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M.Sc. Physics

THE STOPPING POWER FOR SECONDARY ELECTRONS FROM Co^{60} IN LIGHT ELEMENTS

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A thesis presented to the Faculty of Graduate Studies and Research in partial fulfillment for the degree of Master of Science.

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PREFACE

It is well known that the current per unit volume from small gamma ray ionization chambers made of light elements is inversely proportional to the stopping power per electron of the element for the secondary electrons of the gamma rays. In many elements, stopping powers of electrons due to radium gamma rays have been measured using methods based on this fact. Radioactive isotopes with a great range of gamma ray energy energies are now available, and it should be possible to measure the variation with energy of the stopping power for the secondary electrons in the same way.

The measurements described in this paper were made using the gamma rays of Co^{60} and ionization chambers of graphite, magnesium, aluminium and calcium.

The currents were measured using an FP 54 electrometer circuit due to Dubridge (11), modified to use a Townsend balance condenser. This particular circuit was chosen as the author had gained experience in its use while working at the Chalk River Laboratories of the National Research Council. All machine work necessary to the construction of the apparatus was done by the writer.

This work was done with the financial assistance of a National Research Council Studentship.

The writer gratefully acknowledges the assistance and advice of Mr. S. Doig with regard to the machine work. He is also indebted to Dr. H.G.I. Watson and Mr. R.K. Eadie for measuring the Townsend balance condenser, and to Mr. J.J. Mathison for pictures of the apparatus and photographic copies of the figures. Mr. J. Dainty, formerly of the National Research Council, Chalk River, suggested the problem, and Dr. J.S. Foster gave invaluable advice and encouragement. The thesis was typed by Mrs. F.S.Eadie.

INTRODUCTION

This paper describes measurements of ionization currents, due to gamma rays of Co^{60}, which pass through small aluminium, graphite, magnesium and calcium ionization chambers. From these measurements the relative stopping powers of these elements for the secondary electrons of the gamma rays have been deduced.

The measurements are in a sense preliminary, since they are intended to reveal the accuracy of the method and the feasibility of extending the measurements over a wide range of gamma ray energies. Under favourable conditions, the variation of stopping power for secondary electrons with energies ranging from 0.1 Mev to 5 Mev might then be examined.

measurements of [illegible] independent [illegible] [illegible] fully [illegible]

The method is based upon the fact that if a small cavity in an "infinite" homogeneous medium is irradiated with gamma rays, the distribution of electrons within the cavity is identical with the distribution in the medium before the introduction of the cavity. Bragg (1) first used this fact to estimate the relative stopping power of various elements for β -rays in 1910. Fricke and Glasser (2)(3) recognized and applied this fact to the problem of X-ray and radium dosimetry in 1925. Independently Gray (4)(5) in 1936, measured the variation of stopping power in elements with atomic numbers from one to twenty-nine, for secondary electrons of radium gamma rays. He showed that this variation agreed fairly well with that deduced from the theoretical predictions of Bethe (6).

This subject is of wide interest to workers in medical radiology, as it is from such measurements that the correct biological dose of gamma rays, hard X-rays and fast neutrons is obtained.

THEORY

Consider the ionization per cc. in a small air-filled cavity in an infinite homogeneous medium.

Let J_v be the ionization per unit volume in the cavity.

N the number of β-particles per cm^2. crossing the cavity and the medium.

$(\frac{dE}{dx})_a$ the energy loss per cm. by the β-particles in air.

$(\frac{dE}{dx})_m$ the energy loss per cm. by the β-particles in the medium.

E_v the energy absorbed per unit volume of the medium.

W the energy required to form an ion pair.

f the flux of gamma rays in quanta per cm^2/sec.

${}_e\sigma_a$ the Compton scattering cross section per electron of the medium for gamma rays of Co^{60}.

Then

$$J_v = \frac{N \cdot (\frac{dE}{dx})_a}{W}$$

$$E_v = N \cdot (\frac{dE}{dx})_m$$

$$\therefore \quad E_v = \frac{J_v \, W (\frac{dE}{dx})_m}{(\frac{dE}{dx})_a} = J_v \, W \rho$$

This is the Bragg-Gray Relation

$$\text{where} \quad \rho = \frac{(\frac{dE}{dx})_m}{(\frac{dE}{dx})_a}$$

Two assumptions are made in reducing E_v to this form.

a) The distribution of electrons in the medium is unaffected by the presence of the cavity. This is true if the atomic number of the medium is not very different from that of air and if the energy lost by electrons in crossing the cavity is small.

i.e. atomic
nos.

b) The ionization due to absorption of gamma rays in the air is small.

For ~~mediums~~ media of different atomic number

$$E_v = N_z \, E f \, ({}_e\sigma_a + \tau)$$ absorption Coeff

where τ is the photoelectric crossection, N_z is the number of electrons per unit volume of the medium, and E is the energy of the gamma rays.

If τ is small, as for elements of low atomic number,

$$\rho J_v W = N_z \, E \, f({}_e\sigma_a)$$

$$\therefore \quad J_v = \frac{N_z K}{\rho} \quad \text{where K is constant.}$$

Now ρ is the relative stopping power of the medium with respect to air. Therefore, if S_e is the relative stopping power per electron of the medium,

$$J_v = \frac{K}{S_e}$$

Gray has shown that the variation in S_e with atomic number, for secondary electrons from radium gamma rays, agrees well with that predicted by Bethe (6) when arrived at in this way. It is pointed out by Laurence (7) that Bloch's theory (8) of the rate of loss of energy of β-rays, although not as satisfactory theoretically as that of Bethe, is in better agreement with the experimental values arrived at by White and Millington (9) using another method.

EXPERIMENTAL WORK

I General

Photographs of the apparatus are shown in Fig. 1 and Fig. 2. These show the position of the source and ionization chamber with respect to the walls of the room and the rest of the apparatus.

The ion chamber and source were placed at a maximum distance from scattering material.

The source, enclosed in a brass capsule with walls 1/16" thick, was held in a cup in the end of an aluminium rod 1/2" in diameter. This was supported by the iron stand shown in Fig. 1, approximately 90 cm. from the floor.

II Ionization Chambers

The medium with the small air cavity consists of an ionization chamber of volume approximately 10 cc. It was estimated that the ionization due to absorption of gamma rays in the air of the cavity would be only 2% of the total ionization. As the atomic numbers of the media mediums (graphite, magnesium, aluminium and calcium) were low, this volume would satisfy the theoretical requirements. It was desirable to have such a volume for the following experimental reasons:

1) Easily measured currents of the order of 10^{-13} amp. could be obtained by using approximately 100 mc. of Co^{60} at distances which could be measured with an error of less than 1%.

2) Dead space, due to collection of ions by the guard ring of the ionization chamber, is practically independent of the size of the chamber. It is difficult to estimate the volume of this dead space and to apply the correction to the total volume. A correction of 0.06 cc. was made to the measured volumes of the ionization chambers for this effect. This was approximately equal to the error in measuring the volumes.

3) The volume of the ionization chamber could be measured to an accuracy of better than 1% by filling with a liquid and weighing.

The design of the ionization chambers, and ~~with~~ the [illegible] source position, is shown in Fig. 3. The walls of all four chambers were equivalent to 3 mm. of graphite in surface density, giving the same gamma ray absorption in each. Mayneord (10) has shown that the ionization increases

60
all
very
[illegible]

with wall thickness in graphite ion chambers of this size to a flat maximum at 3 mm. wall thickness and then decreases slowly. He made a 2% correction to the ionization current for absorption of the gamma rays of radium in graphite ion chambers of 3 mm. wall thickness.

[illegible]

The thicknesses of the walls of the ionization chambers were:

Graphite		0.125 in.
Aluminium		0.125 in.
Magnesium		0.188 in.
Calcium	1)	0.235 in.
	2)	0.301 in. sides 0.288 in. wall facing source.

Two thicknesses are given for the calcium ionization chamber, as a coating of calcium nitride formed on the surface. One series of measurements was first made with the ion chamber, then a fresh calcium surface was obtained by reboring the chamber for the second series. The thickness of the wall facing the source was not altered appreciably and no serious difference would be expected in results for the two series of measurements.

[illegible] ?

The volumes of the aluminium and magnesium ionization chambers were obtained by filling with water and weighing. For the calcium ion chamber oil was used, and for the graphite chamber mercury. The density of the oil was measured by using a specific gravity bottle and comparing the weight with that of distilled water. All densities were corrected for temperature.

[illegible]

An aluminium collecting electrode weighing 0.9 gm. was used for all the ion chambers. It was estimated that not more than 2% of the ionization was due to this electrode, which would give a negligible correction to the total ion current. The density of the aluminium was obtained by measuring the volume and weighing a cylinder of the aluminium stock from which the electrode was made. The volume of the electrode was then found by weighing and calculating from the density.

All the ionization chambers, except the one of aluminium, were changed slightly in volume after a complete set of measurements on all the chambers had been made. This was done by trimming down the end at which the chamber was supported, as shown in Fig. 3. This change in volume, amounting to 0.25 cc., was made to see if any significant change would be made in the dead space. None was observed.

The distance of the geometrical centre of the ionization chamber from the back wall of the chamber was compared with the distance of the point, from the back wall, which gave the average of gamma ray intensities at the front and back walls. These points coincided for a source distance of 60 cm. but the latter point moved 0.1 cm. towards the source for a source distance of 40 cm. These calculations do not take into account the fact that the Compton electrons are scattered mainly in the forward direction, but indicate that the error in taking the geometrical centre of the ionization chamber as its centre cannot be greater than 0.1 cm. at a source distance of 60 cm.

The details of construction of the guard ring and central electrode insulator are shown in Fig. 3. This insulator was carefully machined to give a clean surface of high insulation and was then waxed into position. What [illegible]

Measurements of room temperature were taken on a mercury thermometer, and the barometric pressure was obtained from the McGill University Observatory.

III Electrometer Circuit

The ionization current was measured using the Townsend balance method in conjunction with an FP 54 electrometer tube circuit due to Dubridge (11). The complete circuit is shown in Fig. 4. The circuit was so designed that effects due to battery drift and filament emission were minimized. The electrometer tube, with the Townsend balance condenser, was contained in an evacuated a vacuum box to eliminate ionization currents other than that from the ionization chamber. Leads for the electrodes other than that to the control grid were brought in through wax seals. The pressure in the vacuum box was maintained at less than 1 mm. Hg while measurements were taken.

The balance condenser was of the cylindrical type and was mounted directly above the electrometer tube with the central + d electrode making contact with the grid cap. The condenser insulation was made of polystyrene and a resistance of at least 10^{16} ohms was achieved by using clean machined surfaces. The grid electrode and w.h.p. its insulator were prevented from "seeing" other insulators by guard rings.

The earthing switch was mounted on top of the condenser and ? was let into the vacuum by an O-Ring seal. The contacts were totally enclosed to prevent fields present on opening the switch from affecting the insulators in the grid circuit and thus causing the ? galvanometer ~~to jump~~. deflection to be erratic.

The calculated capacity of the condenser was 9.7×10^{-12} farads. The measured value of $10.54 \pm 0.02 \times 10^{-12}$ farads was found by comparison with a standard condenser, calibrated by the Bell Telephone Laboratories, at the Northern Electric Company, Montreal. This value was checked at the MacDonald Physics Laboratory.

The condenser was used with the central electrode and case kept at ground potential and was measured under the same conditions so that there would be no stray capacitance between the two. Thus the value of the condenser in use should agree with the value shown, within the accuracy stated.

IV Measurements

In use, the electrometer circuit is balanced with the galvanometer reading zero and the earthing switch closed. The earthing switch is opened, the galvanometer reading allowed to increase to a given value, and the timer started. The galvanometer reading is then brought to zero and kept at zero by varying the voltage on the balance condenser. When the voltage on the condenser has reached a known value the galvanometer reading is again allowed to increase to the former value and the timer stopped.

If the leakage current in the grid circuit is i_a, the ionization current is i_c, and i_1 is the total current, then

$$i_1 = i_c + i_a \quad = C\frac{dV}{dt_1} \qquad \ldots\ldots\ldots (1)$$

where C is the capacity of the balance condenser and dt is the time required to vary the voltage on the condenser an amount dV, while keeping the galvanometer reading at zero.

By reversing the voltage on the ionization chamber, i_c is reversed while i_a remains constant, so that

$$-i_c + i_a = -C\frac{dV}{dt_2}$$

Therefore,

$$i_c = \frac{C}{2}\left\{\frac{dV}{dt_1} + \frac{dV}{dt_2}\right\} \qquad \ldots\ldots\ldots (2)$$

$$i_a = \frac{C}{2}\left\{\frac{dV}{dt_1} - \frac{dV}{dt_2}\right\} \qquad \ldots\ldots\ldots (3)$$

Voltages of 1.0 to 1.5 volts to ground are used for "dV".

These were compared against an Eppley standard cell, using a Rubicon potentiometer giving an accuracy of at least 0.1%. The time "dt" was usually around 100 sec., as measured by a stop watch. These readings were compared with those of a standard clock and the error found to be negligible. The accuracy with which the stop watch could be read was 0.2 sec., giving an error of 0.2%.

The current "i_a" is mainly due to grid current in the FP54, which is between 5×10^{-16} and 2×10^{-15} amp. This estimate was made using Equation (2), Page 8, where i_c was of the order of 10^{-13} amp. This involved taking differences of currents 100 times greater than the grid current. If the grid current varies between these limits in one reading it would limit the accuracy of the results to 1%.. However, as readings taken with the voltage applied to the graphite ionization chamber in the sequence + - - + + - - +, and also in the sequence + + + + + - - - - -, are all consistent within themselves and with each other to within 0.5%, it is improbable that the grid current varies by this much.

All measurements were made with a reversible potential of 93 volts, applied to the outer electrode of the chamber from two 45 volt "B" batteries. As the ion chamber has a capacity of 2 uuf, a change of 1 volt in this voltage in 100 sec. would be equivalent to a current of

$$\frac{2 \times 10^{-12} \times 1}{100} = 2 \times 10^{-14} \text{ amp.}$$

This is equal to 20% of the ionization current.

Readings taken with the same polarity of voltage applied to the chamber are consistent within 2% among themselves, so that the variation in voltage is probably not more than 0.1 volts in 100 sec. This, however, is the factor that limits the accuracy with which the ion current can be measured.

In measuring currents from the calcium ionization chamber it was observed that the current decreased slowly over a period of several minutes after the voltage was reversed, and then became constant. This was attributed to the fact that the calcium nitride layer on the surface was a very poor conductor and slowly charged up to the maximum potential. This would affect the grid circuit in much the same way as the changing potential on the outer electrode, as described above. The variations in the current observed were of the order of 20%. This effect was not noticed in making measurements with any of the other ionization chambers.

RESULTS

The measurements made on the different ionization chambers are shown in Tables I to XIV. Each table shows a series of approximately 20 readings, made over a period of from one to two hours on one chamber. The mean result of each of these tables is summarized in Table XV.

In Tables I to XIV, "i_1" is the current calculated from the equation $i_1 = C\frac{dV}{dt_1}$ for positive or negative voltage on the ion chamber, shown under H.T. The current "i_c" is the ionization current from the chamber, corrected for grid current and calculated from the equation $i_c = \frac{C}{2}\left\{\frac{dV}{dt_1} + \frac{dV}{dt_2}\right\}$

All measurements were made in groups of from four to six readings. The voltage applied to the condenser is shown under "dV" and was measured to 1 part in 10^5 after each group of measurements. The variation in "dV" between measurements is 1 part in 10^4, so that a mean is taken between the two readings for any one group and is shown under "Mean dV".

Temperature readings were usually taken after each group of measurements and if the temperature varied by more than one degree a mean was taken for that group and the current corrected accordingly. All currents corrected to a temperature of 0°C are shown as such at the top of the column. If the temperatures did not vary appreciably the current was not corrected for temperature until the mean of the series was obtained.

The barometric pressure was obtained from the McGill Observatory before and after each series of 20 readings. In no case was the difference between the two readings more than 2 mm. of Hg. The mean of the two barometer readings is shown at the top of each table. The correction of the ionization currents to 760 mm. Hg is made to the mean of the readings of each series.

All currents were initially calculated on the basis that the Townsend balance condenser had a capacity of 10×10^{-12} farads. To obtain the true current a correction is applied to the mean of each series of results and the result titled "I", subscripted with the abbreviation for the element of which the ion chamber was made.

The volumes of the chambers shown are corrected for the volume of the central electrode, the supporting insulator, dead space and, in the case of the graphite chamber, for the meniscus of the mercury.

The column titled "d" shows the distance from the front face of the source to the back of the ion chamber.

The column titled "r" shows the distance from the centre of the source to the centre of the ion chamber, where the distance from the back to the centre of the chamber was calculated as described above.

The column "$r^2 I \times 10^{-10}$" shows the calculated current for the centre of the source at a distance of 1 cm. from the centre of the ion chamber. The column "J_v" shows the above current divided by the volume of the chamber.

Table I contains results of measurements made with varying voltage on the graphite ionization chamber. These are plotted in Fig. 4. The current varied by about 1% between 56 volts and 93 volts applied to the ion chamber. Clearly all but a negligible fraction of the ions formed in the chamber were being collected.

Table II shows the results of measuring the ion current from the graphite ion chamber when placed at varying distances from the source. These results are plotted against $1/r^2$ in Fig. 5. The mean slope of this curve is 6.07×10^{-10} amp. cm^2. This curve shows that taking the centre of the ionization chamber as the geometrical centre cannot be seriously in error.

Tables III to VI show measurements made with the aluminium ionization chamber. The volume of this chamber was not changed.

Tables VII and VIII show measurements made with the magnesium ionization chamber.

Tables IX and X show measurements made on the calcium ion chambers. To avoid the effect of the charging up of the insulating layer, no measurements were made until several minutes after reversing the voltage on the chamber. Each set of readings on this chamber was made over a period of two hours. In this time a noticeable layer of calcium nitride formed. In Table IX the results are those obtained with a calcium nitride layer on the surface; in Table X the results are those obtained with a freshly machined surface.

Tables XI to XIV show measurements made on the graphite ion chamber. Measurements were taken both with series of positive and then series of negative readings, and with positive and negative readings alternating. There were no serious discrepancies between measurements taken in the two different ways.

In Table XV the results for all measurements shown in Tables II to XIV are summarized. The ratios of the ionization observed in the different ionization chambers to that in the graphite chamber are shown in the column titled "$\frac{(J_v)}{(J_v)_{\text{Graphite}}}$", and plotted in Fig. 6.

DISCUSSION OF RESULTS

As the graphite ion chamber approximates fairly well to the air walled ionization chamber specified in the definition of the roentgen, it is possible to evaluate the intensity of the gamma radiation at 1 cm. from the source in roentgen units.

1 r/hr. gives 0.926×10^{-13} amp./cc.

$\therefore$ Intensity giving 6.07×10^{-13} amp./cc. = 666 r/hr.

The ratios of the ionization in the aluminium, magnesium and calcium chambers to that in the graphite chamber are respectively 1.05, 1.06 and 0.96. The values obtained for all chambers are consistent within themselves, and the ratios between ionization in the magnesium, aluminium and graphite chambers are in agreement with ratios obtained by Gray (4) and Mayneord (10) for these materials, using radium gamma rays. The value for calcium, however, is 10% low from what is expected by Bethe's formula. This may be due to the following reasons:

1) The calcium might absorb enough air to reduce the pressure in the ionization chamber.

2) The face of the ionization chamber opposite the source was not making good electrical contact with the rest of the chamber, so that the chamber was not saturated.

To test reason 1) the following experiment was carried out:

A freshly machined piece of calcium, weighing 10 gm. was allowed to stand for 24 hours, and it was found that it increased in weight by 12 mg. This piece had a surface area of about 10 cm^2. The ion chamber had an inner surface area of 24 cm^2. Therefore, the amount absorbed by the ion chamber in two hours would be approximately 2.3 mg. This corresponds to absorption of 2 cc. of air, which would reduce the pressure by 20%.

One would then expect a discrepancy of the order of 20% between the first and last readings taken in any series of measurements on the calcium ionization chamber. In the measurements shown in Table X there is a discrepancy of 1.5% between the very first and the very last reading taken on the calcium chamber. The largest difference between any readings in the initial and final groups is 2%. The front face of this ionization chamber was quite a loose fit, so that one would expect equilibrium to be maintained between the pressures inside and out.

Reason 2. seems the more likely, since the calcium nitride layer is a very good insulator and could easily form in the joins between the walls. If the front face was insulated from the rest of the chamber it would cause an increase in the dead space current to that face, which could easily amount to 20% of the total current.

To test the second reason measurements were made on the calcium ionization chamber with a separate high voltage connection to the front face. The current obtained from these measurements was compared with currents obtained from measurements on the graphite ionization chamber made at the same time. New measurements were made in the graphite chamber as the source had been removed from its capsule and might not have been replaced in the same position as it was for previous measurements. The results of these measurements are shown in Table XVI.

From the results shown in Table XVI it would seem that the second reason is correct, as J_v for the calcium ionization chamber has increased from 5.83×10^{-11} amp. to 6.55×10^{-11} amp. It was also observed that the effect of the changing current with time was much reduced. It would seem, therefore, that the front face of the ion chamber charged up slowly through the highly insulating calcium nitride layer to some fixed potential. This would cause the variation in the observed ionization current with time due to the varying charge induced on the collecting electrode. The potential at which equilibrium was reached must, however, have been such that the ionization chamber was not saturated.

This explanation could be tested by taking saturation curves with the front face of the chamber connected to the high potential only through the calcium nitride layer. These curves could be compared with saturation curves obtained with different measured voltages placed on the front face while the rest of the outer electrode is kept at a potential of 90 volts.

The new ratio $\frac{(J_v)}{(J_v)_{\text{Graphite}}}$ for the calcium ionization chamber obtained from the measurements shown in Table XVI is 1.11. Although not too much confidence can be placed in this last result it might be significant that this ratio for all the ion chambers measured falls below the curve calculated by Gray for the secondary electrons of radium gamma rays. The differences are of the order of 2%, which is within the accuracy of the measurements. These, however, could probably be improved so that the accumulative error is less than 1%.

The root mean square deviation of the ionization currents from the graphite, aluminium and magnesium ionization chambers is approximately 0.2% and for the calcium chamber approximately 0.4%. This would indicate that the accuracy of the measuring system is sufficient to detect variations of less than 1% in ionization currents due to gamma rays of different energy.

The accumulative error in J_v is approximately 1.5%, except for the calcium chamber, where it is approximately 3%. This is due to inaccuracies in measuring the volumes and distances from the source to the ionization chambers.

The error due to uncertainty in the distance from the source to the chamber could be reduced by taking many readings at different distances from source to chamber, as was done for the graphite chamber. It should be possible to reduce the error in r^2I'' to 0.5% using this method.

It is not possible to measure the volumes of ionization chambers of this size with an accuracy of better than 0.5% by filling with liquid. By accurately machining the chambers, as described by Mayneord (10), an accuracy of 0.1% can be achieved. Mayneord, in his precision work on the measurements of gamma rays of radium, makes no mention of dead space in his ionization chamber, which had a volume of 6.28 cc.

From the measurements that have been made on the gamma rays of Co^{60} it would seem that it is feasible to attempt to measure the variation of the stopping power of electrons with energy by this method. There are, however, several additional factors that should be investigated. These are:

1) Scattering of the gamma rays by surrounding objects. This probably would not increase the ion current by more than 0.5% and for the same geometry of source and chamber would not vary appreciably with energy.

2) Pair production would become important as the higher gamma ray energies were approached. This would make it necessary to investigate absorption of the gamma rays in the different ionization chambers to make them all equivalent in wall thickness.

3) The variation of ionization current with the size of the ionization chamber and with the pressure in the cavity should be studied to determine what size chamber would be necessary for the lowest energy of gamma ray used.

BIBLIOGRAPHY

(1) Bragg, W.H. Phil. Mag. 20, pp. 385-416. 1941.

(2) Fricke and Glasser. Am. Jour. Roentg., Vol. 13. p.453. 1925.

(3) Glasser and Fricke. Am. Jour. Roentg., Vol. 13. p.462. 1925.

(4) Gray, L.H. Proc. Roy. Soc. Vol.A 156, p.578. 1936.

(5) Gray, L.H. Brit. Jour. Radiology 10, pp. 600-612, 721-742. 1937.

(6) Bethe. Ann. Physik. Vol.5, p. 325, 1930.

(7) Laurence, G.C. Can. Jour. Research. A 15, pp. 67-68. 1937.

(8) Bloch, F.Z. Physik 81, pp. 363-373. 1933.

(9) White, P. and Millington, G. Proc. Roy. Society. A 120, pp. 701-726. 1928.

(10) Mayneord, W.V. Brit. Jour. Radiology 10, p.536. 1937.

(11) Dubridge, L.A. Rev. Sci. Inst. Vol. 4, P. 532. 1933.

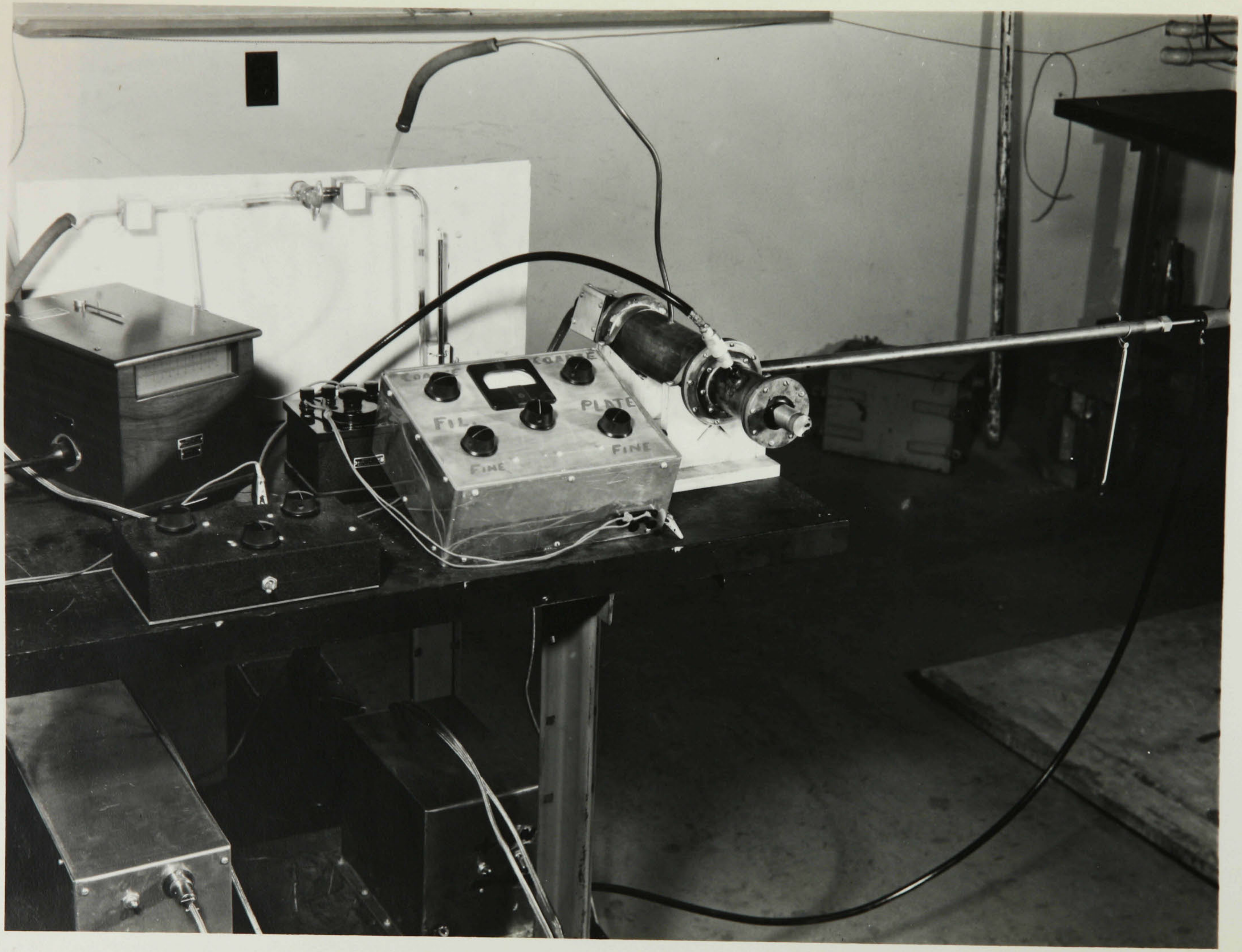
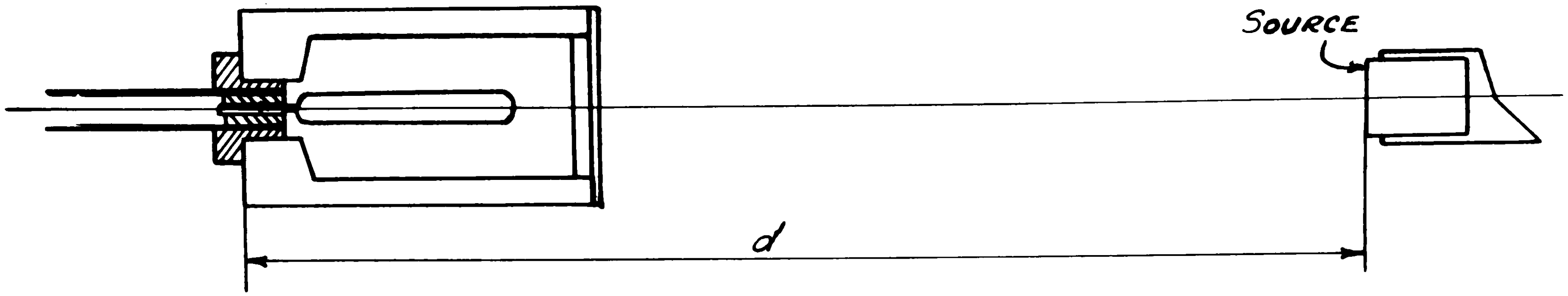
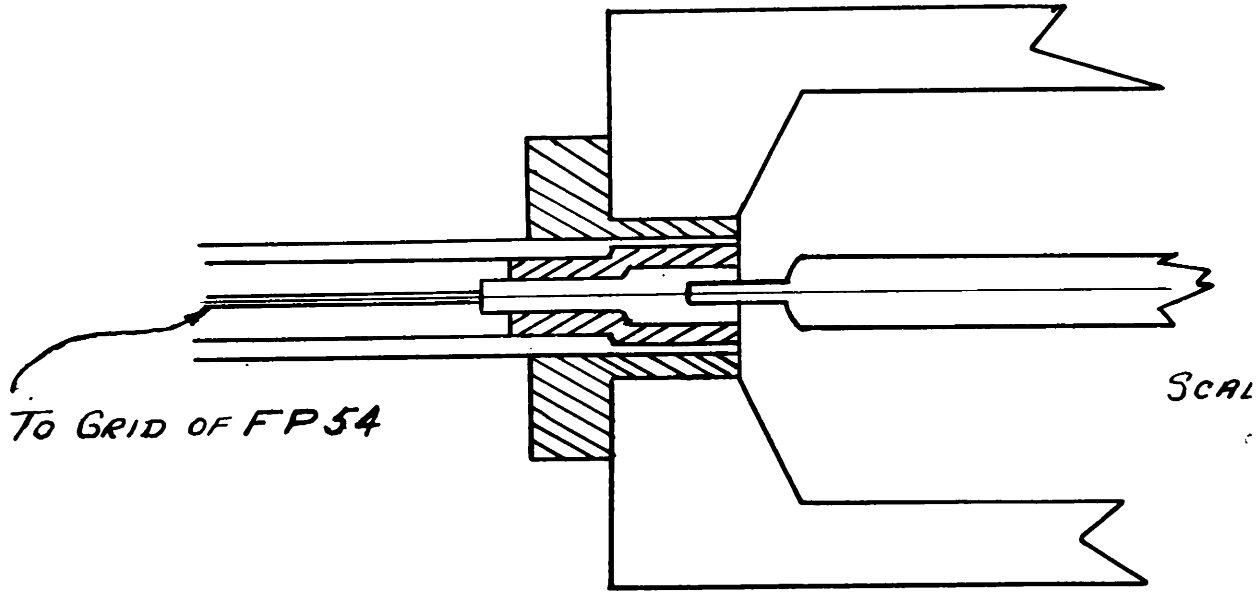


FIG. 1

FIG. 2

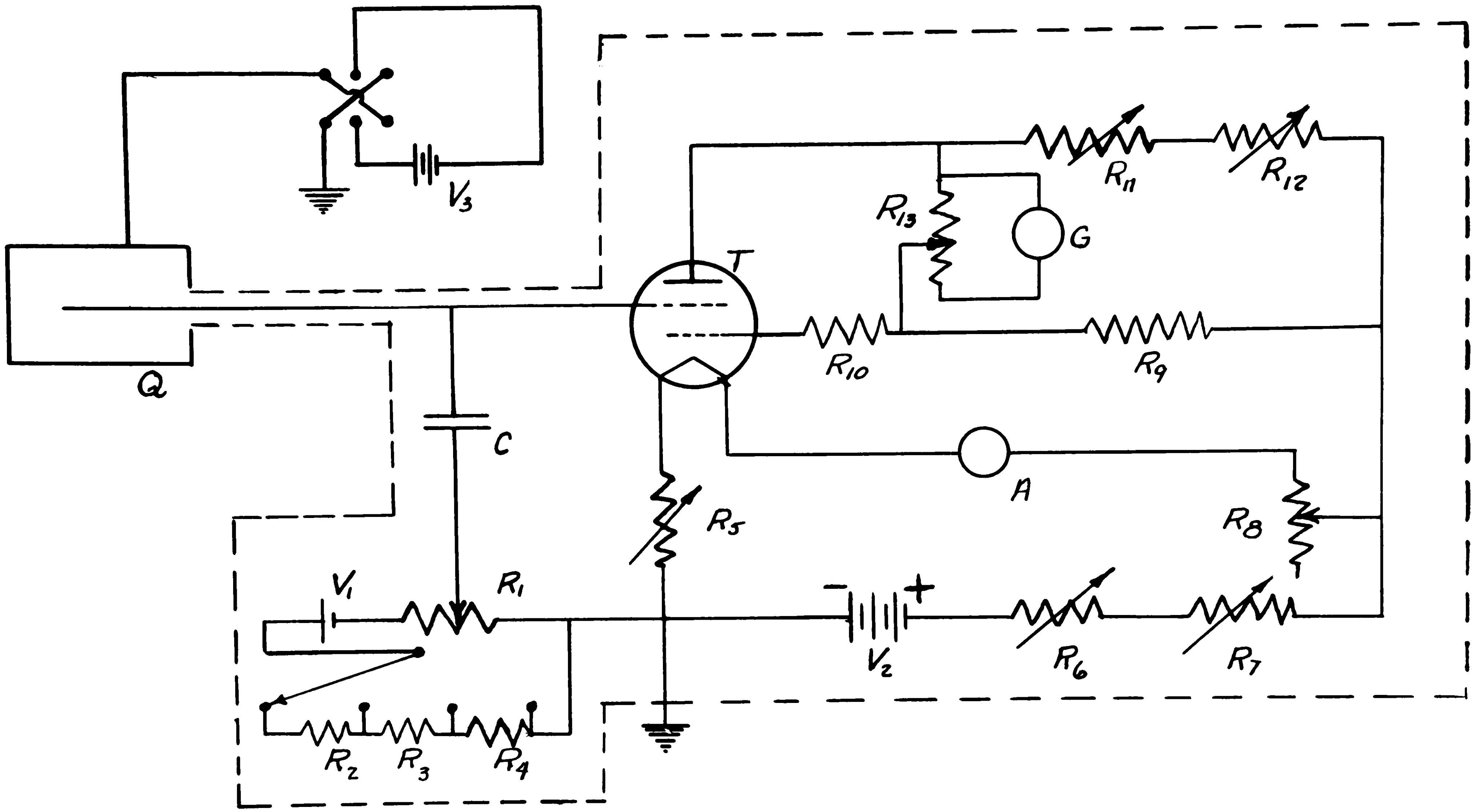


Section Through Ionization Chamber Showing Position Relative To That of Source



Enlarged Section of Ionization Chamber Showing Details of Guard Ring and Insulators.

Fig. 3



LEGEND ON PAGE 22a

ELECTROMETER CIRCUIT

FIG. 4

LEGEND FOR FIG. 4

R_1	Potentiometer to vary voltage on Townsend condenser.	R_8	100 ohms.
R_2		R_9	2000 ohms.
R_3		R_{10}	7000 ohms.
R_4		R_{11}	10,000 ohms.
R_5	100 ohms.	R_{12}	50 ohms
R_6	10 ohms.	R_{13}	Ayrton Shunt.
R_7	50 ohms.		

V_1	2 volt battery
V_2	12 volt battery
V_3	90 volt battery
T	FP 54 electrometer tube
A	100 micro-ampere ammeter
G	galvanometer; sensitivity 10^{-9} amp./mm.
C	Townsend balance condenser
Q	Ionization chamber

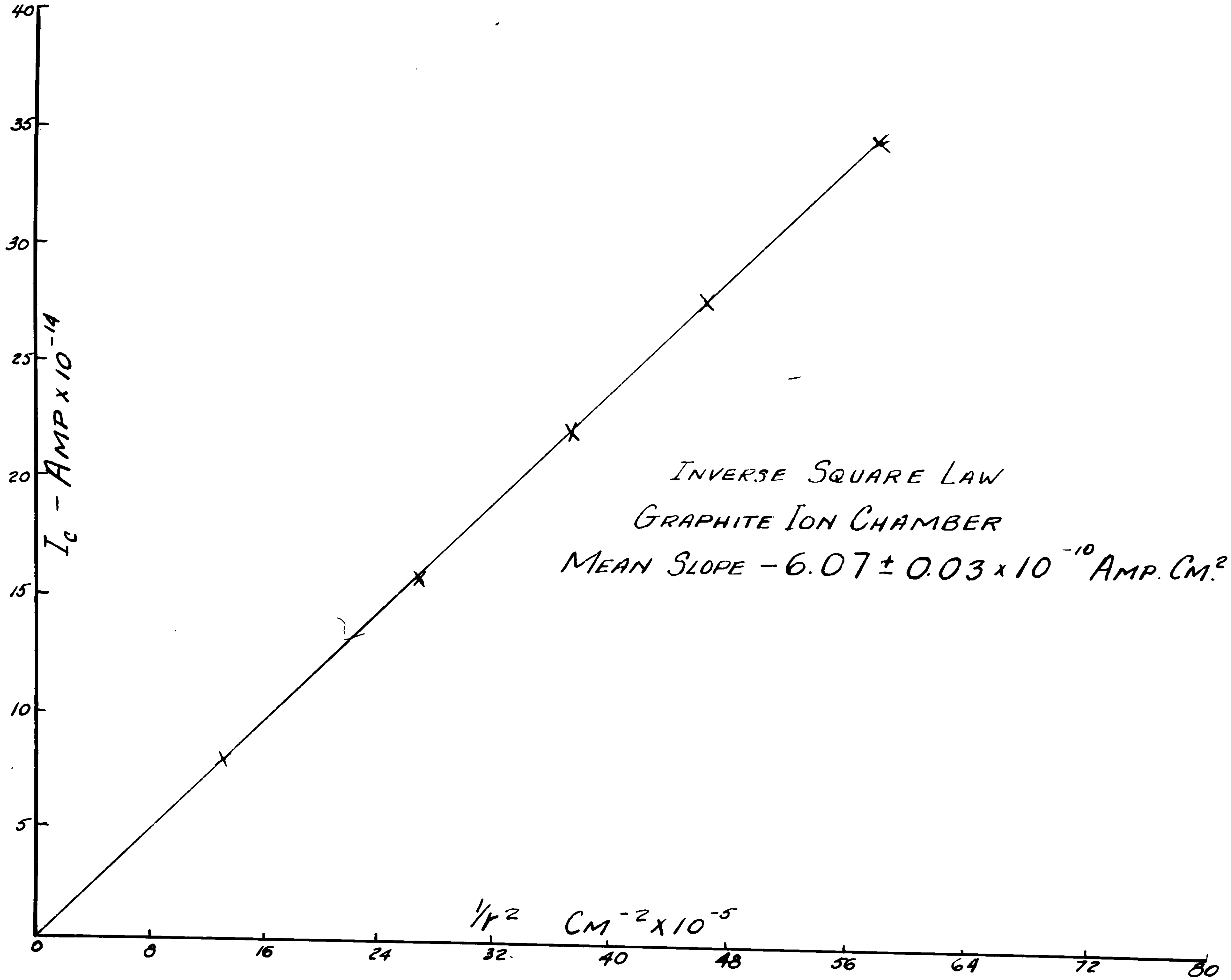

Inverse Square Law
Graphite Ion Chamber
Mean Slope – 6.07 ± 0.03 x 10^-10 Amp. Cm.^2
I_c – Amp x 10^-14
1/r^2 Cm^-2 x 10^-5
0
5
10
15
20
25
30
35
40
0
8
16
24
32
40
48
56
64
72
80

Fig 5

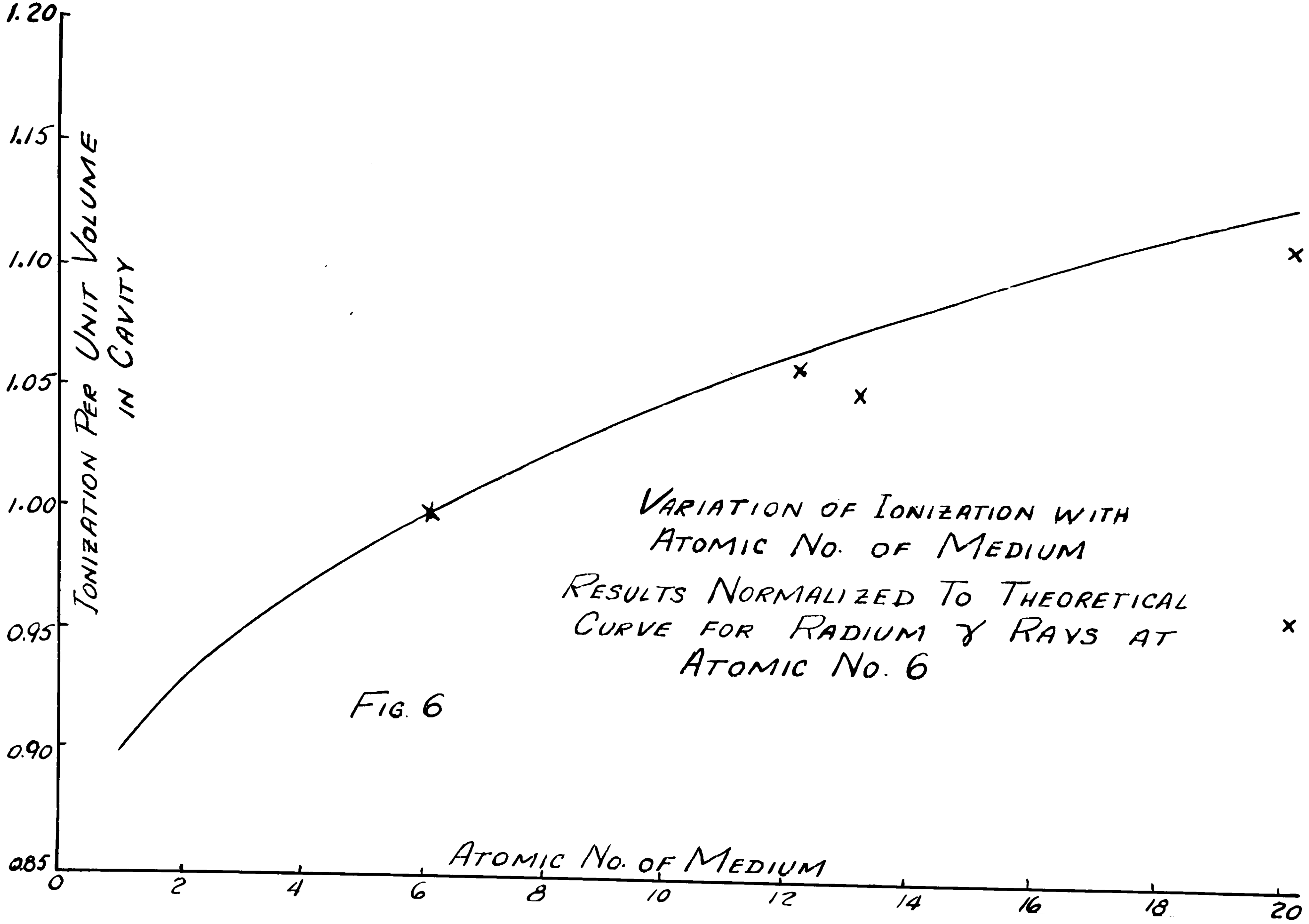
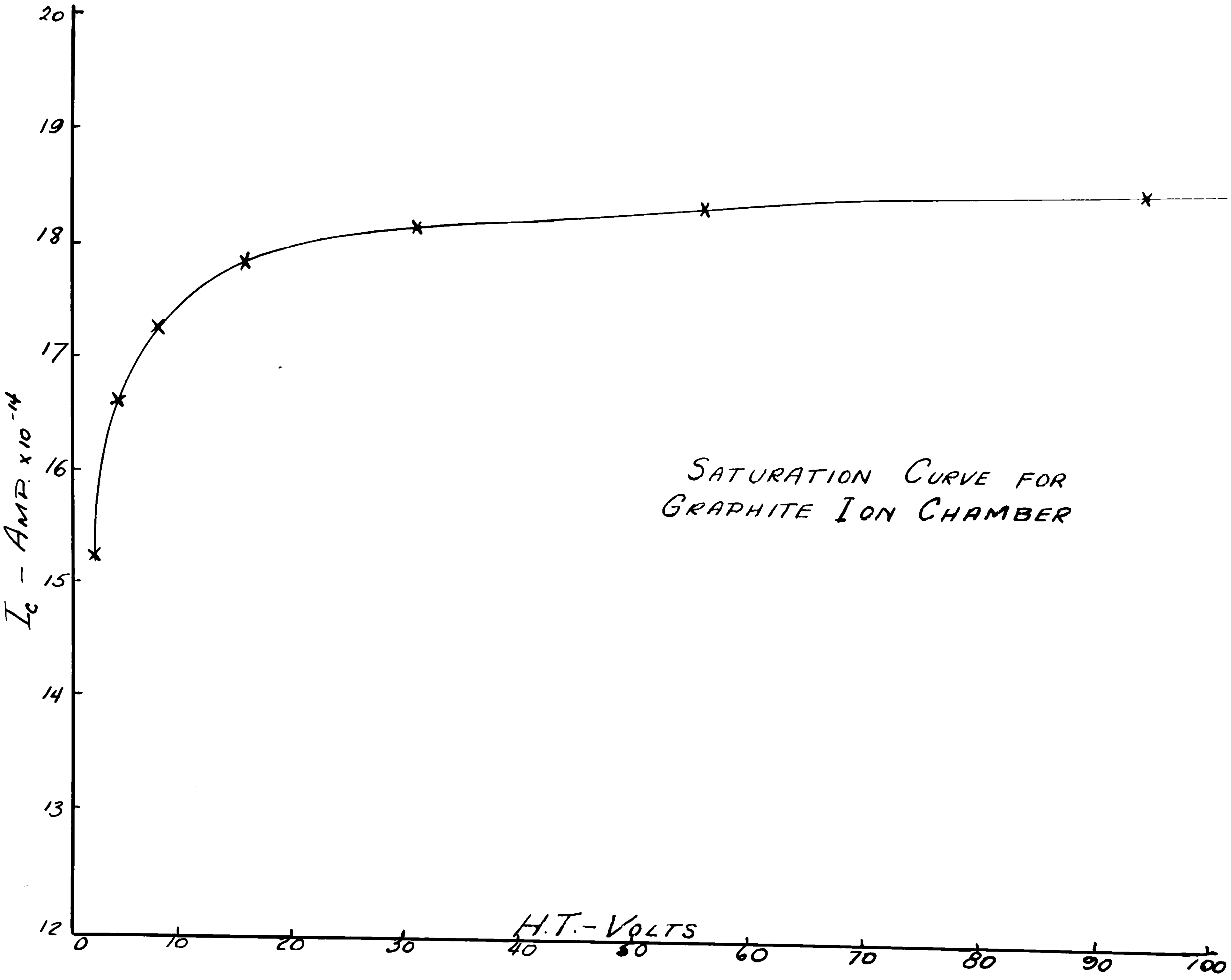

1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0
2
4
6
8
10
12
14
16
18
20
Ionization Per Unit Volume in Cavity
Atomic No. of Medium
Variation of Ionization with Atomic No. of Medium
Results Normalized To Theoretical Curve for Radium γ Rays at Atomic No. 6
Fig. 6

Fig. 6



SATURATION CURVE FOR
GRAPHITE ION CHAMBER

FIG. 7.

SATURATION CURVE FOR GRAPHITE ION CHAMBER

TABLE I

March 4, 1949.

Mean Bar. Pressure: 762.5 mm. Hg
Mean Temperature: 23.1°C
Distance from Centre of Source to Centre of Ion Chamber: 56.85 cm.
Volume of Ion Chamber: 9.94 cc.

	H.T. + - Volts	dV Volts	Mean dV Volts	dt Sec.	i_1 amp.x10^{-14}	Mean i_1 amp.x10^{-14}	i_c amp.x10^{-14}	i_c at 0°C 760 mm. Hg	I_C amp.x10^{-14}
1.	+ 93.0	1.5475	1.547	94.8	16.30				
2.	+ 93.0		1.547	94.6	16.33	16.32			
3.	+ 93.0		1.547	94.6	16.33		16.21	17.57 ± 0.02	18.51 ± 0.03
4.	- 93.0		1.547	95.6	16.18				
5.	- 93.0		1.547	96.2	16.06	16.10			
6.	- 93.0	1.5466	1.547	96.2	16.06				
7.	+ 55.0	1.5497	1.549	95.8	16.18				
8.	+ 55.0		1.549	95.6	16.20	16.17			
9.	+ 55.0		1.549	96.0	16.13		16.11	17.45 ± 0.02	18.40 ± 0.03
10.	- 55.0		1.549	96.4	16.08				
11.	- 55.0		1.549	96.8	16.04	16.05			
12.	- 55.0	1.5482	1.549	96.8	16.04				
13.	+ 30.0	1.5482	1.548	96.3	16.08				
14.	+ 30.0		1.548	97.0	15.95	16.03			
15.	+ 30.0		1.548	96.4	16.05				
16.	- 30.0		1.548	97.4	15.89		15.92	17.24 ± 0.02	18.19 ± 0.03
17.	- 30.0		1.548	98.0	15.79	15.81			
18.	- 30.0	1.5475	1.548	98.2	15.75				

(Cont'd.)

TABLE I (Cont'd.)

SATURATION CURVE FOR GRAPHITE ION CHAMBER

	H.T. + - Volts	dV Volts	Mean dV Volts	dt Sec.	i_1 amp.x10^{-14}	Mean i_1 amp.x10^{-14}	i_c amp.x10^{-14}	i_c at 0°C 760 mm. Hg	I_C amp.x10^{-14}
19.	+ 15.0	1.4717	1.471	93.3	15.78	15.76	15.66	16.95 ± 0.02	17.88 ± 0.03
20.	+ 15.0		1.471	93.2	15.79				
21.	+ 15.0		1.471	93.6	15.72				
22.	- 15.0		1.471	94.6	15.57	15.56			
23.	- 15.0		1.471	94.4	15.60				
24.	- 15.0	1.4705	1.471	94.8	15.53				
25.	- 7.4	1.5466	1.546	102.4	15.09	15.12	15.16	16.40 ± 0.02	17.30 ± 0.03
26.	- 7.4		1.546	102.0	15.15				
27.	- 7.4		1.546	102.2	15.12				
28.	+ 7.4		1.546	101.6	15.21	15.21			
29.	+ 7.4		1.546	101.6	15.21				
30.	+ 7.4		1.546	101.8	15.20				
31.	+ 4.0	1.5462	1.546	107.2	14.40	14.47	14.58	15.78 ± 0.02	16.63 ± 0.03
32.	+ 4.0		1.546	106.6	14.50				
33.	+ 4.0		1.546	106.6	14.50				
34.	- 4.0		1.546	105.2	14.69	14.69			
35.	- 4.0		1.546	105.1	14.70				
36.	- 4.0	1.5457	1.546	105.2	14.69				
37.	- 2.0	1.1003	1.100	78.3	14.06	14.07	13.39	14.49 ± 0.02	15.28 ± 0.03
38.	- 2.0		1.100	78.3	14.06				
39.	- 2.0		1.100	78.0	14.10				
40.	+ 2.0		1.100	86.7	12.69	12.72			
41.	+ 2.0		1.100	86.5	12.71				
42.	+ 2.0	1.1003	1.100	86.2	12.75				

TABLE II

INVERSE SQUARE LAW FOR GRAPHITE ION CHAMBER

March 4, 1949.

Mean Bar. Pressure: 762.5 mm. Hg
Mean Temperature: 22.0°C
Volume of Ion Chamber: 9.94 cc.

	d cm.	r	H.T. + -	dV Volts	Mean dV Volts	dt Sec.	i_1 at 0°C 760 mm. Hg amp.x10^{-14}	Mean i_1 amp.x10^{-14}	i_c amp.x10^{-14}	I_C amp.x10^{-14}	$\frac{1}{r^2}$ cm.$^{-2}$x10^{-5}
1.	53.61	52.2 ± 0.1	+	1.5578	1.557	80.4	20.95				
2.			+		1.557	80.3	20.96				
3.			+		1.557	80.3	20.96	20.96			
4.			-		1.557	80.8	20.81				
5.			-		1.557	80.7	20.82				
6.			-	1.5567	1.557	80.9	20.80	20.81	20.88 ± 0.03	22.00 ± 0.03	36.6 ± 0.2
7.	89.83	88.4 ± 0.1	+	0.9328	0.933	132.4	7.60				
8.			+	0.7439	0.744	105.2	7.63				
9.			+		0.744	105.3	7.61	7.62			
10.			-		0.744	108.6	7.39				
11.			-		0.744	108.8	7.38				
12.			-	0.7436	0.744	109.0	7.37	7.38	7.50 ± 0.03	7.91 ± 0.03	12.8 ± 0.2
13.	63.20	61.8 ± 0.1	+	1.1052	1.106	80.7	14.81				
14.			+		1.106	79.5	15.03				
15.			+		1.106	79.5	15.03	14.96			

INVERSE SQUARE LAW FOR GRAPHITE ION CHAMBER

TABLE II (Cont'd.)

	d. cm.	r	H.T. + -	dV Volts	Mean dV Volts	dt Sec.	i_1 at 0°C 760 mm. Hg amp.x10^{-14}	Mean i_1 amp.x10^{-14}	i_c amp.x10^{-14}	I_C amp.x10^{-14}	$\frac{1}{r^2}$ cm.$^{-2}$x10^{-5}
16.	63.20	61.8 ± 0.1	-	1.1052	1.106	80.3	14.89				
17.			-		1.106	81.0	14.75				
18.			-	1.1076	1.106	81.2	14.71	14.78	14.87 ± 0.03	15.67 ± 0.03	26.2 ± 0.2
19.	43.05	41.6 ± 0.1	+	1.5541	1.554	51.2	32.80				
20.			+		1.554	51.0	32.98				
21.			+		1.554	50.9	33.00	32.93			
22.			-		1.554	51.4	32.71				
23.			-		1.554	51.4	32.71				
24.			-		1.554	51.4	32.71	32.71	32.82 ± 0.03	34.61 ± 0.03	57.6 ± 0.2
25.	48.25	46.8 ± 0.1	+	1.5533	1.553	64.2	26.18				
26.			+		1.553	64.4	26.10				
27.			+		1.553	64.4	26.10	26.13			
28.			-		1.553	65.1	25.78				
29.			-		1.553	65.0	25.81				
30.			-	1.5533	1.553	65.1	25.78	25.79	25.96 ± 0.03	27.35 ± 0.03	45.7 ± 0.2

ALUMINIUM ION CHAMBER

TABLE III

February 5, 1949.
Mean Bar. Pressure: 764.6 mm.

	H.T. + -	Temp. °C	Mean Temp. °C	dV Volts	Mean dV Volts	dt Sec.	i_1 amp.x10^{-14}	i_c amp.x10^{-14}	i_c at 0°C amp.x10^{-14}
1.	+	24.0	23.9	1.5476	1.547	133.2	11.61		
2.	-		23.9		1.547	134.4	11.52	11.56	12.57
3.	-		23.9		1.547	135.2	11.44		
4.	+	23.8	23.9	1.5462	1.547	133.5	11.60	11.52	12.53
5.	+		23.7		1.546	133.1	11.61		
6.	-		23.7		1.546	135.1	11.44	11.52	12.55
7.	-		23.7		1.546	135.0	11.45		
8.	+	23.5	23.7	1.5453	1.546	133.2	11.61	11.53	12.54
9.	+		24.0		1.545	132.9	11.64		
10.	-		24.0		1.545	134.7	11.48	11.56	12.56
11.	-		24.0		1.545	135.2	11.42		
12.	+	24.5	24.0	1.5444	1.545	132.9	11.64	11.53	12.55
13.	+		24.5		1.544	133.2	11.60		
14.	-		24.5		1.544	134.9	11.46	11.53	12.60
15.	-		24.5		1.544	134.9	11.46		
16.	+	24.6	24.5	1.5439	1.544	133.6	11.57	11.51	12.58
17.	+		24.6		1.544	133.3	11.59		
18.	-		24.6		1.544	134.5	11.48	11.53	12.60
19.	-		24.6		1.544	135.1	11.43		
20.	+	24.7	24.6	1.5434	1.544	133.3	11.58	11.51	12.59

Mean i_c at 0°C amp.x10^{-14}	Mean i_c at 0°C and 760 mm. Hg amp.x10^{-14}	I_{Al} amp.x10^{-14}	Vol. cc.	d cm.	r cm.	r^2 cm^2.	$r^2 I_{Al}$ amp.x10^{-10}	J_v amp.x10^{-11}
12.57 ± 0.01	12.51 ± 0.01	13.20 ± 0.02	8.05 ± 0.05	63.30	62.1 ± 0.1	3854 ± 25.	5.08 ± 0.05	6.32 ± 0.10

TABLE IV

ALUMINIUM ION CHAMBER

February 7, 1949

Mean Bar. Pressure: 750.0 mm.

	H.T. + -	Temp. ^{o}C	Mean Temp. ^{o}C	dV Volts	Mean dV Volts	dt Sec.	i_1 amp.x10^{-14}	i_c amp.x10^{-14}	i_c at $0^{o}C$ amp.x10^{-14}
1.	+	23.9	23.7	1.5454	1.545	134.3	11.50		
2.	-		23.7		1.545	136.4	11.32	11.41	12.41
3.	-		23.7		1.545	136.2	11.35		
4.	+		23.7		1.545	133.8	11.56	11.46	12.45
5.	+	23.5	23.3	1.5439	1.543	133.8	11.54		
6.	-		23.3		1.543	136.7	11.29	11.42	12.41
7.	-		23.3		1.543	136.7	11.29		
8.	+		23.3		1.543	133.3	11.58	11.43	12.41
9.	+	23.0	24.0	1.5426	1.542	133.7	11.55		
10.	-		24.0		1.542	135.6	11.38	11.46	12.46
11.	-		24.0		1.542	137.0	11.27		
12.	+		24.0		1.542	133.3	11.58	11.43	12.42
13.	+	25.0	24.7	1.5414	1.541	134.2	11.49		
14.	-		24.7		1.541	135.7	11.38	11.43	12.47
15.	-		24.7		1.541	136.0	11.34		
16.	+		24.7		1.541	133.8	11.55	11.45	12.48
17.	+	24.5	25.2	1.5407	1.540	134.3	11.48		
18.	-		25.2		1.540	136.9	11.27	11.37	12.42
19.	-		25.2		1.540	137.6	11.20		
20.	+	26.0	25.2	1.5397	1.540	134.4	11.46	11.33	12.40

Mean i_c at $0^{o}C$ amp.x10^{-14}	Mean i_c at $0^{o}C$ and 760 mm. Hg amp.x10^{-14}	I_{Al} amp.x10^{-14}	Vol. cc.	d cm.	r cm.	r^2 cm^2.	$r^2 I_{Al}$ amp.x10^{-10}	J_v amp.x10^{-11}
12.43 ± 0.01	12.52 ± 0.01	13.21 ± 0.02	8.05 ± 0.05	63.30	62.1 ± 0.1	3854 ± 25.	5.10 ± 0.05	6.34 ± 0.10

ALUMINIUM ION CHAMBER

TABLE V

February 18, 1949.

Mean Bar. Pressure: 765.8 mm.

	H.T. + -	Temp. ^{o}C	Mean Temp. ^{o}C	dV Volts	Mean dV Volts	dt Sec.	i_1 amp.x10^{-14}	i_c amp.x10^{-14}	i_c at 0^{o}C amp.x10^{-14}
1.	+	25.0	24.7	1.5239	1.524	129.6	11.78		
2.	-		24.7		1.524	132.3	11.51	11.65	12.69
3.	-		24.7		1.524	132.5	11.50		
4.	+	24.5	24.7	1.5243	1.524	130.2	11.70	11.60	12.64
5.	+		24.6		1.524	130.1	11.72		
6.	-		24.6		1.524	132.4	11.50	11.61	12.65
7.	-		24.6		1.524	132.2	11.52		
8.	+		24.6		1.524	130.5	11.68	11.60	12.62
9.	+	24.8	24.9	1.5235	1.523	130.1	11.71		
10.	-		24.9		1.523	133.0	11.46	11.58	12.62
11.	-		24.9		1.523	133.0	11.46		
12.	+		24.9		1.523	130.0	11.72	11.59	12.63
13.	+	25.0	25.0	1.5220	1.521	129.9	11.72		
14.	-		25.0		1.521	132.2	11.51	11.61	12.69
15.	-		25.0		1.521	133.1	11.43		
16.	+	25.1	25.1	1.5209	1.520	130.3	11.68	11.56	12.62
17.	+		25.1		1.520	130.2	11.68		
18.	-		25.1		1.520	132.6	11.47	11.57	12.63
19.	-		25.1		1.520	133.3	11.48		
20.	+	25.1	25.1	1.5203	1.520	129.6	11.73	11.60	12.68

Mean i_c at 0^{o}C amp.x10^{-14}	Mean i_c at 0^{o}C and 760 mm. Hg amp.x10^{-14}	I_{Al} amp.x10^{-14}	Vol. cc.	d cm.	r cm.	r^2 cm^2.	$r^2 I_{Al}$ amp.x10^{-10}	J_v amp.x10^{-11}
12.65±0.01	12.55 ± 0.01	13.23 ± 0.02	8.05 ± 0.05	63.30	62.1 ± 0.1	3860 ± 25.	5.11 ± 0.05	6.35 ± 0.1

ALUMINIUM ION CHAMBER

TABLE VI

February 18, 1949.

Mean Bar. Pressure: 764.7 mm

	H.T. + -	Temp. °C	Mean Temp. °C	dV Volts	Mean dV Volts	dt Sec.	i_1 amp.x10^{-14}	i_c amp.x10^{-14}	i_c at 0°C amp.x10^{-14}
1.	+	24.8	25.0	1.5183	1.518	130.0	11.69		
2.	-		25.0		1.518	131.8	11.53	11.61	12.69
3.	-		25.0		1.518	132.3	11.47		
4.	+		25.0		1.518	129.2	11.75	11.61	12.70
5.	+	25.2	25.2	1.5178	1.517	130.0	11.68		
6.	-		25.2		1.517	131.4	11.54	11.61	12.70
7.	-		25.2		1.517	132.8	11.43		
8.	+		25.2		1.517	129.4	11.72	11.57	12.64
9.	+	25.2	25.2	1.5170	1.518	129.1	11.75		
10.	-		25.2		1.518	131.2	11.57	11.66	12.72
11.	-		25.2		1.518	131.1	11.48		
12.	+		25.2		1.518	129.4	11.72	11.60	12.69
13.	+	25.2	25.2	1.5193	1.519	129.8	11.70		
14.	-		25.2		1.519	131.6	11.55	11.62	12.70
15.	-		25.2		1.519	132.2	11.49		
16.	+		25.2		1.519	128.8	11.80	11.64	12.72
17.	+	25.2	25.2	1.5189	1.518	130.2	11.65		
18.	-		25.2		1.518	131.5	11.53	11.59	12.68
19.	-		25.2		1.518	132.7	11.42		
20.	+	25.2	25.2	1.5179	1.518	128.8	11.78	11.60	12.69

Mean i_c at 0°C amp.x10^{-14}	Mean i_c at 0°C and 760 mm. Hg amp.x10^{-14}	I_{Al} amp.x10^{-14}	Vol. cc.	d cm.	r cm.	r^2 cm^2.	r^2I_{Al} amp.x10^{-10}	J_v amp.x10^{-11}
12.69 ± 0.01	12.62 ± 0.01	13.32 ± 0.02	8.05 ± 0.05	63.30	63.1 ± 0.1	3860 ± 25.	5.15 ± 0.05	6.39 ± 0.10

MAGNESIUM ION CHAMBER

TABLE VII

February 5, 1949.

Mean Bar. Pressure: 765.0 mm. Hg

	H.T. + -	Temp. ^{o}C	Mean Temp. ^{o}C	dV Volts	Mean dV Volts	dt Sec.	i_1 amp.x10^{-14}	i_c amp.x10^{-14}	i_c at $0^{o}C$ amp.x10^{-14}
1.	+	25.1	25.1	1.5484	1.547	109.0	14.20		
2.	-		25.1		1.547	110.0	14.08	14.14	15.48
3.	-		25.1		1.547	109.6	14.13		
4.	+		25.1		1.547	108.3	14.29	14.21	15.53
5.	+	25.0	25.0	1.5460	1.546	108.0	14.31		
6.	-		25.0		1.546	109.3	14.15	14.23	15.56
7.	-		25.0		1.546	109.0	14.19		
8.	+		25.0		1.546	108.2	14.28	14.23	15.56
9.	+	25.0	25.0	1.5449	1.545	108.1	14.30		
10.	-		25.0		1.545	109.2	14.15	14.22	15.55
11.	-		25.0		1.545	109.3	14.13		
12.	+		25.0		1.545	107.8	14.35	14.24	15.57
13.	+	25.0	24.9	1.5441	1.544	107.7	14.35		
14.	-		24.9		1.544	109.2	14.13	14.24	15.54
15.	-		24.9		1.544	109.3	14.12		
16.	+		24.9		1.544	107.3	14.39	14.25	15.55
17.	+	24.8	24.8	1.5435	1.543	107.3	14.39		
18.	-		24.8		1.543	109.0	14.17	14.28	15.56
19.	-		24.8		1.543	109.3	14.12		
20.	+	24.8	24.8		1.543	107.1	14.41	14.26	15.54

Mean i_c at $0^{o}C$ amp.x10^{-14}	Mean i_c at $0^{o}C$ and 760 mm. Hg amp.x10^{-14}	I_{Mg} amp.x10^{-14}	Vol. cc.	d cm.	r cm.	r^2 cm^2.	$r^2 I_{Mg}$ amp.x10^{-10}	J_v amp.x10^{-11}
15.54 ± 0.01	15.44 ± 0.01	16.29 ± 0.02	9.66 ± 0.05	63.30	61.7 ± 0.1	3802 ± 25.	6.19 ± 0.05	6.41 ± 0.10

MAGNESIUM ION CHAMBER

TABLE VIII

February 19, 1949.
Mean Bar. Pressure: 767.4 mm. Hg

	H.T. + -	Temp. $^{\circ}C$	Mean Temp. $^{\circ}C$	dV Volts	Mean dV Volts	dt Sec.	i_1 amp.x10^{-14}	Mean i_1 amp.x10^{-14}	i_c amp.x10^{-14}
1.	+	24.0	24.0	1.5109	1.511	107.6	14.06		13.90
2.	+		24.0		1.511	108.1	13.99		
3.	+		24.0		1.511	108.0	14.00		
4.	+		24.0		1.511	108.2	13.98		
5.	-	24.0	24.0	1.5103	1.510	109.4	13.80	Mean of all negative readings: -13.80 ± 0.01	
6.	-		24.0		1.510	109.6	13.78		
7.	-		24.0		1.510	109.2	13.81		
8.	-		24.0		1.510	109.2	13.81		
9.	+	24.0	24.0	1.5094	1.509	107.2	14.08		
10.	+		24.0		1.509	107.8	14.00		
11.	+		24.0		1.509	108.2	13.92		
12.	+		24.0	1.5090	1.509	107.7	14.01		
13.	-	24.0	24.0	1.5089	1.509	108.8	13.88	Mean of all positive readings: +14.01 ± 0.01	
14.	-		24.0		1.509	109.4	13.79		
15.	-		24.0		1.509	109.2	13.81		
16.	-		24.0		1.509	109.8	13.75		
17.	+	24.0	24.0	1.5084	1.508	107.2	14.06		
18.	+		24.0		1.508	107.3	14.04		
19.	+		24.0		1.508	107.6	14.01		
20.	+	24.0	24.0	1.5081	1.508	107.6	14.01		

Mean i_c at $0^{\circ}C$ amp.x10^{-14}	Mean i_c at $0^{\circ}C$ and 760 mm. Hg amp.x10^{-14}	I_{Mg} amp.x10^{-14}	Vol. cc.	d cm.	r cm.	r^2 cm^2.	$r^2 I_{Mg}$ amp.x10^{-10}	J_v amp.x10^{-11}
15.11 ± 0.01	14.99 ± 0.01	15.80 ± 0.02	9.42 ± 0.05	63.28	62.0 ± 0.1	3843 ± 25.	6.08 ± 0.06	6.45 ± 0.11

TABLE IX

CALCIUM ION CHAMBER

February 7, 1949.

Mean Bar. Pressure: 755.0 mm. Hg

	H.T. + -	Temp. °C	Mean Temp. °C	dV Volts	Mean dV Volts	dt Sec.	i_1 amp.x10^{-14}	Mean i_1 amp.x10^{-14}	i_c amp.x10^{-14}
1.	+	24.0	23.9	1.5344	1.534	111.9	13.72		
2.	+		23.9		1.534	111.5	13.77		
3.	+		23.9		1.534	110.7	13.87		
4.	+		23.9		1.534	110.8	13.86	Mean of all positive readings: +13.89 ± 0.04	
5.	+	23.8	23.9		1.534	110.0	13.96		
6.	-		23.9		1.534	111.4	13.78		
7.	-		23.9		1.534	112.4	13.66		
8.	-		23.9		1.534	111.7	13.75		
9.	-		23.9		1.534	112.2	13.69		
10.	-	24.0	23.9	1.5337	1.533	113.0	13.58		13.82 ± 0.04
11.	+		23.9		1.533	111.2	13.80		
12.	+		23.9		1.533	110.7	13.86		
13.	+		23.9		1.533	110.2	13.92	Mean of all negative readings: -13.76 ± 0.03	
14.	+		23.9		1.533	109.2	14.04		
15.	+	23.8	23.9	1.5331	1.533	108.8	14.10		
16.	-		23.9		1.533	110.0	13.82		
17.	-		23.9		1.533	110.1	13.92		
18.	-		23.9		1.533	110.0	13.82		
19.	-	23.9	23.9	1.5328	1.533	111.3	13.78		

Mean i_c at 0°C amp.x10^{-14}	Mean i_c at 0°C and 760 mm. Hg amp.x10^{-14}	I_{Ca} amp.x10^{-14}	Vol. cc.	d cm.	r cm.	r^2 cm^2.	$r^2 I_{Ca}$ amp.x10^{-10}	J_v amp.x10^{-11}
15.03 ± 0.03	15.15 ± 0.03	15.98 ± 0.04	10.19 ± 0.05	63.30	61.55 ± 0.1	3789 ± 25.	6.04 ± 0.10	5.93 ± 0.15

TABLE X

CALCIUM ION CHAMBER

February 21, 1949.
Mean Bar. Pressure: 777.7 mm. Hg

	H.T. + -	Temp. °C	Mean Temp. °C	dV Volts	Mean dV Volts	dt Sec.	i_1 amp.x10^{-14}	Mean i_1 at 0°C amp.x10^{-14}	
1.	-	23.0	22.8	1.4924	1.492	99.0	15.09		
2.	-		22.8		1.492	99.2	15.03		
3.	-		22.8		1.492	99.4	15.01	16.28	
4.	-		22.8		1.492	99.6	14.99		
5.	-		22.8	1.4917	1.492	99.8	14.97		
6.	+	22.6	22.6	1.4909	1.490	98.1	15.19		
7.	+		22.6		1.490	99.2	15.01		
8.	+		22.6		1.490	98.4	15.15		Mean of all positive readings: +16.41 ± 0.04
9.	+		22.6		1.490	97.0	15.38		
10.	+		22.6		1.490	97.6	15.28	16.41	
11.	+		22.6		1.490	98.2	15.18		
12.	+		22.6		1.490	98.0	15.20		
13.	+		22.6		1.490	99.2	15.01		
14.	+		22.6		1.490	98.0	15.20		
15.	+	22.6	22.6	1.4901	1.490	98.3	15.17		
16.	-		22.6	1.4896	1.489	98.2	15.15		Mean of all negative readings: -16.14 ± 0.04
17.	-		22.6		1.489	99.6	14.93		
18.	-		22.6		1.489	100.4	14.81		
19.	-		22.6		1.489	101.0	14.72		
20.	-		22.6		1.489	100.6	14.80	16.07	
21.	-		22.6		1.489	100.8	14.78		
22.	-		22.6		1.489	100.4	14.81		
23.	-		22.6		1.489	100.8	14.78		
24.	-	22.7	22.6		1.489	100.0	14.88		

Mean i_c at 0°C amp.x10^{-14}	Mean i_c at 0°C and 760 mm. Hg amp.x10^{-14}	I_{Ca} amp.x10^{-14}	Vol. cc.	d cm.	r cm.	r^2 cm^2.	$r^2 I_{Ca}$ amp.x10^{-10}	J_v amp.x10^{-11}
16.28 ± 0.04	15.91 ± 0.04	16.79 ± 0.05	11.23 ± 0.05	63.28	61.87 ± 0.1	3817 ± 25.	6.44 ± 0.10	5.72 ± 0.15

GRAPHITE ION CHAMBER

TABLE XI

February 7, 1949.

Mean Bar. Pressure: 755.0 mm. Hg

	H.T. + -	Temp. ^{o}C	Mean Temp. ^{o}C	dV Volts	Mean dV Volts	dt Sec.	i_1 amp.x10^{-14}	i_c amp.x10^{-14}	i_c at $0^{o}C$ amp.x10^{-14}
1.	+	23.0	22.8	1.5319	1.532	108.9	14.09		
2.	-		22.8		1.532	110.4	13.88	13.98	15.15
3.	-		22.8		1.532	110.6	13.87		
4.	+	22.6	22.8	1.5316	1.532	107.9	14.21	14.04	15.21
5.	+		22.9	1.5309	1.531	108.6	14.12		
6.	-		22.9		1.531	110.2	13.90	14.01	15.19
7.	-		22.9		1.531	110.3	13.89		
8.	+	23.1	23.1	1.5310	1.531	108.2	14.17	14.03	15.21
9.	+		23.1		1.531	108.1	14.18		
10.	-		23.1		1.531	110.2	13.90	14.04	15.25
11.	-		23.1		1.531	110.3	13.89		
12.	+		23.1		1.531	108.0	14.20	14.05	15.26
13.	+	23.1	23.3	1.5306	1.530	109.0	14.04		
14.	-		23.3		1.530	110.2	13.89	13.96	15.16
15.	-		23.3		1.530	110.6	13.85		
16.	+	23.4	23.4	1.5302	1.530	108.1	14.15	14.00	15.20
17.	+		23.4		1.530	108.0	14.18		
18.	-		23.4		1.530	110.3	13.87	14.02	15.23
19.	-		23.4		1.530	110.8	13.82		
20.	+	24.5	23.4	1.5299	1.530	108.2	14.14	13.98	15.19

Mean i_c at $0^{o}C$ amp.x10^{-14}	Mean i_c at $0^{o}C$ and 760 mm. Hg amp.x10^{-14}	I_C amp.x10^{-14}	Vol. cc.	d cm.	r cm.	r^2 cm^2.	$r^2 I_C$ amp.x10^{-10}	J_v amp.x10^{-11}
15.21 ± 0.01	15.32 ± 0.01	16.16 ± 0.02	10.09 ± 0.05	63.30	61.6 ± 0.1	3789 ± 25.	6.12 ± 0.05	6.07 ± 0.10

CARBON ION CHAMBER

TABLE XII

February 18, 1949.
Mean Bar. Pressure: 763.8 mm. Hg

	H.T. + -	Temp. ^{o}C	Mean Temp. ^{o}C	dV Volts	Mean dV Volts	dt Sec.	i_1 amp.x10^{-14}	i_c amp.x10^{-14}	i_c at $0^{o}C$ amp.x10^{-14}
1.	+	25.0	25.0	1.5166	1.516	110.1	13.76		
2.	-		25.0		1.516	111.6	13.59	13.67	14.91
3.	-		25.0		1.516	111.7	13.58		
4.	+		25.0		1.516	110.0	13.78	13.68	14.92
5.	+	25.0	24.5	1.5161	1.516	109.7	13.81		
6.	-		24.5		1.516	111.7	13.58	13.69	14.90
7.	-		24.5		1.516	112.2	13.50		
8.	+		24.5		1.516	109.5	13.83	13.66	14.87
9.	+	24.0	24.5	1.5159	1.516	109.5	13.83		
10.	-		24.5		1.516	111.8	13.56	13.69	14.90
11.	-		24.5		1.516	112.7	13.45		
12.	+		24.5		1.516	109.6	13.82	13.63	14.84
13.	+	25.1	25.1	1.5153	1.515	110.5	13.71		
14.	-		25.1		1.515	112.3	13.49	13.65	14.92
15.	-		25.1		1.515	111.5	13.59		
16.	+		25.1		1.515	110.0	13.78	13.68	14.95
17.	+	25.1	25.1	1.5150	1.515	110.4	13.71		
18.	-		25.1		1.515	112.0	13.53	13.62	14.89
19.	-		25.1		1.515	112.2	13.50		
20.	+	25.1	25.1	1.5147	1.515	110.2	13.74	13.62	14.89

Mean i_c at $0^{o}C$ amp.x10^{-14}	Mean i_c at $0^{o}C$ and 760 mm. Hg amp.x10^{-14}	I_C amp.x10^{-14}	Vol. cc.	d cm.	r cm.	r^2 cm^2.	$r^2 I_C$ amp.x10^{-10}	J_v amp.x10^{-11}
14.90 ± 0.01	14.86 ± 0.01	15.67 ± 0.02	9.94 ± 0.05	63.24	61.8 ± 0.1	3819 ± 25.	5.98 ± 0.05	6.01 ± 0.10

CARBON ION CHAMBER

TABLE XIII

February 19, 1949.
Mean Bar. Pressure: 767.4 mm. Hg

	H.T. + -	Temp. ^{o}C	Mean Temp. ^{o}C	dV Volts	Mean dV Volts	dt Sec.	i_1 amp.x10^{-14}	Mean i_1 amp.x10^{-14}	i_c amp.x10^{-14}
1.	+	24.0	24.0	1.5074	1.507	107.9	13.98		
2.	+		24.0		1.507	108.2	13.92		
3.	+		24.0		1.507	108.3	13.91		
4.	+		24.0		1.507	108.0	13.94		
5.	-	24.0	24.0	1.5070	1.507	109.1	13.80	Mean of all positive readings: +13.98 ± 0.02	
6.	-		24.0		1.507	109.0	13.81		
7.	-		24.0		1.507	109.5	13.76		
8.	-		24.0	1.5065	1.507	109.8	13.71		
9.	+	24.0	24.0	1.5063	1.506	107.6	14.00		
10.	+		24.0		1.506	107.6	14.00		
11.	+		24.0		1.506	107.6	14.00		
12.	+		24.0	1.5058	1.506	108.0	13.95		13.88 ± 0.02
13.	-	24.0	24.0	1.5056	1.505	109.2	13.79		
14.	-		24.0		1.505	109.3	13.78	Mean of all negative readings: -13.77 ± 0.01	
15.	-		24.0		1.505	109.1	13.80		
16.	-		24.0		1.505	109.2	13.79		
17.	-	24.0	24.0		1.505	109.5	13.76		
18.	-		24.0	1.5052	1.505	109.6	13.75		
19.	+		24.0	1.5051	1.505	106.6	14.13		
20.	+		24.0		1.505	107.4	14.00		
21.	+	24.0	24.0	1.5045	1.505	107.4	14.00		

Mean i_c at $0^{o}C$ amp.x10^{-14}	Mean i_c at $0^{o}C$ and 760 mm. Hg amp.x10^{-14}	I_C amp.x10^{-14}	Volq cc.	d cm.	r cm.	r^2 cm^2.	$r^2 I_C$ amp.x10^{-10}	J_v amp.x10^{-11}
15.09 ± 0.02	14.94 ± 0.02	15.76 ± 0.03	9.94 ± 0.05	63.28	61.8 ± 0.1	3820 ± 25.	6.02 ± 0.05	6.06 ± 0.10

CARBON ION CHAMBER

TABLE XIV

February 21, 1949.
Mean Bar. Pressure: 778.3 mm. Hg

	H.T. + -	Temp. ^{o}C	Mean Temp. ^{o}C	dV Volts	Mean dV Volts	dt Sec.	i_1 amp.x10^{-14}	Mean i_1 amp.x10^{-14}	i_c amp.x10^{-14}
1.	+	22.0	22.0	1.5033	1.503	105.6	14.26		
2.	+		22.0		1.503	105.8	14.23		
3.	+		22.0		1.503	106.1	14.19		
4.	+		22.0		1.503	105.8	14.23		
5.	+		22.0	1.5033	1.502	105.6	14.25	Mean of all positive readings: +14.24 ± 0.02	
6.	+		22.0		1.502	105.8	14.21		
7.	+		22.0	1.5025	1.502	105.9	14.20		
8.	-		22.0	1.5023	1.501	107.0	14.04		
9.	-		22.0		1.501	106.4	14.11		
10.	-		22.0		1.501	106.6	14.09		
11.	-		22.0		1.501	107.2	14.01		14.14 ± 0.02
12.	-		22.0		1.501	107.0	14.03		
13.	-		22.0		1.501	107.2	14.01		
14.	-		22.0	1.5010	1.501	107.0	14.04	Mean of all negative readings: -14.03 ± 0.02	
15.	+		22.0	1.5006	1.500	104.8	14.32		
16.	+		22.0		1.500	105.2	14.25		
17.	+		22.0		1.500	105.4	14.22		
18.	+		22.0	1.5001	1.500	105.3	14.24		
19.	-		22.0	1.4998	1.499	106.6	14.06		
20.	-		22.0		1.499	107.0	14.01		
21.	-		22.0		1.499	107.4	13.96		
22.	-	22.0	22.0	1.4992	1.499	107.2	13.98		

Mean i_c at $0^{o}C$ amp.x10^{-14}	Mean i_c at $0^{o}C$ and 760 mm. Hg amp.x10^{-14}	I_C amp.x10^{-14}	Vol. cc.	d cm.	r cm.	r^2 cm^2.	$r^2 I_C$ amp.x10^{-10}	J_v amp.x10^{-11}
15.28 ± 0.02	14.91 ± 0.02	15.72 ± 0.03	9.94 ± 0.05	63.28	61.8 ± 0.1	3820 ± 25.	6.01 ± 0.05	6.04 ± 0.10

SUMMARY OF RESULTS

TABLE XV

Table No.	Ion Chamber	r cm.	r^2 cm^2.	r^2I amp.x10^{-10}	Vol. cc.	J_v amp.x10^{-11}	Mean J_v amp.x10^{-11}	$\frac{(J_v)}{(J_v)_{Graphite}}$
II	Graphite	52.2 ± 0.1	2730 ± 25.	6.00 ± 0.00	9.94 ± 0.05	6.04		
II	Graphite	88.4 ± 0.1	7820 ± 25.	6.18 ± 0.00	9.94 ± 0.05	6.23		
II	Graphite	61.8 ± 0.1	3815 ± 25.	5.98 ± 0.00	9.94 ± 0.05	6.02		
II	Graphite	41.6 ± 0.1	1732 ± 25.	6.00 ± 0.00	9.94 ± 0.05	6.04		
II	Graphite	46.8 ± 0.1	2190 ± 25.	5.98 ± 0.00	9.94 ± 0.05	6.03		
XI	Graphite	61.6 ± 0.1	3789 ± 25.	6.12 ± 0.02	10.09 ± 0.05	6.07 ± 0.10		
XII	Graphite	61.8 ± 0.1	3819 ± 25.	5.98 ± 0.02	9.94 ± 0.05	6.01 ± 0.10		
XIII	Graphite	61.8 ± 0.1	3820 ± 25.	6.02 ± 0.02	9.94 ± 0.05	6.06 ± 0.10		
XIV	Graphite	61.8 ± 0.1	3820 ± 25.	6.01 ± 0.02	9.94 ± 0.05	6.04 ± 0.10	6.05 ± 0.05	1.00
VII	Magnesium	61.7 ± 0.1	3802 ± 25.	6.17 ± 0.02	9.66 ± 0.05	6.41 ± 0.10		
VIII	Magnesium	62.0 ± 0.1	3843 ± 25.	6.08 ± 0.02	9.42 ± 0.05	6.45 ± 0.10	6.43 ± 0.10	1.06 ± 0.03
III	Aluminium	63.1 ± 0.1	3854 ± 25.	5.08 ± 0.02	8.05 ± 0.05	6.32 ± 0.10		
IV	Aluminium	62.1 ± 0.1	3854 ± 25.	5.10 ± 0.02	8.05 ± 0.05	6.34 ± 0.10		
V	Aluminium	62.1 ± 0.1	3854 ± 25.	5.11 ± 0.02	8.05 ± 0.05	6.35 ± 0.10		
VI	Aluminium	62.1 ± 0.1	3860 ± 25.	5.15 ± 0.02	8.05 ± 0.05	6.39 ± 0.10	6.35 ± 0.05	1.05 ± 0.02
IX	Calcium	61.6 ± 0.1	3789 ± 25.	6.04 ± 0.02	10.19 ± 0.05	5.93 ± 0.15		
X	Calcium	61.8 ± 0.1	3817 ± 25.	6.44 ± 0.02	11.23 ± 0.05	5.72 ± 0.15	5.83 ± 0.15	0.96 ± 0.03

TABLE XVI

FURTHER MEASUREMENTS ON CALCIUM ION CHAMBER

April 5, 1949.

Mean Temperature: 20.6°C
Mean Bar. Pressure: 759.8 mm. Hg

Graphite Ionization Chamber

$d = 60.85$ cm.
$r = 59.39$ cm.
$r^2 = 3528 \pm 20.$ cm^2.

	H.T. + -	dV Volts	Mean dV Volts	dt Sec.	i_1 at 0°C 760 mm. Hg amp.x10^{-14}	I_C amp.x10^{-14}	r^2I_C amp.x10^{-14}	J_v amp.x10^{-14}
1.	+	1.5597	1.560	105.6	16.75			
2.	+	1.5603	1.560	105.4	16.77			
3.	-		1.560	107.4	16.47			
4.	-	1.5605	1.560	107.0	16.53	16.63	5.87	5.90

Calcium Ionization Chamber

$d = 60.85$ cm.
$r = 59.34$ cm.
$r^2 = 3516 \pm 20.$ cm^2.

Mean Temperature: 19.6°C
Mean Bar. Pressure: 759.8 mm. Hg

	H.T. + -	dV Volts	Mean dV Volts	dt Sec.	i_1 at 0°C 760 mm. Hg amp.x10^{-14}	I_{Ca} amp.x10^{-14}	r^2I_{Ca} amp.x10^{-14}	J_v amp.x10^{-14}
1.	-	1.5608	1.561	85.5	20.66			
2.	-		1.561	85.5	20.66			
3.	-	1.5607	1.561	86.1	20.51			
4.	+	1.5607	1.561	83.9	21.02			
5.	+		1.561	83.9	21.02			
6.	+	1.5607	1.561	83.8	21.03	20.81	7.35	6.55