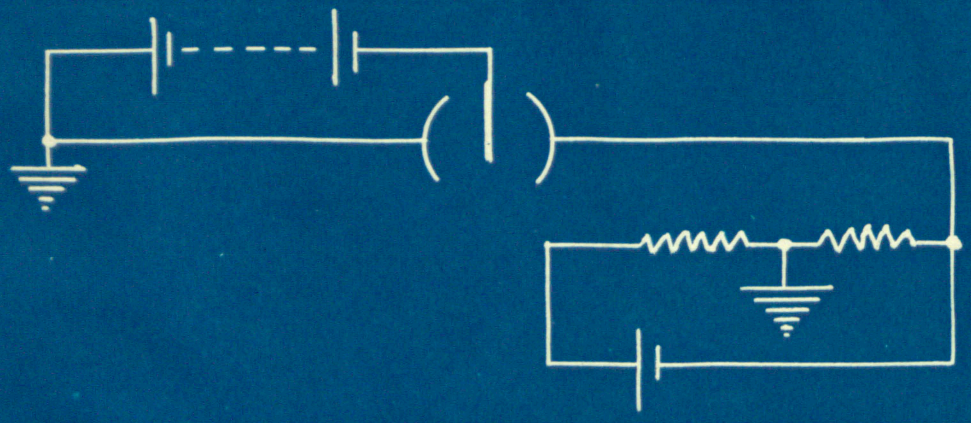


Fig. 20

Potentiometer for Calibration of Electrometer

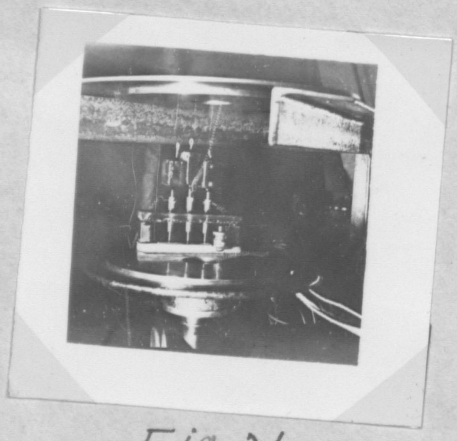


Fig. 21

Considerable difficulty was experienced with the switches used for connecting the electrometer either to the first or second ionization-chamber and/or the ground. At first a little switch was constructed with three levers arranged to drop on a common contact leading to the electrometer. These levers could be worked independently at first by means of threads, and later by means of rods. One lever was connected to the ground, the other two to the front and rear ionization-chambers, respectively. The insulation was of amber, and the contacts gold-plated. This was not satisfactory, however, so the levers were amalgamated with mercury and arranged to drop into mercury cups. The accompanying picture, Figure 21, shows this installed in the turret over the axis of the spectrometer, just under the electrometer. This switch gave continual trouble due to insulation leakage and to erratic electromotive forces.

A relay type switch was next tried. This was so designed as to provide a long leakage path over and through the amber supports, and employed mercury cup contacts. By proper shielding induction effects due to the relay magnets were overcome, but still the erratic electro-motive forces persisted. At last the arrangement shown in Figure 22 was adopted. When it was desired to "switch" from one chamber to the other, a door in the turret was opened and the spring

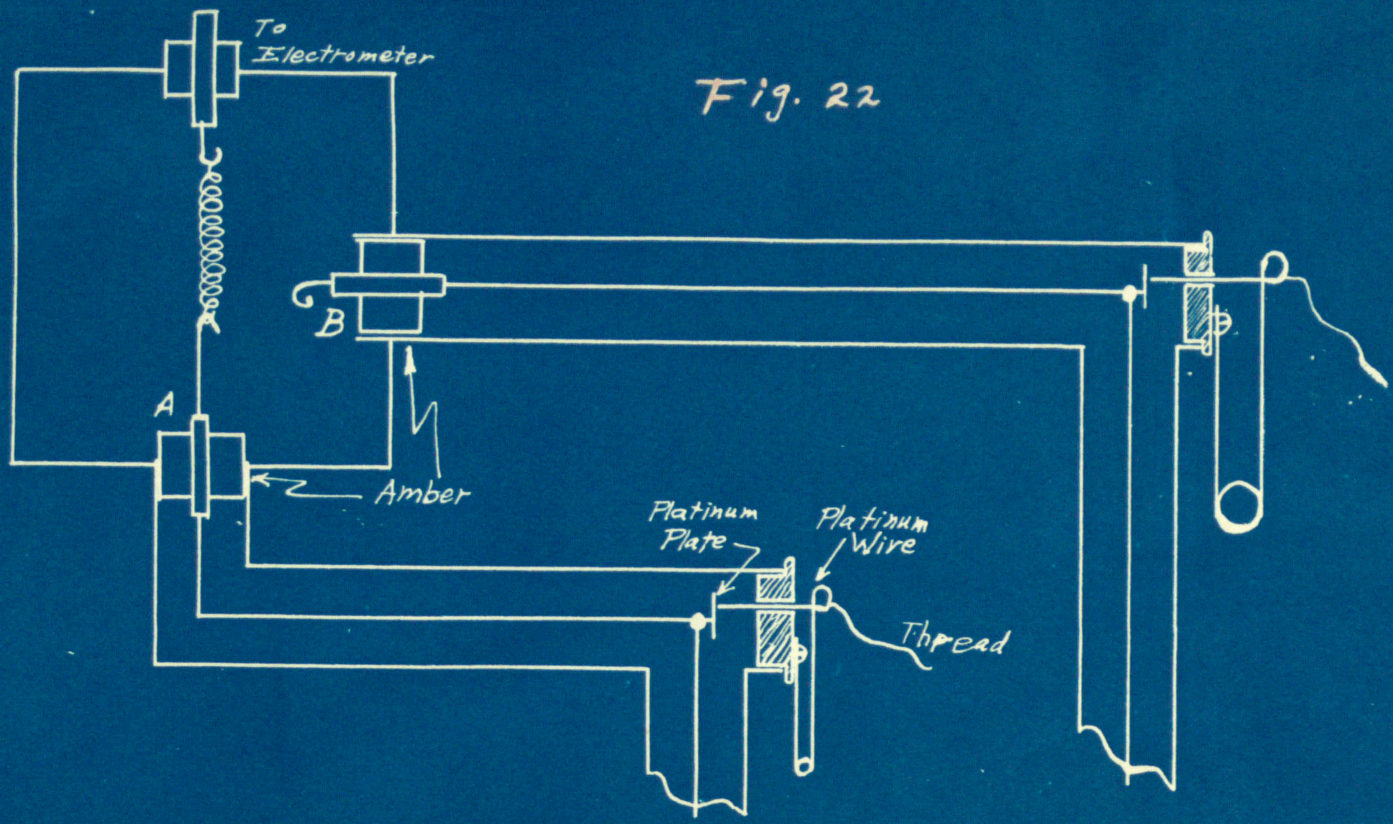

To
Electrometer
B
A
Amber
Platinum
Plate
Platinum
Wire
Thread

Fig. 22

unhooked from the one chamber lead, and hooked on the other. The spring and hooks were made of brass. This method did not allow such quick switching, but it eliminated all insulators except those that would have been necessary anyhow. It was completely satisfactory. Grounding was accomplished by means of a platinum wire touching against a small platinum sheet mounted on the lead from the ionization-chamber. A separate ground was used for each chamber. These switches did not give a "kick" of as much as one millimeter to the electrometer index, even when the sensitivity was 3500 mm per volt.

When working at such high sensitivities as were necessary in this investigation, great care had to be used in the placing of lead shields to cut off scattered rays. It was even necessary to put lead around the ionization-chambers. Even then it was found that the natural leak was different in the two positions of the chambers.

The rear ionization-chamber, which was designed and built in the departmental shops, was filled with argon gas at a pressure of 29 lbs. per square inch (above atmospheric). No appreciable leakage occurred during a period of three months, after the right kind of gaskets were found for it, and the front end soldered tightly shut. A celluloid window successfully

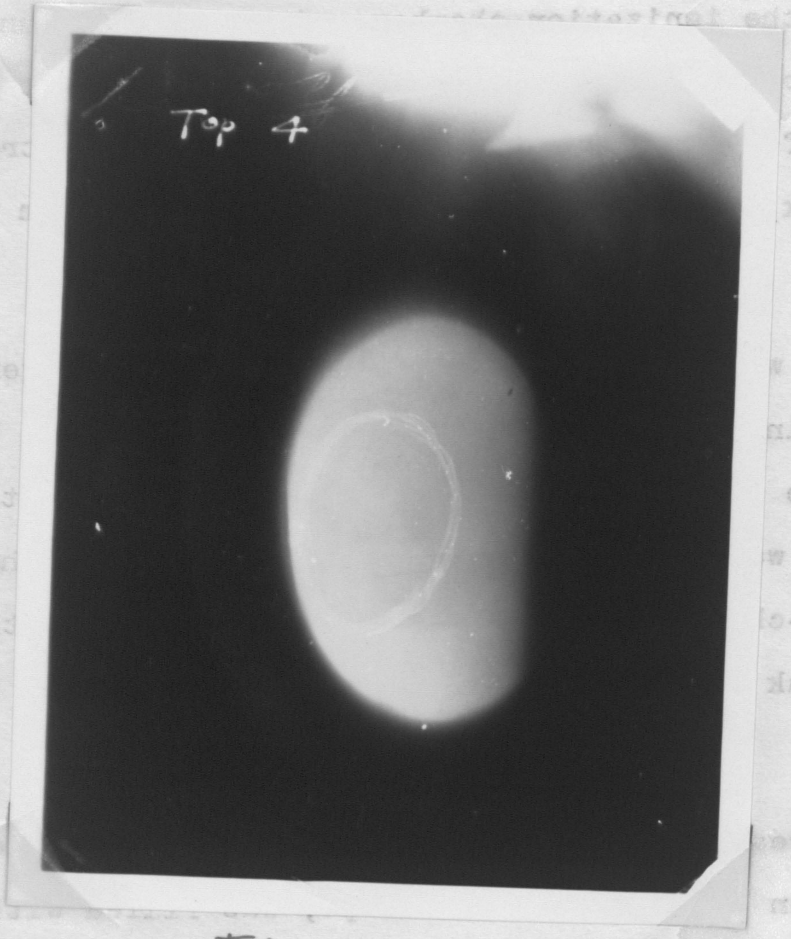


Fig. 23

withstood the pressure, although it bulged considerably.

The front chamber, which was supplied with the spectrometer, was found to be unsuitable for use at pressures much different from atmospheric, without completely rebuilding it. Not only that, but it was desirable to use very thin cellophane windows on it, both front and rear, in order to reduce the error due to X-ray absorption in them. This ionization-chamber was therefore operated at atmospheric pressure.

It was found that the electrometer readings were often interfered with by the vibrations from people walking in the building, vehicles driving by, etc. Most of the work, therefore, had to be done at night. In making an observation on the fluorescent yield, several trials of the ionization-currents would be made and the average taken. If one or two departed seriously from the average, they were discarded before the average was taken on the assumption that they were affected by vibrations.

In lining up the apparatus, a film was first put in the position of R_1, and an exposure made. This is shown as the large spot on Figure 23. This was then put back in position after being developed. A diff~~erent~~ used source of light was placed in the position of R_2 and allowed to

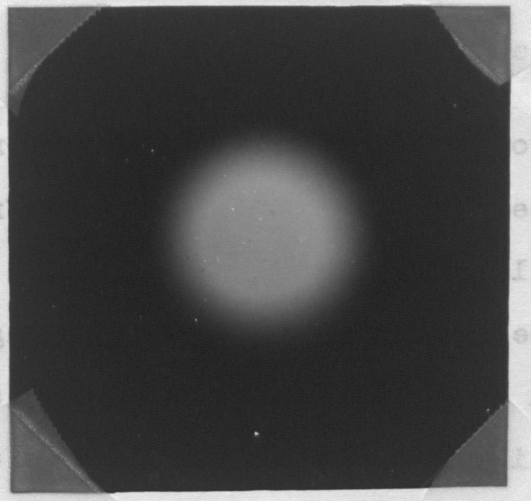


Fig. 24

shine through the diaphrams and baffles back onto the film placed at R_1. The tank containing the X-ray tube and supporting the film in position R_1 was then moved back and forth until the spot of light was centered on the spot caused by the X-rays at R_1.

A small diaphram was then put in at S_1 and a picture taken of the beam at the front of the first ionization-chamber, the radiator having been replaced at R_1. This showed that the beam is small enough to go in through the window of the ionization-chamber although it is not perfectly centered.

Another photograph was then taken with the large diaphram at S_1 in order to find out the distribution of intensity throughout the beam. As will be seen, the center seems to show a light spot. From this it would appear that the ratios of the energies passing out through the large and the small diaphrams would not necessarily be in the same ratio as their areas. Dr. Allen suggested that this effect might be caused by the L-radiations of lead excited in the edges of S_1. This was tested by taking another picture through enough thickness of aluminum to absorb nearly all of the L-radiation of lead and only a little of the main beam. But the effect persisted.

Then Mr. Kersten suggested that it might be caused

by diffraction from the space lattice of the edge of the diaphram, and suggested rounding the edges of the diaphram on the emergent side. This was done and another photograph taken. This last still showed the same effect.

It was then decided to measure directly the ratio of the energies passing through the large and the small diaphrams by means of the ionization produced in the front chamber. As this ratio was too great to be measured directly, it was done indirectly by using several diaphrams of intermediate size, so that the ratio for any two was only about seven to one. The results of these measurements showed that the ratio of the energy passing through the largest to that passing through the smallest was within two per cent of the ratio of their areas. The measured value of the ratio was adopted in all subsequent work.

After the main beam had been properly aligned, the following procedure was adopted to fix the correct positions of the ionization-chambers:

With R_1 in place and a small diaphram at S_1, ionization currents were measured in the rear chamber as a function of its position, this being varied by means of a tangent screw. The position of the peak

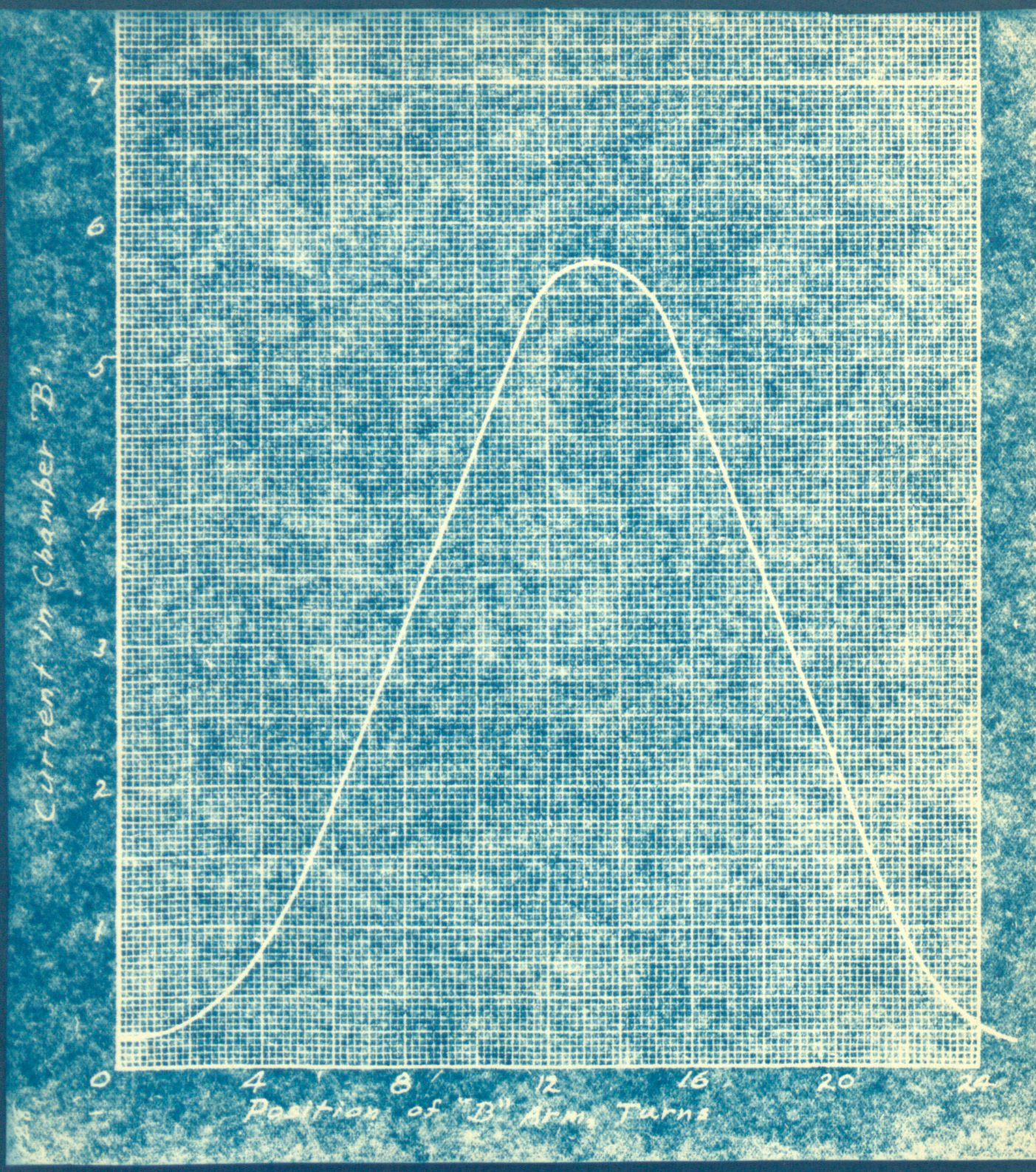

Current in Chamber "B"
0
1
2
3
4
5
6
7
4
8
12
16
20
24
Position of "D" Arm, Turns

Fig. 25

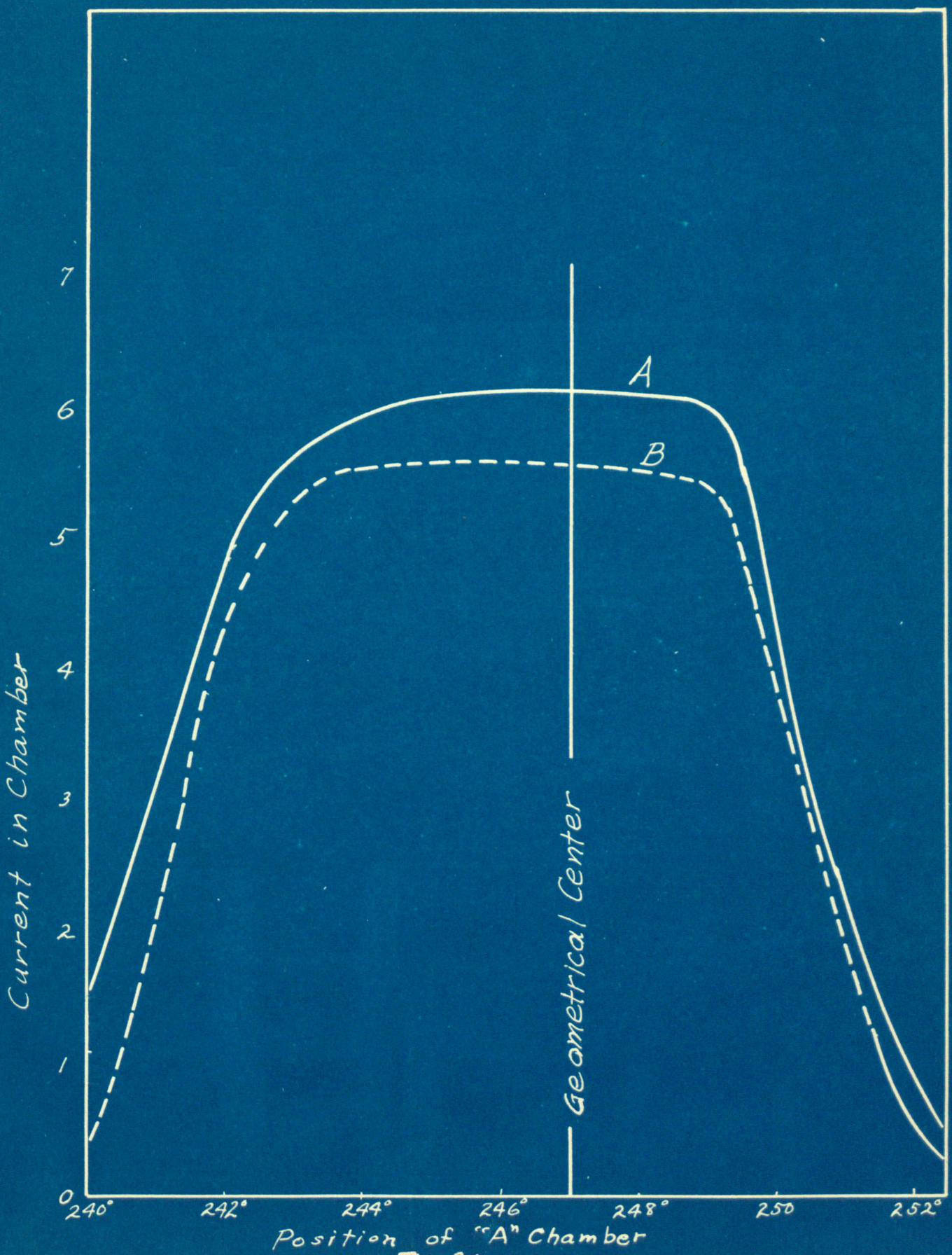

Current in Chamber
0
1
2
3
4
5
6
7
A
B
Geometrical Center
240°
242°
244°
246°
248°
250
252°
Position of "A" Chamber

Fig. 26

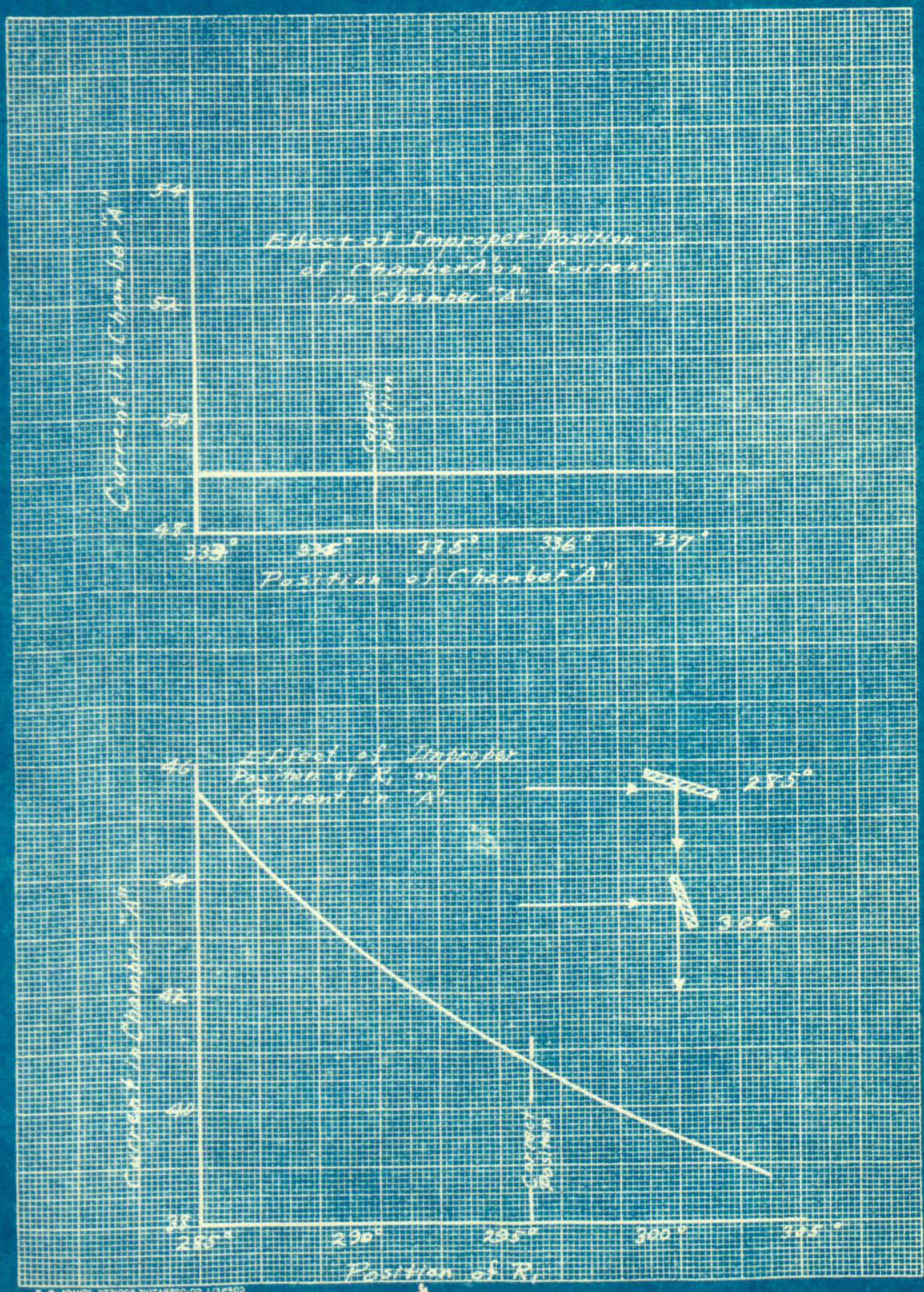

Effect of Improper Position of Chamber "A" in Current in Chamber "B"
Current in Chamber "B" in Milliamperes
Position of Chamber "A"
339°
346°
353°
356°
357°
Effect of Improper Position of R1 on Current in "B"
Current in Chamber "B" in Milliamperes
Position of R1
285°
300°
295°
305°
304°

Fig. 27

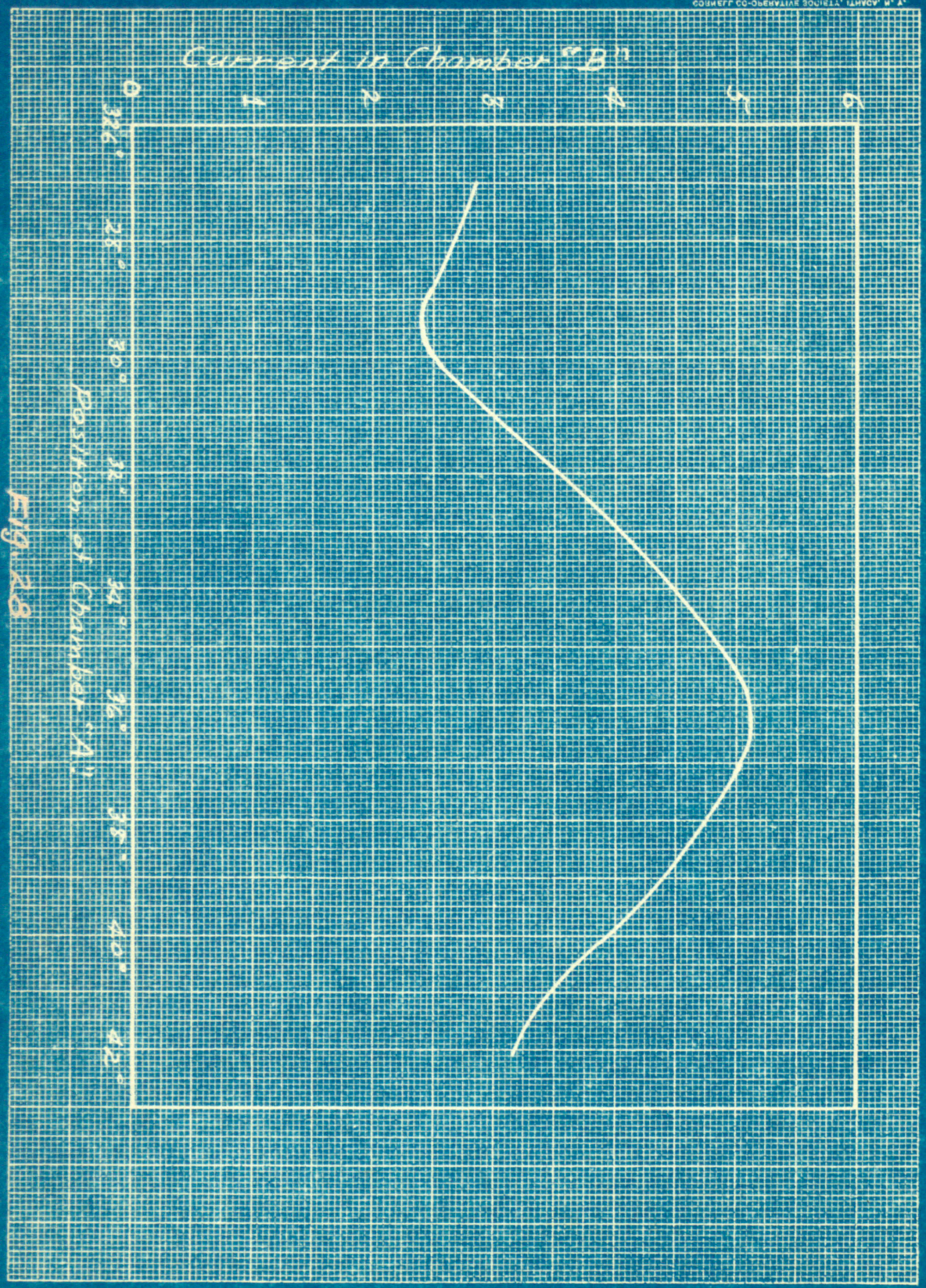

Current in Chamber "B"
0
½
1
1½
2
2½
Pressure of Chamber "A"
12
10
8
6
4
2
0

Figure 8

Current in Chamber "B"
Position of Diaphragm S_2, Cm.
0
1
2
3
4
5
6
7
8
9
10
11
Center
Edge

(Figure 25) was adopted as the correct one. It was $13\frac{1}{2}$ turns from the zero position (i.e., from the place where the arm holding the chamber struck the stop, the tangent screw being backed clear out).

Keeping the chamber fixed in this position, the currents in both front (A) and rear (B) chambers were measured as a function of the position of "A" chamber. Both of these curves (Figure 26) had flat-topped peaks, and so the geometrical center (247°) was adopted as the correct position for chamber "A".

The right-angle position for the rear chamber could then be found by marking a line on the wooden base, at right angles to the first position, by means of a carpenter's square. For the front chamber, the correct position was of course 247° + 90° = 337° on the divided circle. Neither this angle or that of the radiator R_2 (45° to the beam) was critical, however, as Figure 27 shows.

The sizes of the diaphrams were so chosen that no rays ever struck the walls of the chambers in either position.

6. Samples And Auxiliary Data for Computations.

Cobalt

This was loaned by Mr. H.J. Kersten. It is a slab

about 3/16 inch thick, cast for use as an anode in electro-plating. Its degree of purity is unknown.

Nickel

This is in the form of thin cold-rolled sheets, and was obtained from Dr. S.J.M. Allen. It is of unknown purity.

Copper

This is thin commercial sheet copper, presumeably of electrolytic origin. If so, it is of very high purity (over 99%).

Zinc

This is lot number A-109, 30 mesh zinc metal, Special, from Eimer and Emend. It is the grade known by them as "Tested Purity". The following analysis for lot number A-109 is typed on the bottle:

Arsenic (As)	None	Chloride (Cl)	0.001%
Iron (Fe)	0.01%	Lead (Pb)	0.11%
Sulphate (SO_3)	None	Cadmium (Cd)	0.07%

Arsenic

A sample of "Arsenic Metal, C.P." was purchased from Coleman and Bell Company, Norwood, Ohio.

Selenium

This was in the form of sticks, from Eimer and Amend. It was labeled C.P.

Strontium

This was kindly supplied by Dr. Allen. It was a very pure white powder labeled "Strontium Carbonate". Its purity is unknown.

Molybdenum

A plate about 4x4 centimeters square, 1/2 mm thick, was kindly supplied by the Fanteel Products Company. Purity unknown.

Silver

Dr. Allen kindly supplied this sample in the form of a plate 1/8 inch thick. He said that it was especially pure, intended for the determination of electrochemical equivalents.

Cadmium

This was in the form of a stick, obtained from Dr. Allen. Its purity and origin are unknown.

Tin

This was 30 mesh Eimer and Amend's Tested Purity. A typed analysis as follows was pasted to the bottle:

Antimony	Trace	Iron	0.002%
Arsenic	Trace	Lead	0.001%
Copper	0.0001%	Zinc	0.001%

Tested B, filled C119

Antimony

This is a sample of Eimer and Amend's C.P. sticks.

Tellurium

Dr. Farnau kindly supplied this. It was in a bottle labeled "Anode Te". Dr. Farnau said he believe it to be unusually pure.

Barium

No measurements were made on barium, but a sample of barium nitrate was used as the primary radiator, R1. It was obtained from Mallinckrodt, and was labeled "C.P. crystals".

The zinc, selenium, cadmium, tin, antimony and tellurium were melted carefully and cast into circular disks. The arsenic and strontium were in powdered form. They were poured into a form made by drilling a hole in a piece of 1/16 inch celluloid. The bottom and top of the hole were covered over with cellophane. This was so thin that its absorbing effect was negligible.

In order to calculate the fluorescent yield w, the factor C_Z (see eq. 18) must be calculated separately for each sample used.

The values of $\frac{\delta - 1}{\delta}$ were obtained from a table in Wien-Harms Handbuch der Experimental-Physik,

vol. 24, part I, p. 256. This table is calculated from the data on absorption jumps published by the following:

Richtmyer, Phys. Rev., 18, P. 13, 1921.
ibid, 27, p. 1, 1926.
ibid, 30, p. 788, 1927.
Williams and Worsnop, Nature, 108, p. 306, 1921
Richtmyer and Warburton, Phys. Rev., 23, p. 291, 1924.
Stoner and Martin, Proc. Roy.Soc. A, 107,p. 318, 1925.
Jonssen, Diss. Upsala 1926, p. 62.

This was plotted and a smooth curve drawn through the points. From this curve the values of $\frac{\delta - 1}{\delta}$ for the elements used were read off.

The values of μ' and μ'' were interpolated from tables collected by Dr. Allen and kindly furnished to the author.

The wavelengths λ' and λ'' were calculated from values given in the Wien-Harms Handbuch der Experimental-Physik, vol. 24, Part 2. The values used are the weighted mean wavelengths of the α and β lines.[26]

26) These have been weighted 5 and 1, respectively, on the basis of the results of Unnewhr (Phys. Rev. 22, p. 529, 1923), and Compton (Proc. Nat. Acad. 14, p. 549, 1928.

It was originally intended to measure directly the values f' and f'' of the rays absorbed in the front ionization-chamber. However, so little energy was radiated from R_2, and the rear ionization-chamber was so far away from R_2, that very little energy was left to measure. One series of measurements was made of f by putting the radiators in the position R_1 and exciting them with 38 kv X-rays (This voltage corresponds to the excitation-voltage of Ba, which was used as R_1 in the fluorescence measurements.). The conditions of excitation are so different, however, that no faith can be placed in them. The amount of scattered radiation is probably not the same as it was in the fluorescence measurements. In view of these facts, the values of f were calculated from the known absorption coefficients of argon and nitrogen. The gas used in the chambers was the commercial grade of argon containing 14% nitrogen.

Some slight changes that are being made in the diaphram system, will, it is hoped, permit the actual measurement of the fractions absorbed. These changes probably will also permit of the determination of the proportion of scattered radiation present in the fluorescent beams.

The values of C_z are calculated for barium as the primary radiator and M = 1.697.

$$M = \frac{4\pi r^2}{A''} \frac{S'}{S''}$$

r = 11.4 cm.

A'' = 3.19 cm^2.

$\frac{S'}{S''}$ = 0.003305

Calculation of $\frac{\mu' + \mu''}{\mu'}$ for $SrCO_3$

R_1 = Ba, λ' = 0.378 A.U.

λ'' = 0.859 A.U.

Substance	M.W.	$(\mu/\rho)_{\lambda'}$	$(\mu/\rho)_{\lambda''}$
$SrCO_3$	147.63	11.29	15.57
Sr	87.63	18.8	25.0
C	12.00	0.225	0.91
O	16.00	0.32	2.05

$\frac{87.63}{147.63}$ x 18.8 = 11.17

$\frac{12}{147.63}$ x 0.225 = 0.02

$\frac{48}{147.6}$ x 0.32 = 0.10

TOTAL = 11.29

11.29
15.57
26.86

$\frac{26.86}{11.29}$ = 2.375

$\frac{\mu' + \mu''}{\mu'}$ = 2.375

$$\frac{87.63}{147.63} \times 25.0 = 14.83$$

$$\frac{12}{147.63} \times 0.91 = 0.07$$

$$\frac{48}{147.63} \times 2.05 = 0.67$$

Total 15.57

The values of C_z given above are only applicable to runs after Run No. 8. The reason for this will be explained in Section 7.

7. Results.

All of the results obtained to date are exhibited in Table II. The early results (Runs 1 to 8 incl.) are very unreliable due to various causes which will be discussed below. Those of Runs 11, 13 and 14, however, are thought to be quite reliable, especially the ones of elements of higher atomic number than 30 (zinc). As noted before, these results have <u>not</u> been corrected for the scattered radiation present in the fluorescent beams. This correction may become large in the case of radiators far removed from barium, which was the primary radiator in all runs after No. 5. For this reason, greatest weight is attached to the following results, taken from Runs 13 and 14.

Element & No.	$\frac{\delta-1}{\delta}$	μ'	μ''	$\frac{\mu'+\mu''}{\mu'}$	λ''	$\frac{\lambda''}{\lambda'}$	f''	$\frac{f'}{f''}$	C_z
27 Co	0.886	7.0	61	9.72	1.77	4.68	1.00	0.0754	6.58
28 Ni	84	7.7	54	8.01	1.63	4.32	.99	.0760	5.04
29 Cu	82	8.8	49	6.57	1.51	4.00	.98	.0768	3.88
30 Zn	80	9.9	47	5.76	1.41	3.73	.96	.0782	3.24
33 As	74	12.7	37.3	3.94	1.16	3.06	.85	.0882	2.07
34 Se	72	13.9	34.0	3.45	1.09	2.87	.78	.0962	1.85
38 Sr CO_3	65	-	-	2.38	0.859	2.27	.52	.144	1.53
42 Mo	58	23.0	18.7	1.81	.696	1.84	.345	.217	1.43
47 Ag	50	31.0	12.6	1.41	.549	1.45	.205	.366	1.49
48 Cd	49	31.9	11.7	1.37	.525	1.39	.178	.406	1.54
50 Sn	47	34.5	10.0	1.29	.482	1.28	.155	.484	1.60
51 Sb	44	36.5	9.4	1.26	.462	1.22	.140	.536	1.66
52 Te	43	38.2	8.4	1.22	.443	1.17	.125	.600	1.73
56 Ba	-	-	-	-	.378	-	.075	-	-

Values of W

Table No. 2

Element & No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
27 Co					-	-	-	-						0.38
28 Ni					-	0.90	.61	-						.39
29 Cn					0.48	.29	.56	0.33						.43
30 Zn	0.49	0.31	-	-	0.50	.28	.52	.44						.46
33 As			0.46	0.64	0.46	.72	-	-						.53
34 Se			-	-	-	.84	.59	.51						.56
38 Sr					-	-	-	-			0.71		0.72	
42 Mo					.52	.87	.78	.78			.80		.78	
47 Ag					0.50	.56	.75	.67			-		.73	
48 Cd					0.44	.45	.65	.64					.72	
50 Sn					- -	(.73 .63	.66	..67					.67	
51 SB					- -	.69	.63	.59					.64	
52 Te					-	.61	.58	.58					.60	

This run was a determination of the fractions absorbed in the front chamber. See text.

Continuation of Run 9.

Continuation of Run 9 and 10

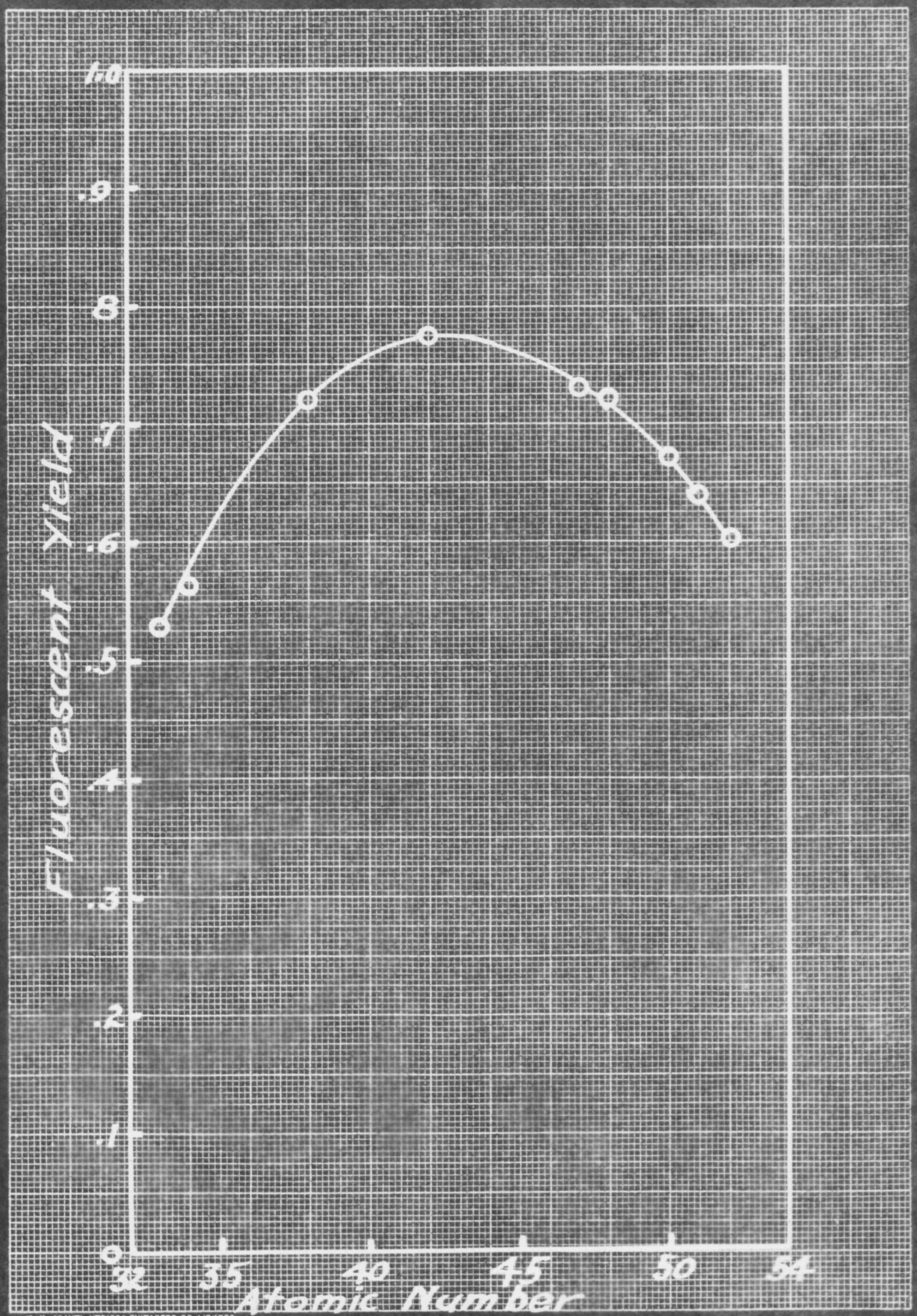

Fluorescent Yield
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
32
35
40
45
50
54
Atomic Number

Fig. 30

Element	w	Element	w
33 Arsenic	0.53	48 Cadmium	0.72
34 Selenium	.56	50 Tin	.67
38 Strontuim	.72	51 Antimony	.64
42 Molybdenum	.78	52 Tellurium	.60
47 Silver	.73		

These values of w are plotted in Figures 30 and 31. This shows that there is a pronounced maximum in the fluorescent yield in the neighborhood of molybdenum. The conclusion is, therefore, that the fluorescent yield does not continuously increase with increase of atomic number, but decreases for the heavy elements. This is in accordance with the prediction made by Dr. S.J.M. Allen in the spring of 1930.

A graph of all the results obtained in Runs 13 and 14 is shown in Figure 31. It will be seen that the slope of the curve is not so great for the elements cobalt (27), nickel (28), copper (29), and zinc (30), as it is for the higher elements. This may be real, or it may be due, as previously noted, to the neglect of the scattered radiation.

The reasons for assigning no weight to the results of Runs 1 to 8, inclusive, are as follows:

1. In these runs, a thick celluloid window was used on the front of the first ionization-chamber. As the

Fluorescent Yield
Atomic Number
Fig. 31
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absorption coefficients of celluloid are not known with much certainty, this introduced a correction factor of unknown magnitude. This was estimated, but probably not with much success. This probably accounts for the very high results obtained for nickel in Runs 6 and 7.

2. An effort was made in these early runs to use argon in the chamber at an absolute pressure of two to three atmospheres. This introduced a possibility of error due to inaccuracy of the pressure gauge, which was not of a precision type. Also the chamber leaked, and it was not possible to keep the pressure absolutely constant during a run.

3. In these runs the outer wall of the chamber was grounded, while the inner shell was raised to a potential of 180 volts by means of "B" batteries. Any ions formed by the X-rays in the space between the outer window and the inner shell had the opportunity of migrating to the grounded outer shell rather than to the inner collector-wire. The number of these lost ions cannot be well estimated, but may have reached a considerable magnitude, since the argon was used under pressure. In the later runs this inner shell was dispensed with, and the outer shell attached to the batteries, thus eliminating this source of error.

RUN #13

April 29, 1932

Ratios of Intensities of Direct & Fluorescent Beams

R_1 = Ba 60kv 34 ma #3 & #6 Diaphrams

Trial of Large (#6) Diaphram. Use Values of C_Z on p. 179.

D mm	t sec	i mm/sec	i corr.	i″/i1	w	Remarks
10	87.2	0.115	–	–	–	→ beam, nat. Leak
100	7.2 7.2 7.2	13.9	13.8	–	–	→ beam
100	10.6 10.2 10.6 9.8 10.2	9.71	9.64	0.698	0.520	⌟ Te
100	~~9.4~~ 9.2 9.2 9.2	10.9	9.80	0.710	0.506	⌟ Sb
100	7.2	13.9	13.8	–	–	→ beam
10	106.0	0.094	–	–	–	→ beam nat. Leak
10	153.0	0.065	–	–	–	⌟ nat. Leak
Change Back to #1 instead of #6 Diaphram use Values of C_Z on p. 167						
100	~~21.2~~ 20.4 20.6	4.88	4.81	0.349	0.602	⌟ Te
Continue to use #1 (small) diaphram. No doubt rays can strike walls of chamber when using #6.						
100	7.2 ~~7.4~~ 7.2	13.9	13.8	–	–	→ beam
10	74.0	0.135	–	–	–	→ beam nat. Leak
10	106.8	0.094	–	–	–	⌟ nat. Leak
100	18.4 18.6 18.4	5.41	5.32	0.386	0.639	⌟ Sb

Remainder of Run Not Reproduced Here.

Fig. 32

A sample page of the original data on Run 13 is shown in Figure 32. This shows the consistency obtained in the ionization readings. It also shows the effect of using such a large diaphram (No. 6) that the rays could strike the walls of the chamber.

Finally, Figure 33 shows the results of Runs 13 and 14 plotted in comparison with those of other workers in this same field. There is only one point on this curve that definitely disagrees with the conclusions reached by the author. That is the one deduced by Martin from the work of Barkla and Beatty on iodine. Not much weight can be given this point, however, since the original data were not taken for the purpose of investigating fluorescent yields.

8. Summary.

The fluorescent yield w of K-shell X-rays has been measured for thirteen elements, five of which had never been measured before. Of the ones that had been measured before, several were only rough approximations. [27]

27) For a discussion of the merits of various measurements of w, see Compton's article, footnote No. 1.

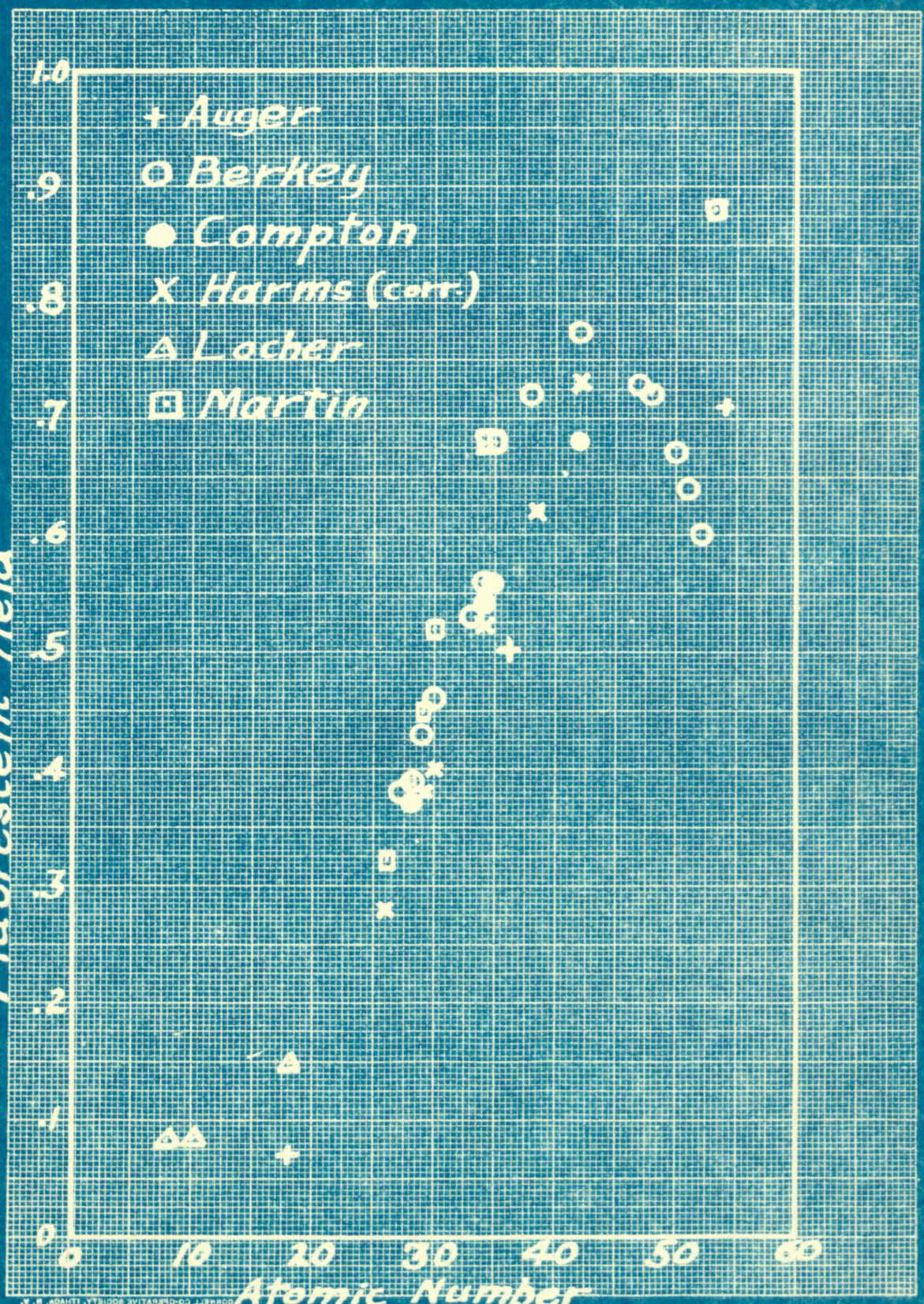
+ Auger
○ Berkey
● Compton
X Harms (corr.)
△ Lacher
□ Martin
Fluorescent Yield
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0
10
20
30
40
50
60
Atomic Number

Fig. 33

This investigation shows that the fluorescent yield increases with atomic number up to molybdenum, beyond which it declines. In no case does the yield approach unity. This gives added confirmation to the theory of the compound photoelectric effect propounded by Auger.

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