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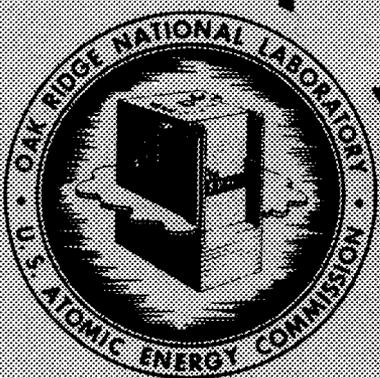
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MEASUREMENT OF THE AVERAGE ENERGY LOST  
BY A 5 MEV ALPHA PARTICLE IN PRODUCING  
AN ION PAIR IN WATER VAPOR

W. F. Patton  
G. S. Hurst  
T. E. Bortner



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HEALTH PHYSICS DIVISION

MEASUREMENT OF THE AVERAGE ENERGY LOST BY A 5 MEV ALPHA  
PARTICLE IN PRODUCING AN ION PAIR IN WATER VAPOR

W. F. Patton, G. S. Hurst, and T. E. Bortner

Date Issued

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## I. INTRODUCTION

A charged particle, while traversing a medium, will interact with the atoms or molecules of the medium and thereby dissipate energy. The particle may act on the atom or molecule with sufficient force to remove an orbital electron, creating an ion pair, i.e., the electron and the residual positive ion.

The average energy used in creating an ion pair (W value) is of prime importance in health physics. At present, the mechanism by which radiation causes tissue damage is uncertain. It is believed by some that the tissue damage is brought about by the total energy released in the tissue (absorbed dose), while others believe that the damage is a function of the ion pairs created in the tissue by the radiation.

In biological experiments involving tissue damage, both the dose and the body damage must be determined. The common method by which dose is measured is with an ionization chamber. In order to correlate the dose measured in an ionization chamber to the dose given to tissue by the same radiation, the ionization chamber gas and the tissue W values must be known.

Experiments involving W values have produced three experimental conclusions concerning the W values of different media. They are as follows:

1. The W value of a medium varies little with the energy of the incident particle.
2. The W value of a medium varies little with the nature of the incident particle.

3. The W values of different media vary only within a narrow range.

These conclusions have been explained in a qualitative manner by a theory developed by Fano,<sup>1</sup> but this theory does not enable one to calculate W values of different media that agree with those determined experimentally. These shortcomings are being investigated further at the present time.

Current thought relates body damage to both ion pair production and specific ionization (number of ions produced per centimeter of path length of the incident particle). This is a reasonable assumption since the destruction of tissue would depend on the number of atoms or molecules changed and the volume of tissue over which these changes take place.

As mentioned above, the W value of the tissue and the W value of the gas used in the ionization chamber must be known in order to ascertain the dose delivered to the tissue. No method of determining the W value of a solid medium has yet been devised. Since the W value of tissue can be neither determined experimentally nor calculated by theory, a reasonable approximation must be made. It is reasonable to assume that the W value of water would be close to the W value of tissue since water is one of the primary constituents of tissue. The purpose of this work was to determine the W value of water vapor, so that it could

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<sup>1</sup> U. Fano, Phys. Rev. 70, 44 (1946).

be used in radiation dose measurements.

To measure the W value of water vapor, alpha particles from Pu<sup>239</sup> with an average energy of 5.14 Mev were used. A collimated source of alpha particles was placed in an ionization chamber in which the alpha particles expend their total energy in the creation of ion pairs. The ion pairs produced were collected on a capacitor and the change of potential on the capacitor due to the charge carried by the ions was observed. The system was calibrated by filling the ionization chamber with a gas of known W value and observing the change of potential across the capacitor due to the charge on the ions produced in the gas. Since different amounts of energy will be dissipated in the collimator for gases of different stopping powers, correction for this energy loss was made for each stopping medium. Knowing the energy lost in the collimator, the change in potential across the capacitor, and the W value of the gas, the system could be calibrated since the W value of any gas is directly proportional to the energy expended in the creation of ion pairs and inversely proportional to the change in potential across the capacitor. Once the system was calibrated, it was only necessary to observe the change in potential across the capacitor due to ions produced by the alpha particles in water vapor, make corrections for energy lost by the particles in water vapor within the collimator, and compare these results with those obtained in the calibration procedure.

## II. APPARATUS

The apparatus used in this experiment was designed specifically to measure the number of ion pairs produced in water vapor by a 5.14 Mev alpha particle.

The basic components of the apparatus as shown in Fig. 1 are: a vacuum system, a stable high voltage supply, an ionization chamber, a vibrating reed electrometer, a variable out-put potentiometer, a Pu<sup>239</sup> alpha particle source, and a capacitor.

A vacuum system, made up of 1/4 inch copper tubing, cold trap, and an ionization chamber, is evacuated with a Welch Duo Seal model 1400B fore pump and a VMF model 260 oil diffusion pump. Figure 2 shows the vacuum system in relation to the other parts of the apparatus. This system was capable of reducing the pressure to less than one micron of Hg pressure as measured by a Hasting vacuum gage.

Commercial gases, under pressure, were used as calibration standards. The pressures of the gases were measured on a Wallace-Tiernan pressure gage which has a range from 0 to 285 centimeters of Hg pressure and is readable to 1 millimeter of Hg pressure. This gage, shown in Fig. 1, was used instead of a mercury manometer to prevent the presence of mercury vapor that could alter the results of the experiment. This gage proved to be both stable and satisfactory. A block diagram of the gas filling apparatus is shown in Fig. 3.

The requirements of the high voltage supply are two-fold. The voltage supply must be stable, since instability of the collection potential will result in erratic behavior of the electrometer and

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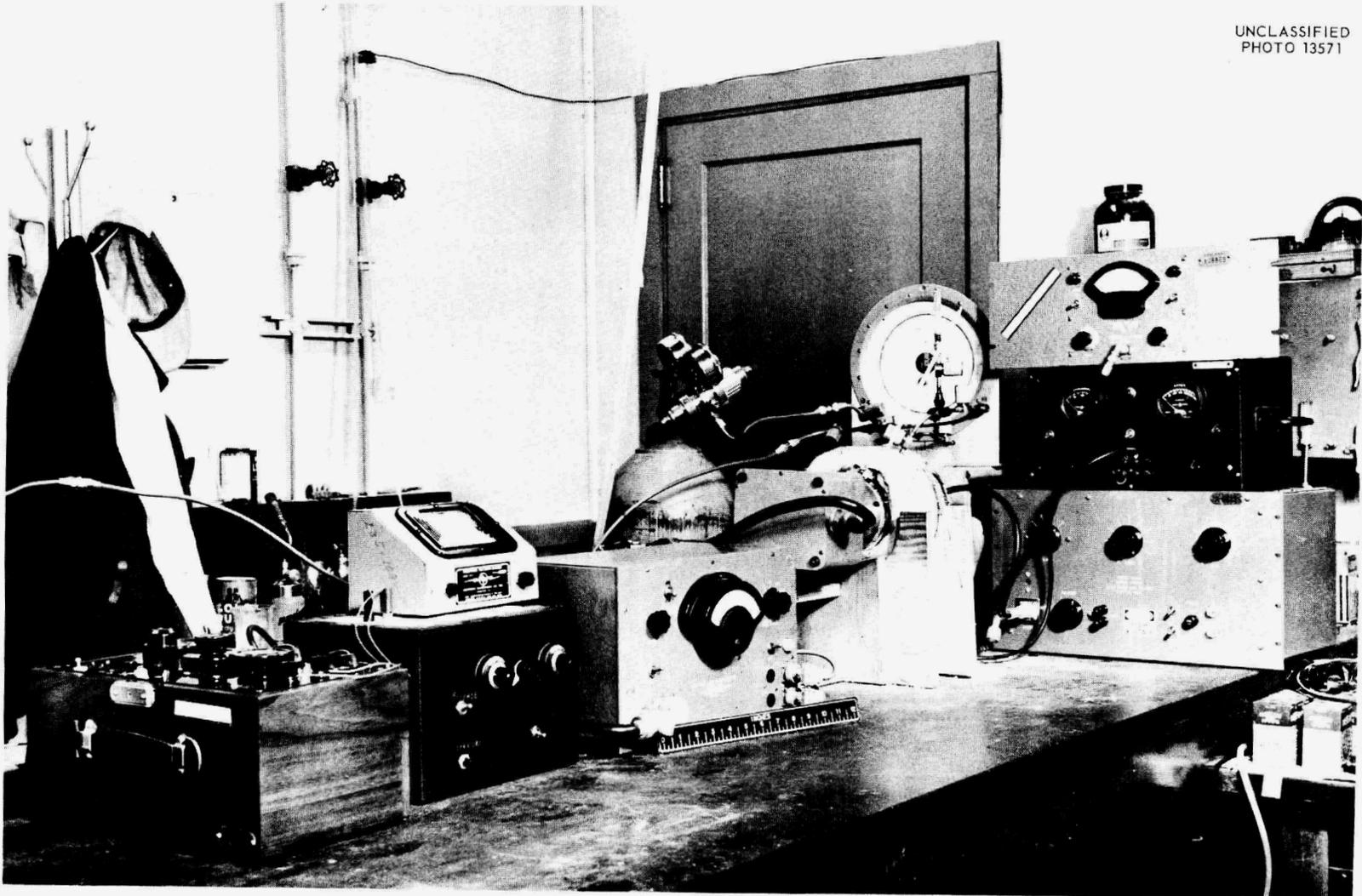


Fig. 1. Photograph of Apparatus.

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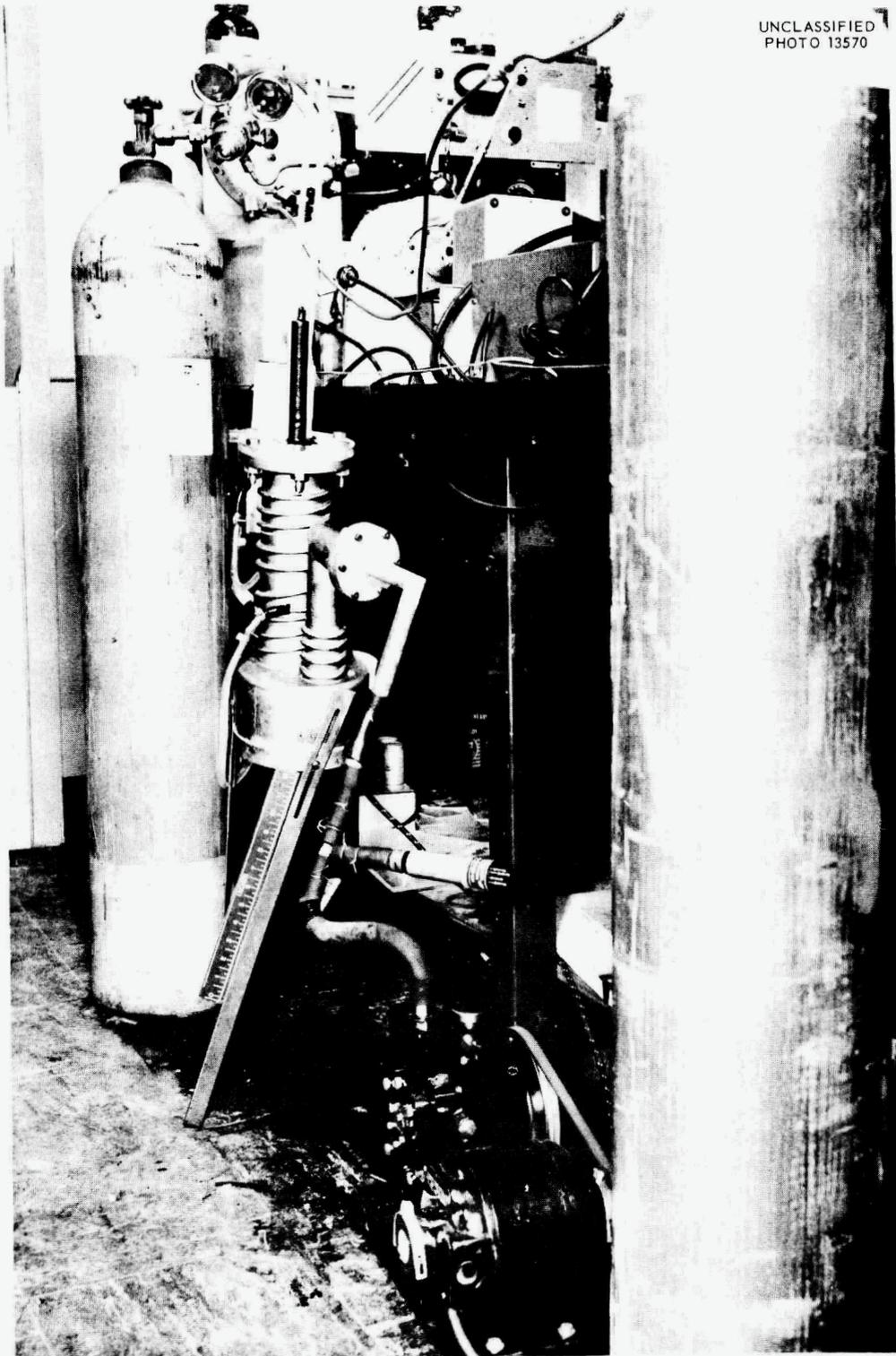


Fig. 2. Photograph of Vacuum System.

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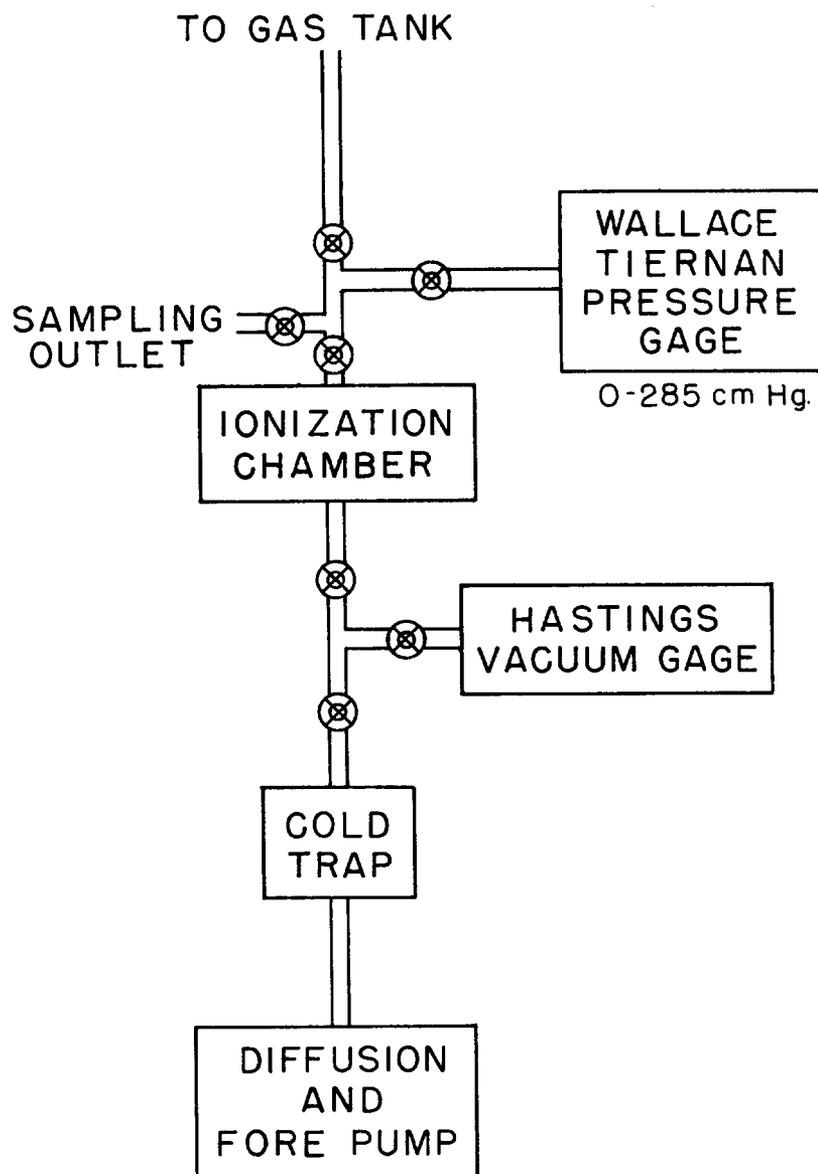


Fig. 3. Block Diagram of Gas Filling Apparatus.

greatly affect the results of ion collection below saturation voltages. The range of the high voltage supply must include all voltages up to 5000 volts, because some gases require a collection voltage of this magnitude to reach saturation or obtain enough of the saturation curve to allow extrapolation of the curve to infinite voltage.

For the range between 0 and 300 volts, a model A2A Variable Voltage Regulated Power Supply, manufactured by the Oregon Manufacturing Company of Portland, Oregon, was used. The output regulation of this instrument is 0.01% according to specifications given by the manufacturer. A model 316 Regulated High Voltage Supply manufactured by the Atomic Instrument Company of Cambridge, Massachusetts, was used for voltages between 450 and 3000 volts. The manufacturer specified an output regulation of 0.01% and a maximum ripple of 0.25 volts RMS for this instrument. A model 400 BD High Voltage Power Supply, manufactured by the John Fluke Manufacturing Company of Seattle, Washington, was used for the range between 3000 and 5000 volts. A specification of 0.01% regulation of output voltage and 0.005 volts RMS maximum ripple was given for this instrument. The specifications given for these instruments were determined from loaded operation on unregulated line voltages. In this application there was no load and the line voltage was regulated to about 2 volts. These conditions would tend to increase the stability of the power supplies.

The requirements of an ionization chamber in which water vapor is to be the stopping medium are numerous. The vapor pressure of water is very low at room temperatures, being approximately 17 mm of Hg pressure.

At this pressure, the range of the alpha particle is very large. It was necessary to have facilities whereby the temperature of the water could be increased, thereby increasing the vapor pressure of the water and decreasing the range of the alpha particle. The size of the ionization chamber is determined by other factors. The chamber must be of small volume to minimize the amount of heat necessary to vaporize the water. The collection volume (volume occupied by the electric field) must be uniformly heated and insulated from the environment for effective temperature control. The chamber must be easily out-gassed since the presence of electronegative gases greatly increases recombination of the ions. Collection field perturbations affect saturation, therefore the electric field must be uniform. Furthermore, there must be sufficient thermal insulation between the ionization chamber and the vibrating reed electrometer to prevent an excessive temperature increase in the vibrating reed electrometer. The case should also provide shielding from external electric fields.

Figure 4 shows a schematic diagram of the ionization chamber as used in this work. The physical connection to the other parts of the apparatus is shown in Fig. 5. The chamber was made up of a brass cylinder of 3-1/4 inch outside diameter and 1/16 inch wall thickness. A stainless steel cylinder connected the case of the ionization chamber to the case of the vibrating reed electrometer, providing sufficient thermal insulation while maintaining electrical contact. Collars of 1/8 inch brass were silver soldered to the ends of the brass cylinder to facilitate fastening the ends of the chamber. The whole of the

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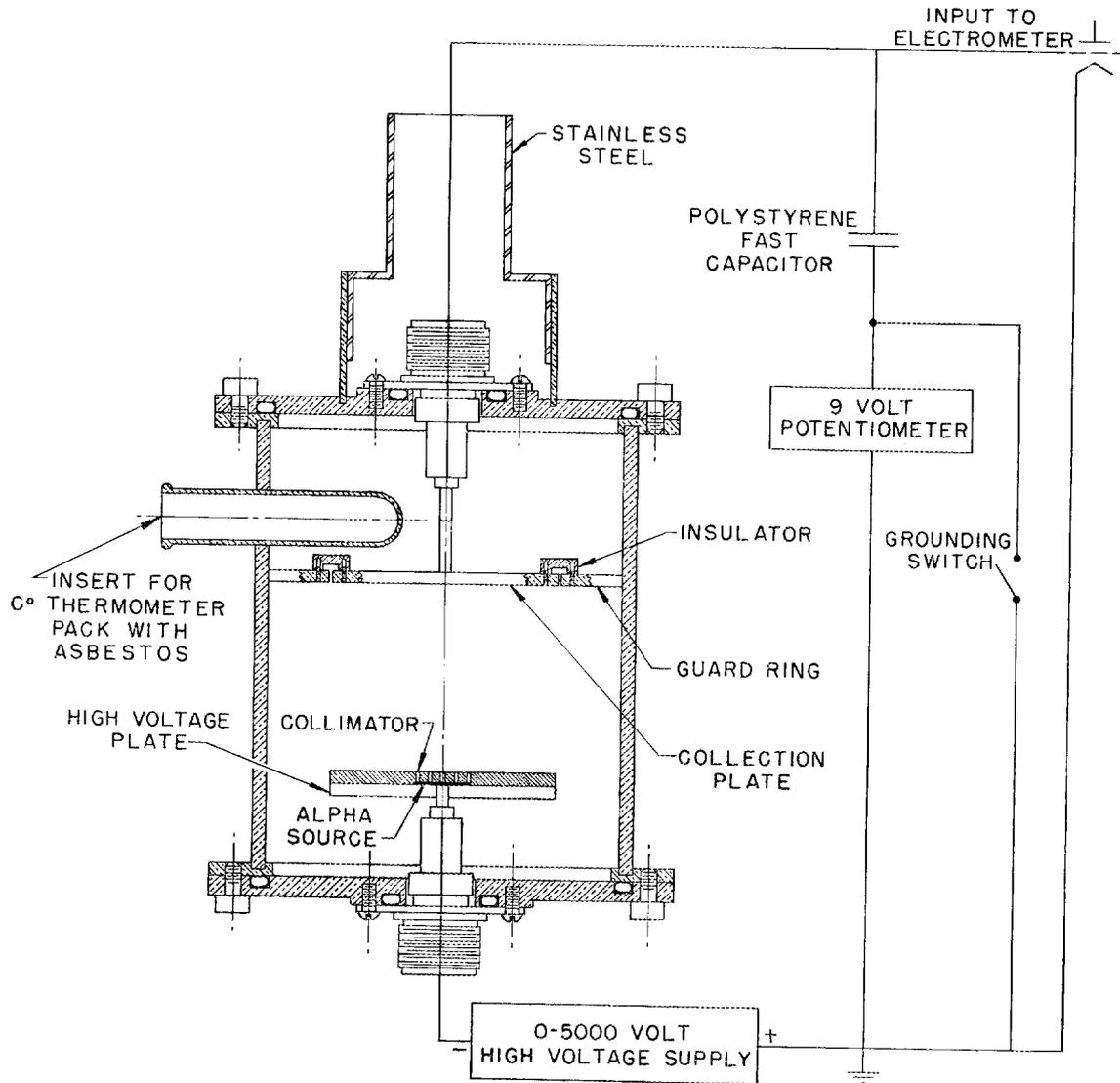


Fig. 4. Schematic Diagram of Ionization Chamber.

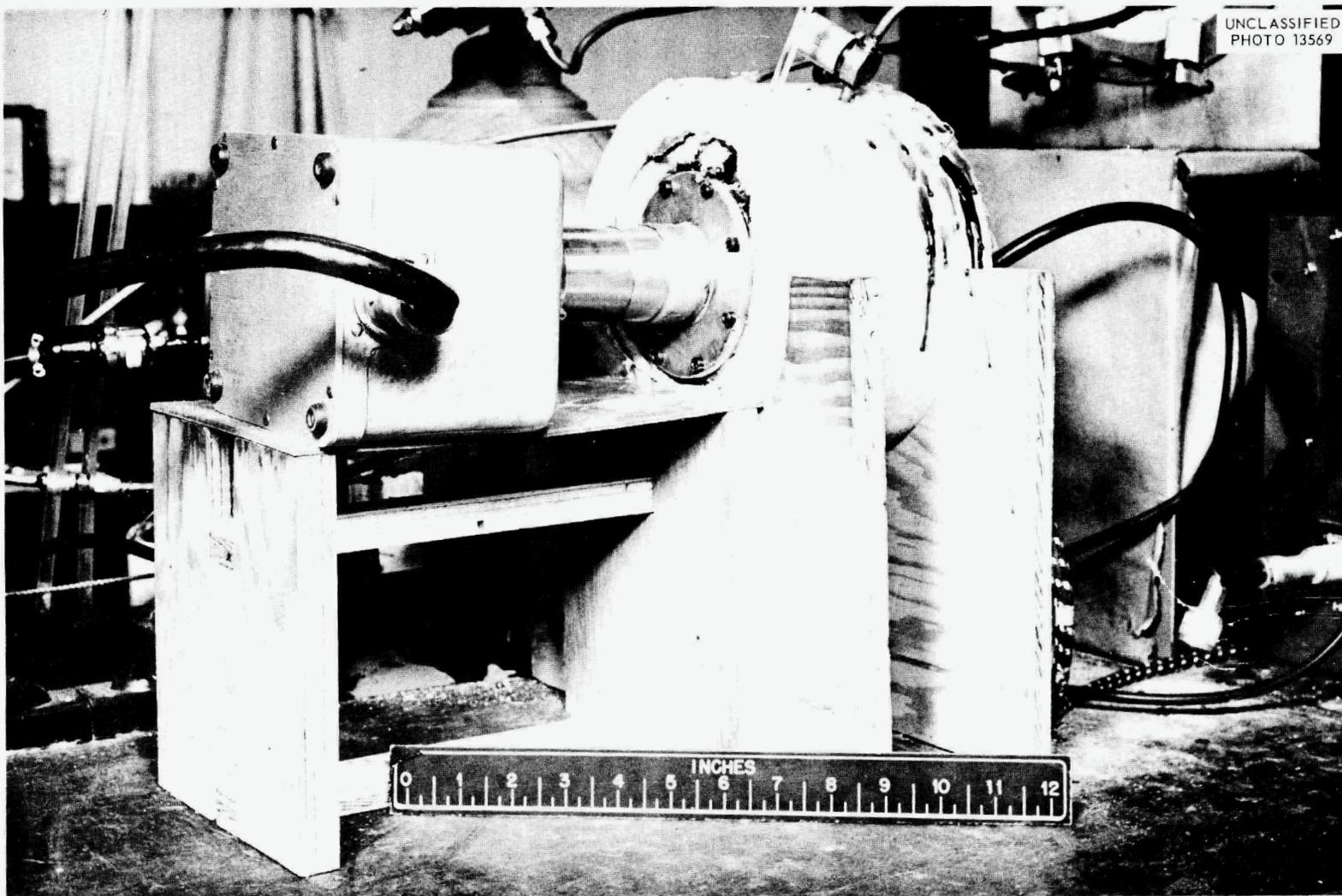


Fig. 5. Photograph of Ionization Chamber.

interior was silver plated to increase the out-gassing speed and to distribute heat evenly throughout the chamber. Copper tubing of 1/4 inch diameter was used to provide leads for evacuation and gas filling. The ends of the chamber, made of 3/8 inch brass plate, were fastened to the cylindrical shell by means of eight 3/16 inch machine screws. A vacuum seal was made with "O" ring gaskets of Neoprene. Electrical leads to the electrometer and the high voltage supply were made with standard Amphenol connectors No. 82-805.

The heat necessary to vaporize the water is provided by a nicrome heating element wound about the radial periphery of the chamber case. A Variac voltage control is used to vary the current in the heating element and therefore the heat produced. Using this method of heating, it is possible to control the temperature of the chamber to 1/2 degree centigrade as determined by a thermometer inserted in the thermometer well of the chamber.

The heat is applied only to the radial periphery of the chamber case. This method of heat application was necessary since access to the interior of the chamber was desired, but was satisfactory since the material of the chamber conducts heat readily.

To limit the range of the alpha particles to the collection volume, collimation of the alpha particles was necessary. According to the theory of Jaffe,<sup>1</sup> the ideal condition, preventing recombination of

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<sup>1</sup> G. Jaffe, Ann. Physik 42, 303 (1913).

the ions before collection, would be to have the particles traverse the collection field at an angle of  $90^\circ$ . The size of the chamber, however, makes this arrangement impractical. In a practical pressure range, the angle is limited to an angle greater than  $20^\circ$ . At higher pressures, too much energy is lost in the collimator. The angle is further limited by the ion diffusion effect. The ion diffusion effect becomes apparent when a large number of ions are formed near the periphery of the collection volume. Under this condition, the ions in the region of high ion density within the collection volume will diffuse to the low ion density region outside the collection volume and will not be collected. For these reasons, the alpha particles were collimated to traverse the field at an angle of  $0^\circ$ .

A model 30 Vibrating Reed Electrometer, manufactured by Applied Physics Incorporated, was used as a null indicator. This instrument is capable of measuring currents as low as  $10^{-17}$  amperes. The electrometer has a drift rate of less than 1 millivolt per minute which is negligible since measurements are of the order of several hundred millivolts per minute.

A reference potential was necessary to measure the potential change on the capacitor. This reference potential balanced out the potential across the capacitor continuously, using the vibrating reed electrometer to indicate the balance. The potential per unit time needed to keep the capacitor potential balanced was a measure of the ion current. Figure 6 is a schematic diagram of the potentiometer designed for this purpose. This instrument is essentially a series of potentio-

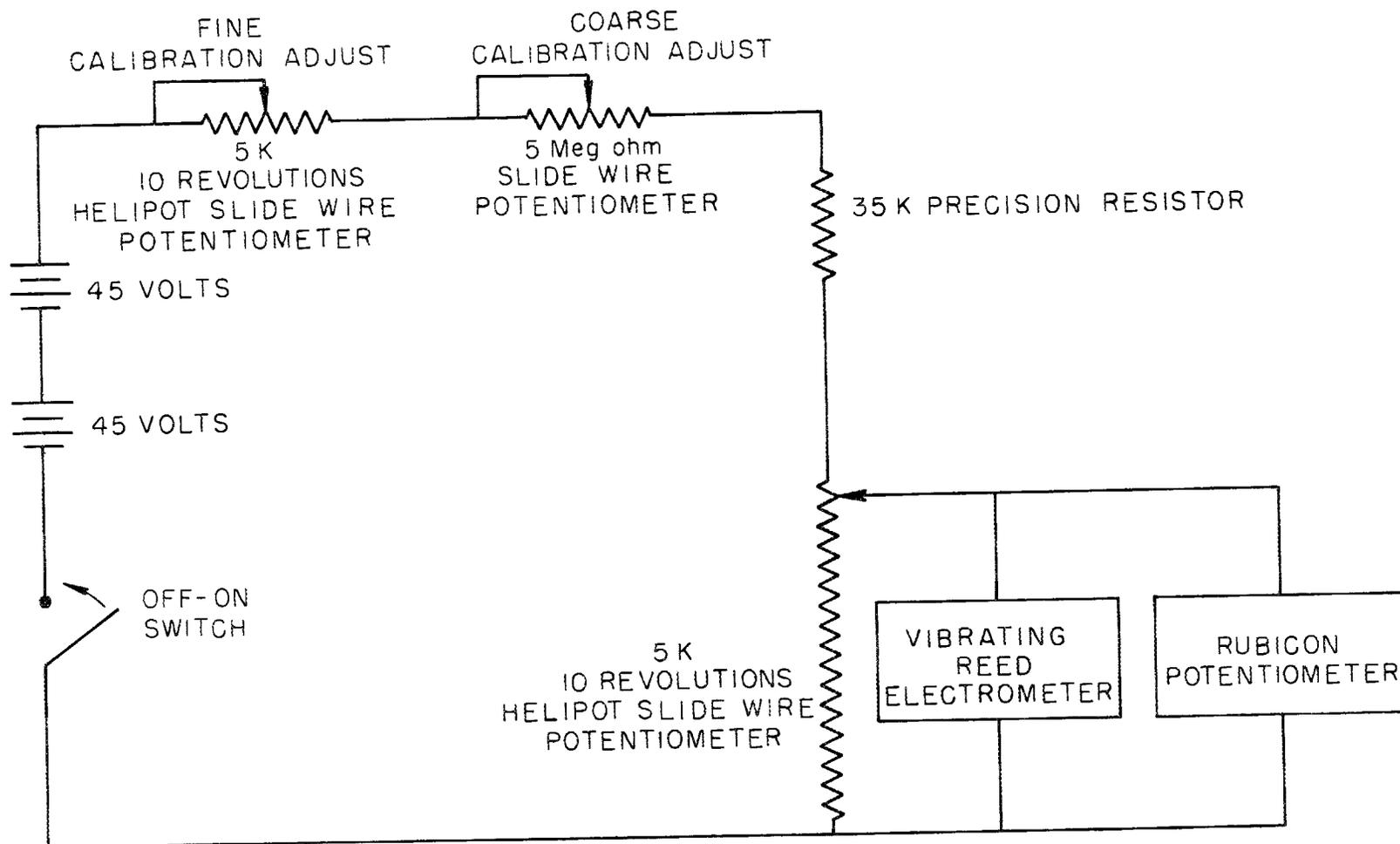


Fig. 6. Schematic Diagram of Potentiometer.

meters connected in series. The first two potentiometers (coarse calibration adjust and fine calibration adjust) are shorted to provide a variable resistance. The voltage needed is tapped off by means of a 10 revolution Helipot slide wire potentiometer. Since a 90 volt battery was used as a potential source and only a few volts tapped off, the variation in any given output potential was negligible. A Rubicon Precision potentiometer was used to calibrate this potentiometer. A typical calibration curve is shown in Fig. 7. The potentiometer was calibrated at 2000 millivolts and compared with different settings of the Rubicon Precision Potentiometer. The output of the potentiometer was found to vary less than 3 millivolts.

The capacitor used was manufactured by the John E. Fast Company. Negligible electrical leakage is encountered through use of this capacitor, which makes it especially applicable to this investigation.

The relation of the high voltage supply, the ionization chamber, the vibrating reed electrometer, and the Rubicon Precision Potentiometer are shown in Fig. 8.

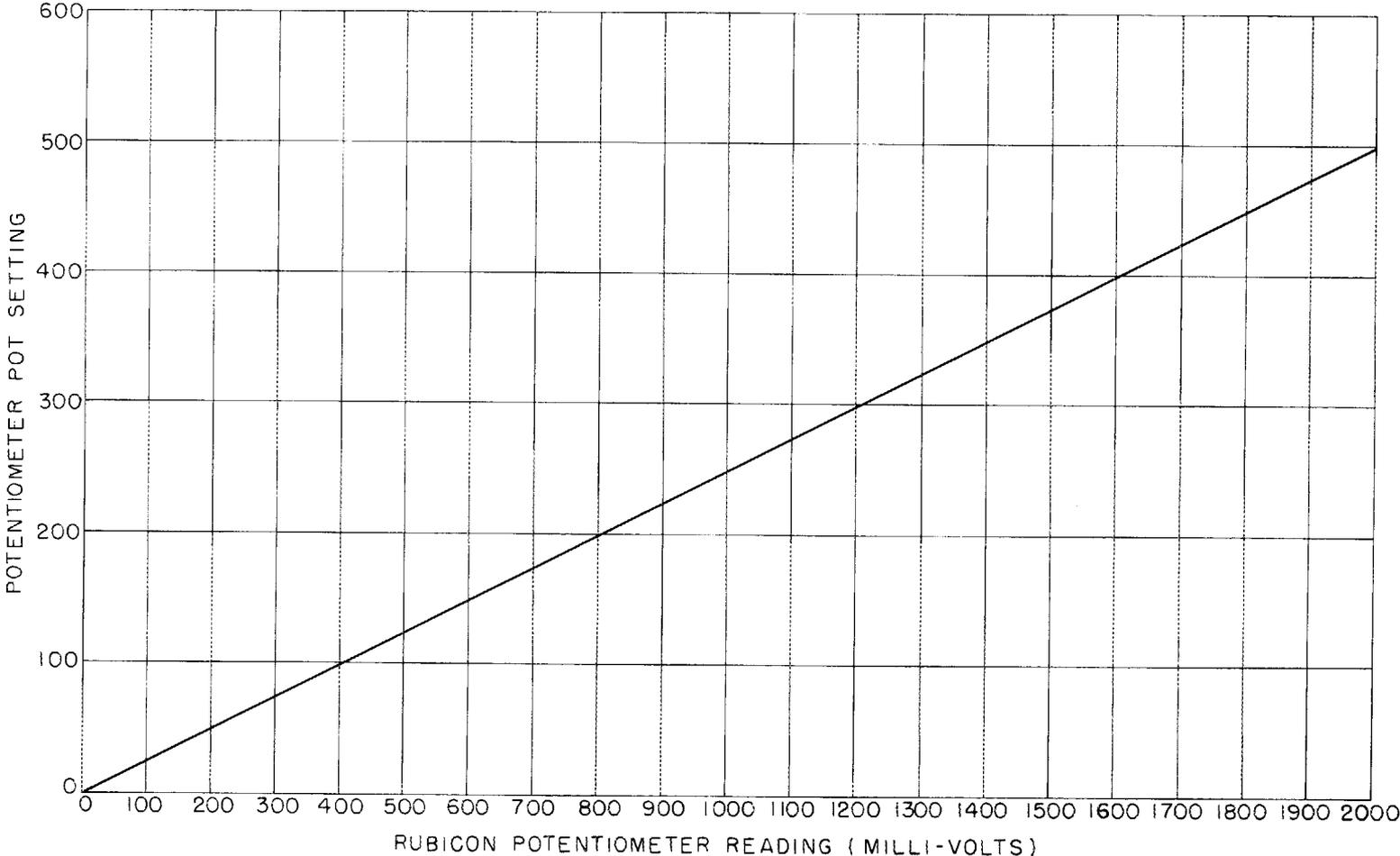


Fig. 7. Potentiometer Calibration Curve.

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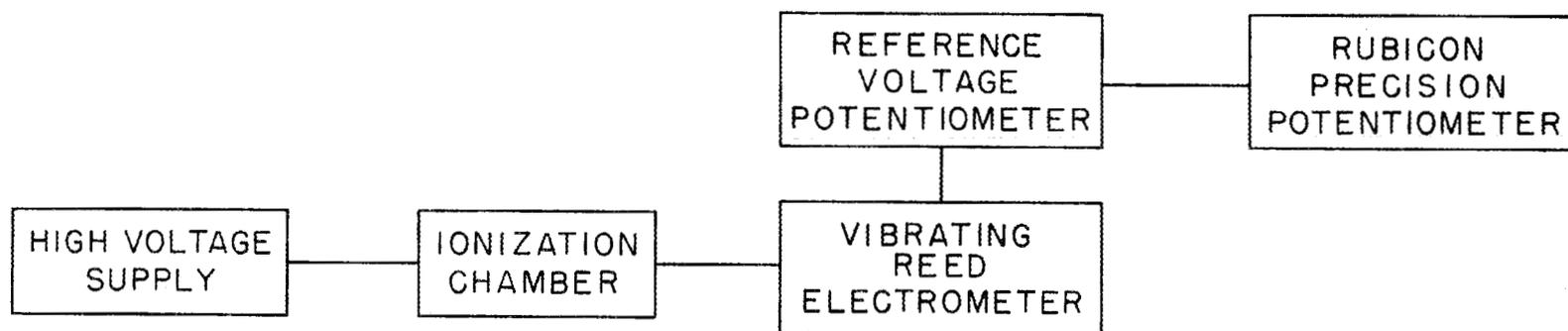


Fig. 8. Block Diagram of Apparatus.

### III. PROCEDURE

The ionization chamber was evacuated to less than 1 micron of Hg pressure. During this evacuation, the chamber was held at a temperature of 100° C to facilitate out-gassing. This along with the added precaution of flushing the chamber with the gas to be used, minimized the amount of impurities in the chamber before a stopping medium entered the chamber.

Nitrogen was selected as a calibration standard because the  $W$  value is little affected by impurities and is well known. Although nitrogen has a high ion diffusion coefficient, collimation was such that this effect was of little importance. Purity of the nitrogen used was 99.9% by mass spectrographic analysis.

In order to measure the energy needed to produce an ion pair, it is necessary to know the amount of energy expended by the particle within the collection volume. To do this, a collimator is used to select only the particles that will be stopped completely in the collection volume. Also, since part of the energy of the particle is expended during the traversal of the collimator, this energy must be subtracted from the original energy of the particle. From the above, we know the amount of energy that has been expended in the collection volume by the incident particle.

From the theory of Jaffe,<sup>1</sup> it is seen that minimum recombination will occur if the particles traverse the collection volume normal to

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<sup>1</sup> Op. Cit.

the collection field. To affect this condition, the source must be located on the radial periphery of the collection volume. Due to the geometry of the collection volume, a high degree of collimation is necessary if this source location is to be used. With this arrangement there are two converse effects, At low pressures (resulting in a longer range for the particle), the particles pass out the other side of the collection volume before ionization is complete. Conversely, at higher pressures (shorter range), more energy is dissipated in the collimator since the path length in the collimator is a higher percentage of the total path length. Optimum ion collection can be obtained by varying the pressure, but it is uncertain that all ions are being collected. For these reasons, this method of source mounting was discarded.

Bortner and Hurst<sup>1</sup> used an uncollimated source in the determination of W values of several gases and obtained results in good agreement with earlier measurements. By using this source arrangement, the alpha particles were emitted at all angles with the collecting field, and yet saturation current was obtained at moderately high voltages. This indicated that the angle of collimation was not too critical in this type determination. A collimator was designed and constructed that would limit the particles to the collection volume and to a  $45^\circ$  angle with the collecting field. Using nitrogen gas, a current of sufficient magnitude was obtained but the pressure at which the particle was confined to the collection volume was higher than that predicted by

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<sup>1</sup> T. E. Bortner and G. S. Hurst, Phys. Rev. 93, 1236 (1954).

calculation for nitrogen. A curve of ionization current versus pressure was taken for argon to see if the effect was due to a characteristic of the gas. Curves for nitrogen and argon are shown in Fig. 9. The effect was intensified in argon. It was concluded that the effect was due to a characteristic of the gas rather than the chamber. In an investigation of the behavior of gaseous ions, it was found that the ion diffusion coefficient was high for nitrogen and even higher for argon. With the particles collimated at  $45^{\circ}$  with the field, a large percentage of the total ionization occurred near the periphery of the collection volume. Since there is a tendency for ions to diffuse from regions of high ion density to regions of low ion density, some of the ions were diffusing out of the collection volume before they could be collected. As the pressure was increased, the region of high ion density receded toward the center of the collection volume and the diffusion effect was no longer in evidence. This explained the difference between the calculated saturation point and the actual saturation point.

Recombination of the ion pairs is readily apparent only in the electronegative gases, i.e., gases in which the probability of electron attachment to form heavy negative ions is large. In these gases, an infinite field is necessary for complete collection. If the incident particle traverses the field at an angle of  $90^{\circ}$ , this effect is minimized. In other gases, recombination is not so apparent, therefore all ions can be collected at voltages only slightly higher than those necessary when the particle traverses the collection volume normal to the field.

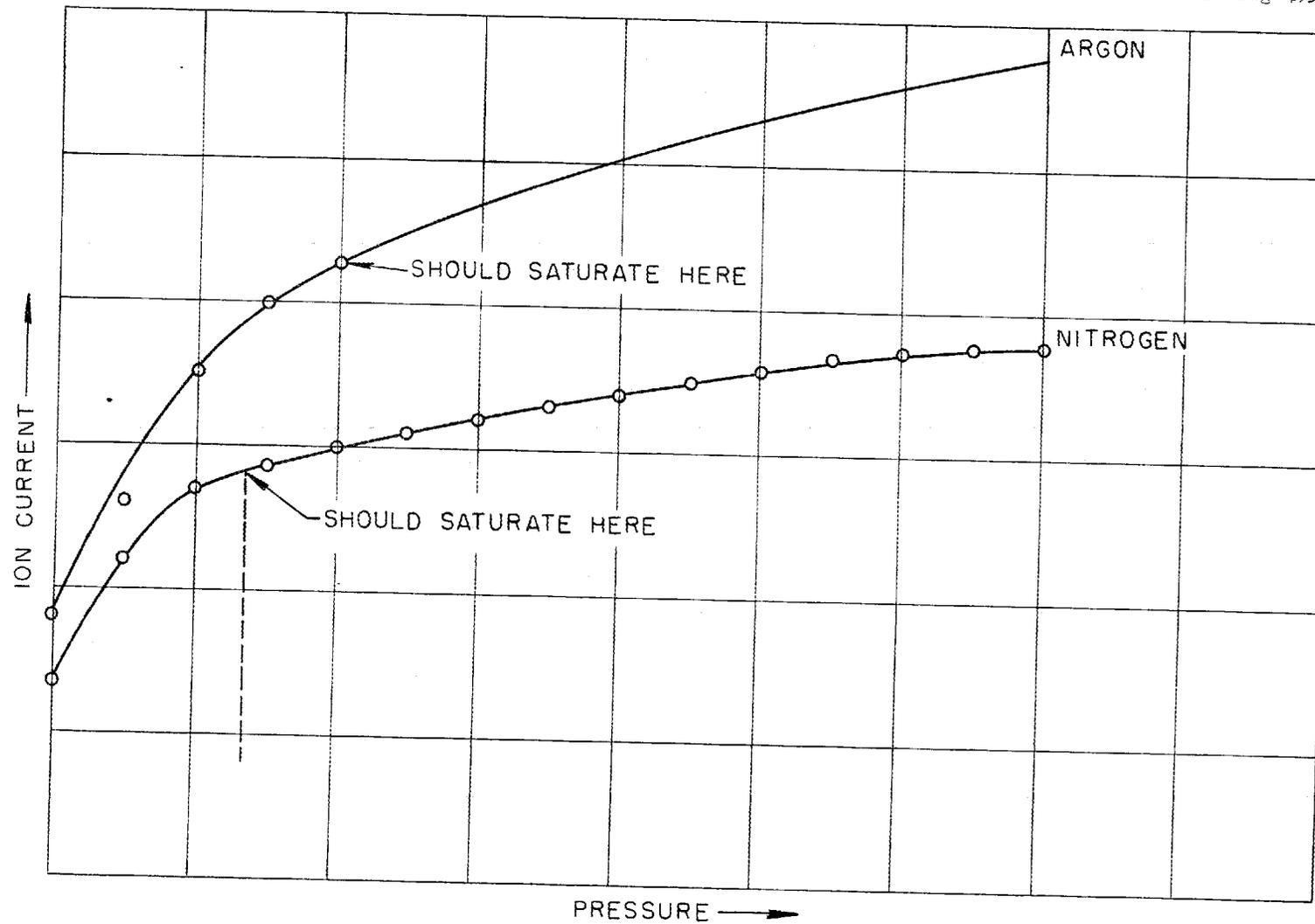


Fig. 9. Curve of Ionization Versus Voltage in Nitrogen and Argon Showing Ion Diffusion Effect.

Through application of Jaffe's theory,<sup>1</sup> it is possible to extrapolate a saturation curve to infinite voltage and therefore to saturation voltage even for the electronegative gases.

Since this extrapolation is possible, a collimator was designed for the single purpose of limiting the alpha particles to the collection volume. Figure 10 shows a pressure versus ionization current curve for nitrogen using this arrangement. It is seen that the particles were completely stopped in the collection volume at a pressure of approximately 100 cm of Hg pressure.

Having ascertained that the alpha particles were being completely stopped within the collection volume, a measure of the charge buildup per unit time on the capacitor was made. To make sure that all ions formed in the collection volume were collected, the pressure was set at a value where all particles would be stopped in the collection volume and an ionization current versus collection voltage curve was determined. Figure 11 shows the curve for nitrogen at a pressure of 100 cm of Hg pressure. It is seen that the ionization current increased with voltage until a voltage of about 600 volts was reached. The ionization current remained constant for higher voltages. The voltage for which no further ionization occurs is called the saturation voltage and the curve is called a current saturation curve.

Water vapor was now introduced by placing a small glass reservoir of water at room temperature into the chamber. Most gases have higher vapor pressures than this so they would be pumped out readily, leaving

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<sup>1</sup> Op. Cit.

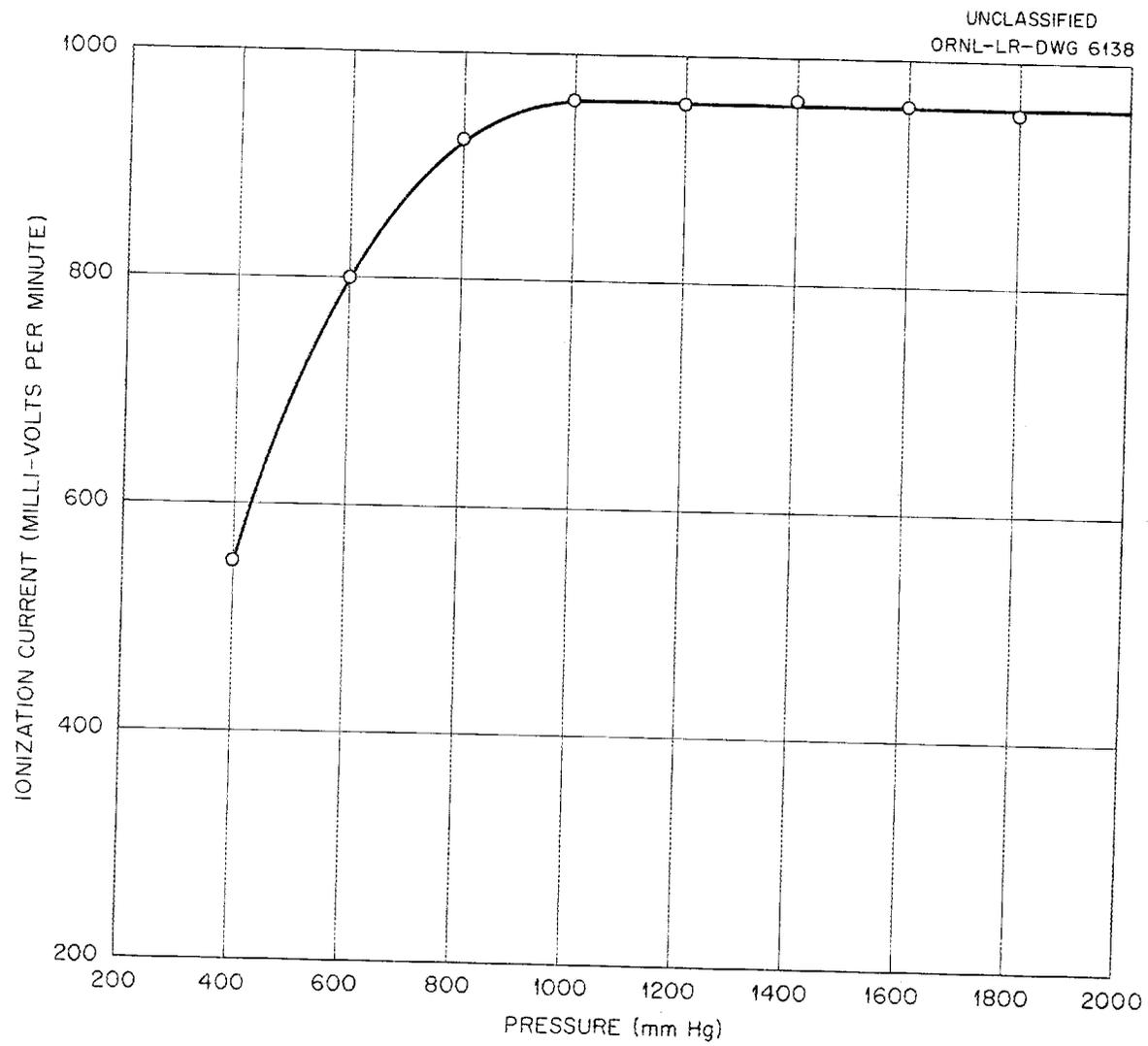


Fig. 10. Curve of Ionization Versus Pressure at Saturation Voltage in Nitrogen.

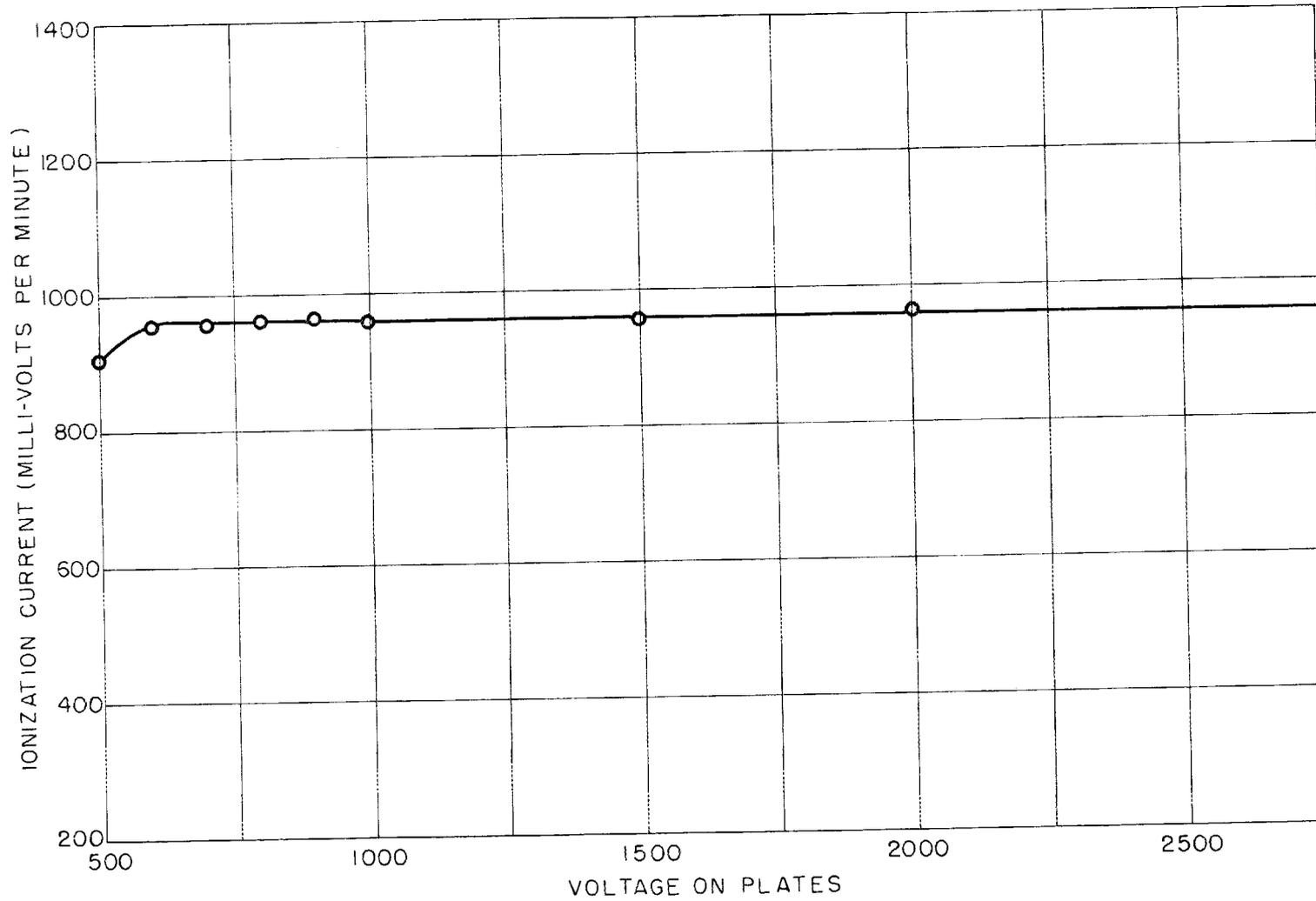


Fig. 11. Ionization Saturation Curve of Nitrogen at 1000 mm Hg.

only water vapor. This, in effect, flushed the chamber with water vapor before the chamber was closed to the vacuum system. Heat was now applied to the chamber until a temperature of  $130^{\circ}$  C was observed on the thermometer. The chamber remained at this temperature for sixteen or more hours to allow the water vapor to saturate the volume of the chamber. As was mentioned before, electrical insulation is essential. One persistent problem was the condensation of water vapor on the electrical insulators, causing electrical leakage. This was solved by making use of the fact that good insulators absorb and release heat slowly. The chamber was heated to a temperature above that at which the determination was to be made and held there until the insulators came to thermal equilibrium with the chamber. The temperature was then lowered to  $125^{\circ}$  C. The insulators were now at a higher temperature than the chamber and water vapor could not condense on the insulating materials. The saturation curve obtained for water vapor is shown in Fig. 12. It is seen from this curve that saturation was uncertain. There seems to be a steady increase in ion current as the voltage is increased. Since saturation should theoretically occur at infinite voltage, the saturation curve is extrapolated to infinite voltage by Jaffe's theory.<sup>1</sup> The extrapolation curve obtained is shown in Fig. 13.

In order to be sure that the particles were being completely stopped in the collection volume, the time rate of change of voltage

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<sup>1</sup> Op. Cit.

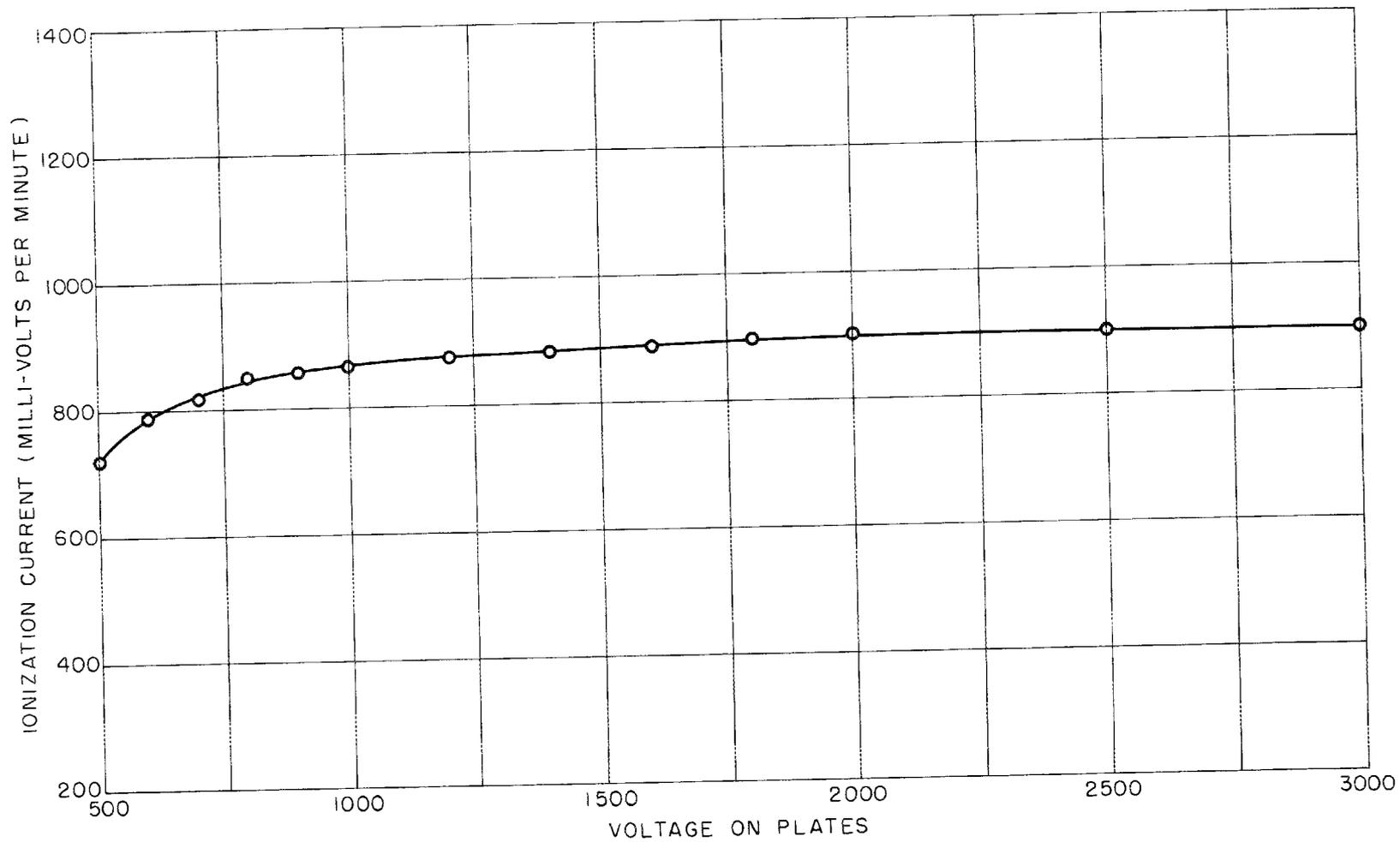


Fig. 12. Ionization Saturation Curve of Water Vapor at 125°C.

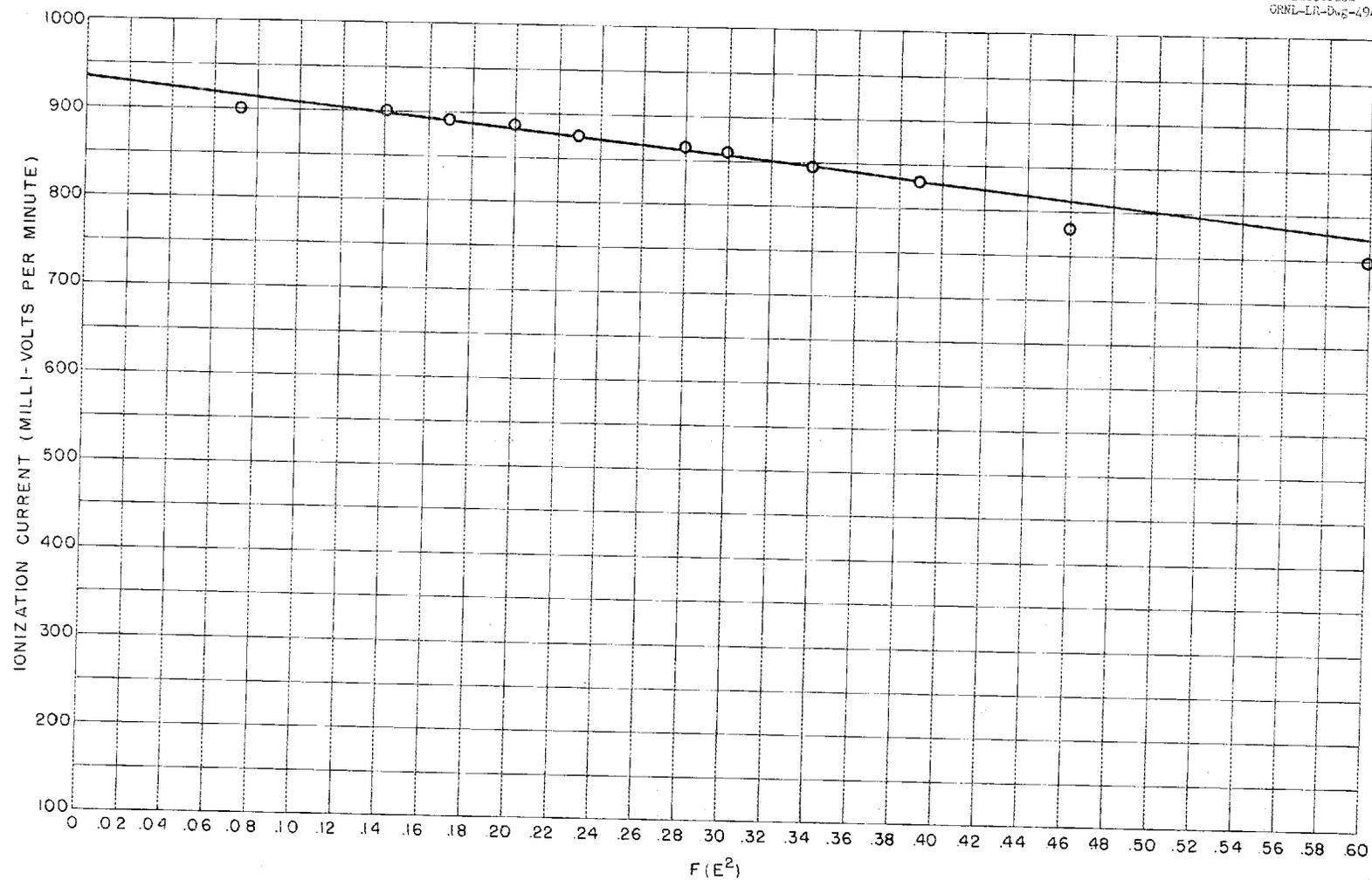


Fig. 13. Jaffe Extrapolation of the Water Vapor Saturation Curve.

across the capacitor was determined at lower temperatures (lower pressures) which means that the path length was increased. The results of this determination are shown in Fig. 14. This indicated that the particles were confined to the collection volume at approximately 1100 mm of Hg pressure which corresponds to a temperature of  $111^{\circ}$  C.

It is possible to derive a formula for the W value of any medium.

The following notation is used.

$e$  = Charge of the electron in coulombs.

$E$  = Energy of the alpha particle in electron volts (5.14 Mev).

$E_c$  = Energy lost in the collimator in electron volts.

$N$  = Number of alpha particles entering the collection volume per minute.

$C$  = Capacitance of system in farads.

$V$  = Volts.

$dV$  = Change in voltage across capacitance.

$Q$  = Charge in coulombs.

$dQ$  = Change in charge on capacitor.

$W$  = Average energy required to create an ion pair in electron volts.

The total energy expended in the collection volume per minute would be

$$N(E - E_c) \text{ ev/min.} \quad (1)$$

From the relation

$$Q = CV, \quad (2)$$

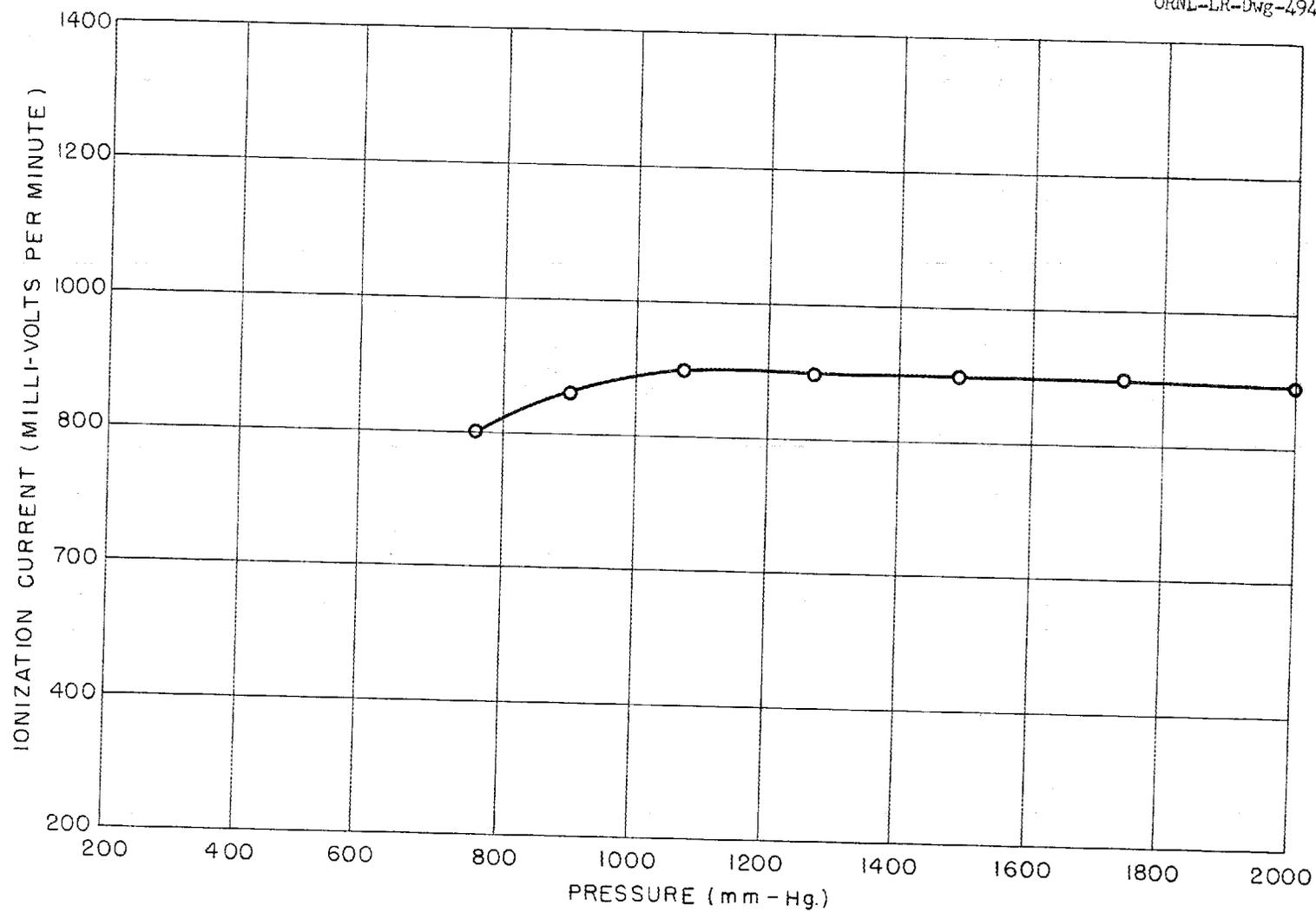


Fig. 14. Curve of Ionization Versus Pressure at Saturation Voltage in Water Vapor.

the time rate of change of charge on the capacitor can be obtained by simple differentiation of (2).

$$dQ/dt = C dV/dt.$$

Expressing  $dQ/dt$  in coulombs per minute,  $C$  in farads and  $dV/dt$  in volts per minute, the number of ion pairs produced per minute would be the time rate of change of charge (3) divided by the charge of the electron in coulombs or

$$\frac{C dV}{e dt} \frac{\text{ion pairs}}{\text{minute}} \quad (4)$$

From (1) and (4) we may obtain the relation

$$W = \frac{Ne}{C} \frac{(E - E_c)}{dV/dt} \frac{\text{electron volts}}{\text{ion pair}} \quad (5)$$

$N$ ,  $e$ , and  $C$  are constant for the system; therefore,

$$W = K \frac{(E - E_c)}{dV/dt} \frac{\text{electron volts}}{\text{ion pair}} \quad (6)$$

$K$  can be evaluated from the known  $W$  value of nitrogen, the measured time rate of change of voltage across the capacitor, the energy of the alpha particle, and the calculated loss of energy in the collimator. The  $W$  value of water vapor was determined by measuring  $dV/dt$ , calculating  $E_c$

in water vapor and using these values in (6).

To verify the validity of the Jaffe extrapolation curve in water vapor, the collection volume of the chamber was enlarged and the particles collimated to traverse the collection volume at an angle of  $20^\circ$  to the electric field. Ethylene was used as the calibrating gas because of its low ion diffusion coefficient. The same procedure was used and the results, given in section IV, were not affected.

## IV. EXPERIMENTAL RESULTS

The saturation curve shown in Fig. 11 gives a saturation ionization current value of  $(960 \pm 5)$  millivolts per minute for nitrogen. All ions produced in the collection volume are represented in this current. In order to evaluate the constant in (6), it is necessary to calculate the energy of the alpha particle that was dissipated in traversing the collimator. This energy loss will be a function of the path length of the particle in the collimator and the mass stopping power of the stopping medium (energy lost per gram per square centimeter of medium). Although the mass stopping power (S) of nitrogen was not found in the literature, the relative mass stopping power (P) is given by Morgan<sup>1</sup> as 1.181. Relative mass stopping power is defined as the mass stopping power of a medium divided by the mass stopping power of air or

$$P = S_{\text{medium}}/S_{\text{air}} \quad (7)$$

The mass stopping power of protons in air for various proton energies is given by Bethe.<sup>2</sup> Since the mass stopping power is directly proportional to the square on the incident particle and inversely to the square of the velocity, we obtain the relation

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<sup>1</sup> K. Z. Morgan, HEALTH CONTROL AND NUCLEAR RESEARCH (unpublished).

<sup>2</sup> H. A. Bethe and J. Ashkin, EXPERIMENTAL NUCLEAR PHYSICS, E. Segre, John Wiley and Sons, New York (1953).

$$S = K' z^2/v^2, \quad (8)$$

where

S = mass stopping power of incident particle in the medium,

K' = proportionality constant,

z = charge on incident particle,

v = velocity of incident particle.

For the alpha particle and the proton to have equivalent velocities, the energy of the proton must be 1/4 the energy of the alpha particle since

$$1/2 M_{\alpha} v_{\alpha}^2 = E_{\alpha},$$

and

$$1/2 M_p v_p^2 = E_p.$$

Solving simultaneously and keeping the velocities equal

$$E_p = M_p/M_{\alpha}.$$

$$E_p = 1/4 E_{\alpha}. \quad (9)$$

A proton having the equivalent velocity of a 5.14 Mev alpha particle would have an energy of 1.285 Mev. The mass stopping power in air corresponding to protons of this energy is given by Bethe<sup>1</sup> as

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<sup>1</sup> Op. Cit.

200 Mev/gm/cm<sup>2</sup>. With this information, it is possible to evaluate the constant of proportionality (K') in equation (8).

$$200 \text{ Mev/gm/cm}^2 = K' \frac{z_p^2}{v_p^2},$$

where

$z_p$  = charge on proton = e,

$v_p$  = velocity of proton.

Solving for K' we obtain

$$K' = 200 \frac{v_p^2}{z_p^2} \frac{\text{Mev}}{\text{gm/cm}^2} \quad (10)$$

Again making use of equation (8), the mass stopping power of a 5.14 Mev alpha particle can be determined.

$$S_{\text{air}} = \frac{200 \frac{v_p^2}{z_p^2} \frac{z_\alpha^2}{v_\alpha^2} \text{Mev}}{\text{gm/cm}^2}$$

$$S_{\text{air}} = \frac{200 \frac{v_p^2}{z_p^2} \frac{z_\alpha^2}{v_\alpha^2} \text{Mev}}{\text{gm/cm}^2}$$

$$S_{\text{air}} = 800 \text{ Mev/gm/cm}^2 \quad (11)$$

$z_\alpha$  = charge on alpha particle =  $2z_p$ .

$v_{\alpha}$  = velocity of alpha particle =  $v_p$ .

$S_{\text{air}}$  = mass stopping power of air for 5.14 Mev  
alpha particles.

The energy dissipated per centimeter of path in the medium can be obtained by multiplying the mass stopping power by the density of the medium. In nitrogen, the density at the pressure used in the determination is  $1.65 \times 10^{-3} \text{ gm/cm}^3$ . The absolute mass stopping power of nitrogen is defined as the relative mass stopping power of nitrogen times the absolute mass stopping power in air. The mass stopping power of the alpha particle in nitrogen can then be calculated.

$$S_{N_2} = S_{\text{air}} \times P_N .$$

$$S_{N_2} = (800 \text{ Mev/gm/cm}^2) \times (1.01) .$$

$$S_{N_2} = 808 \text{ Mev/gm/cm}^2 . \tag{12}$$

$S_{N_2}$  = mass stopping power in nitrogen.

$S_{\text{air}}$  = mass stopping power in air.

$P_{N_2}$  = relative mass stopping power in nitrogen.

Converting this to energy lost per centimeter of path,

$$\frac{dE}{dx} = S_{N_2} \times \delta N_2 .$$

Then

$$\frac{dE}{dx} = \frac{808 \text{ Mev} \times 1.65 \times 10^{-3} \text{ gm}}{\text{gm/cm}^2 \quad \text{cm}^3} .$$

or

$$\frac{dE}{dx} = 1.33 \text{ Mev/cm} . \quad (13)$$

The path length in the collimator was 0.48 centimeters, therefore the total energy lost by the particle in the collimator was

$$E_c = 1.333 \text{ Mev/cm} \times 0.48 \text{ cm} ,$$

or

$$E_c = 0.640 \text{ Mev} . \quad (14)$$

Since the time rate of change of voltage, the energy lost in the collimator, and the W value of nitrogen are known, the proportionality constant in equation (6) can be determined. The W value of nitrogen, as reported by Bortner<sup>1</sup> is  $36.3 \pm 0.3$  electron volts per ion pair.

$$W = \frac{K (E - E_c)}{dV/dt} ,$$

or

$$K = \frac{W (dV/dt)}{(E - E_c)} .$$

Then

$$K = \frac{(36.6 \pm 0.3) (960 \pm 5) \text{ ev millivolts}}{(5.14 - 0.64) \times 10^6 \text{ ev ip minute}} ,$$

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<sup>1</sup> Op. Cit.

or

$$K = (7.74 \pm 0.011) \times 10^{-3} \frac{\text{millivolts}}{\text{ip-minute}} . \quad (15)$$

In order to find the W value of water vapor, the time rate of voltage change across the capacitor and the energy lost in the collimator must be known. The saturation curve for water vapor, shown in Fig. 12, shows that saturation current is neared when a collection voltage of approximately 3000 volts is applied to the chamber.

It is possible to extrapolate this curve to the most probable saturation current through the use of the theory by Jaffe as applied by Wilkinson.<sup>1</sup> Wilkinson shows that if the time rate of change of voltage across the capacitor, observed at various collecting fields, is plotted against the Hankel Function, which is a constant times the square of the field intensity in volts per centimeter, the value of the saturated ion current will occur where the line intersects the ion current axis. Figure 14 shows this extrapolation applied to water vapor data. The constant, which is adjusted until a straight line is obtained, was  $10^{-3}$ . The extrapolated value of the ionization current for water vapor was  $935 \pm 5$  millivolts per minute.

The same procedure was used for calculating the energy lost in the collimator when filled with water vapor as was used when it was filled with nitrogen. The relative mass stopping power of water vapor

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<sup>1</sup> D. H. Wilkinson, IONIZATION CHAMBERS AND COUNTERS, Cambridge University Press, Cambridge (1950).

was derived through use of the additive law developed by Rutherford. The law states that the relative mass stopping power of a compound can be expressed as

$$P_c = \sum F_i P_i ; \quad (16)$$

where

$P_c$  = relative mass stopping power of the compound,

$F_i$  = fractional weight of element  $i$ ,

$P_i$  = relative mass stopping power of element  $i$ .

In water, hydrogen has a fractional weight of  $2/18$  or  $0.111$  and a relative mass stopping power of  $3.0$ . Oxygen has a fractional weight of  $0.899$  and a relative mass stopping power of  $0.96$ . Summing over the two components of water,

$$P_{H_2O} = (0.111 \times 3.0) + (0.899 \times 0.96) ,$$

or  $P_{H_2O} = 1.2 . \quad (17)$

To find the absolute mass stopping power, the relative mass stopping power is multiplied by the mass stopping power of air which is  $800 \text{ Mev/gm/cm}^2$ .

$$S_{H_2O} = 1.2 \times 800 \text{ Mev/gm/cm}^2 ,$$

or  $S_{H_2O} = 960 \text{ Mev/gm/cm}^2 . \quad (18)$

Multiplying this by the density of water at 125° C, the energy lost per centimeter of path in water vapor is obtained.

$$\frac{dE}{dx} = 960 \times 1.3 \times 10^{-3} \frac{\text{Mev}}{\text{cm}},$$

or

$$\frac{dE}{dx} = 1.248 \frac{\text{Mev}}{\text{cm}} . \quad (19)$$

To find the energy lost in the collimator, the energy lost per centimeter is multiplied by the path length in the collimator,

$$E_c = 1.248 \text{ Mev/cm} \times 0.48 \text{ cm},$$

or

$$E_c = 0.599 \text{ Mev} . \quad (20)$$

We can now determine the W value of water vapor from equation (6) since K was evaluated for nitrogen,  $dV/dt$  is known from the extrapolated value of the saturation current for water vapor, and  $E_c$  has been calculated.

The determination is as follows,

$$W = K \frac{(E - E_c)}{dV/dt} .$$

$$W = \frac{(7.744 \pm 0.011) \times 10^{-3} (5.14 - 0.599) \times 10^6 \text{ ev}}{(935 \pm 5) \text{ ion pair}} ,$$

or

$$W = (37.6 \pm 0.2) \text{ ev/ion pair} . \quad (21)$$

To verify the validity of saturation extrapolation, the collection volume was enlarged to permit collimation at an angle of approximately  $20^\circ$  with the collection field. According to Jaffe,<sup>1</sup> this should reduce the rate of recombination. A larger number of ions would be formed near the periphery of the collection volume with this arrangement; therefore, ethylene, having a low ion diffusion coefficient, was used as the calibration gas.

The saturated time rate change of voltage across the capacitor was  $(1090 \pm 5)$  millivolts per minute. The saturation current curve is shown in Fig. 15. The energy lost in the collimator, calculated as above, was 0.72 Mev. This gave a proportionality constant of  $(6.90 \pm 0.03) \times 10^{-3}$  for equation (6).

In water vapor, the saturation curve (Fig. 16), extrapolated by the Jaffe theory as applied by Wilkinson<sup>2</sup> (Fig. 17) shows a saturation value of  $(845 \pm 5)$  millivolts per minute. The energy lost in the collimator was calculated to be 0.52 Mev.

Using the value of  $K$ ,  $dV/dt$ , and  $E_c$  obtained in this determination, equation (6) was used to calculate the  $W$  value of water vapor.

$$W = \frac{(6.90 \pm 0.03) \times 10^{-3} (5.14 - 0.52) \text{ ev}}{(845 \pm 5) \text{ ion pair}},$$

or  $W = 37.7 \pm 0.2 \text{ ev/ion pair.}$

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<sup>1</sup> Op. cit.

<sup>2</sup> Op. cit.

The results of the two determinations indicate that the Jaffe extrapolation is valid.

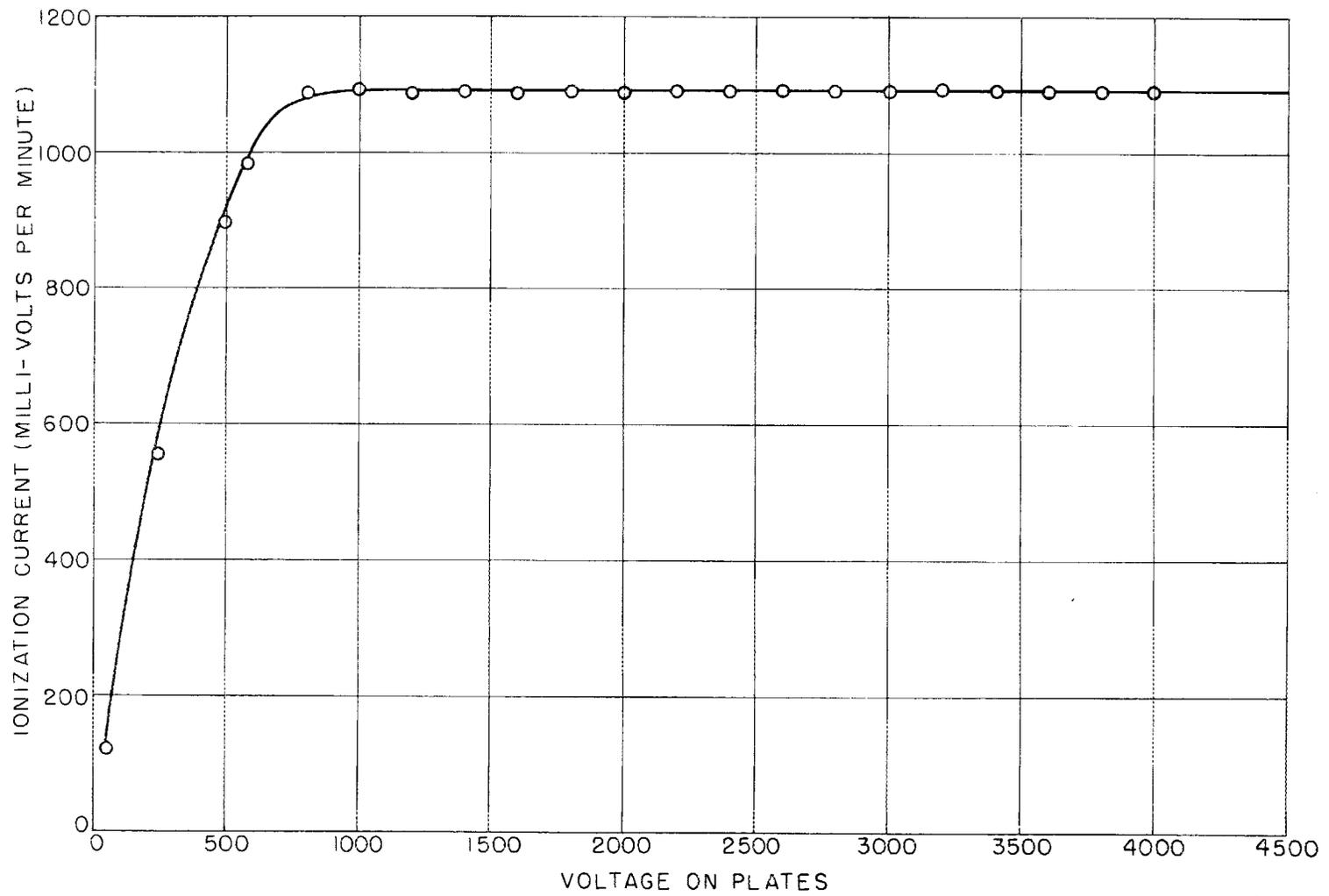


Fig. 15. Ionization Saturation Curve of Ethylene at 1000 mm Hg.

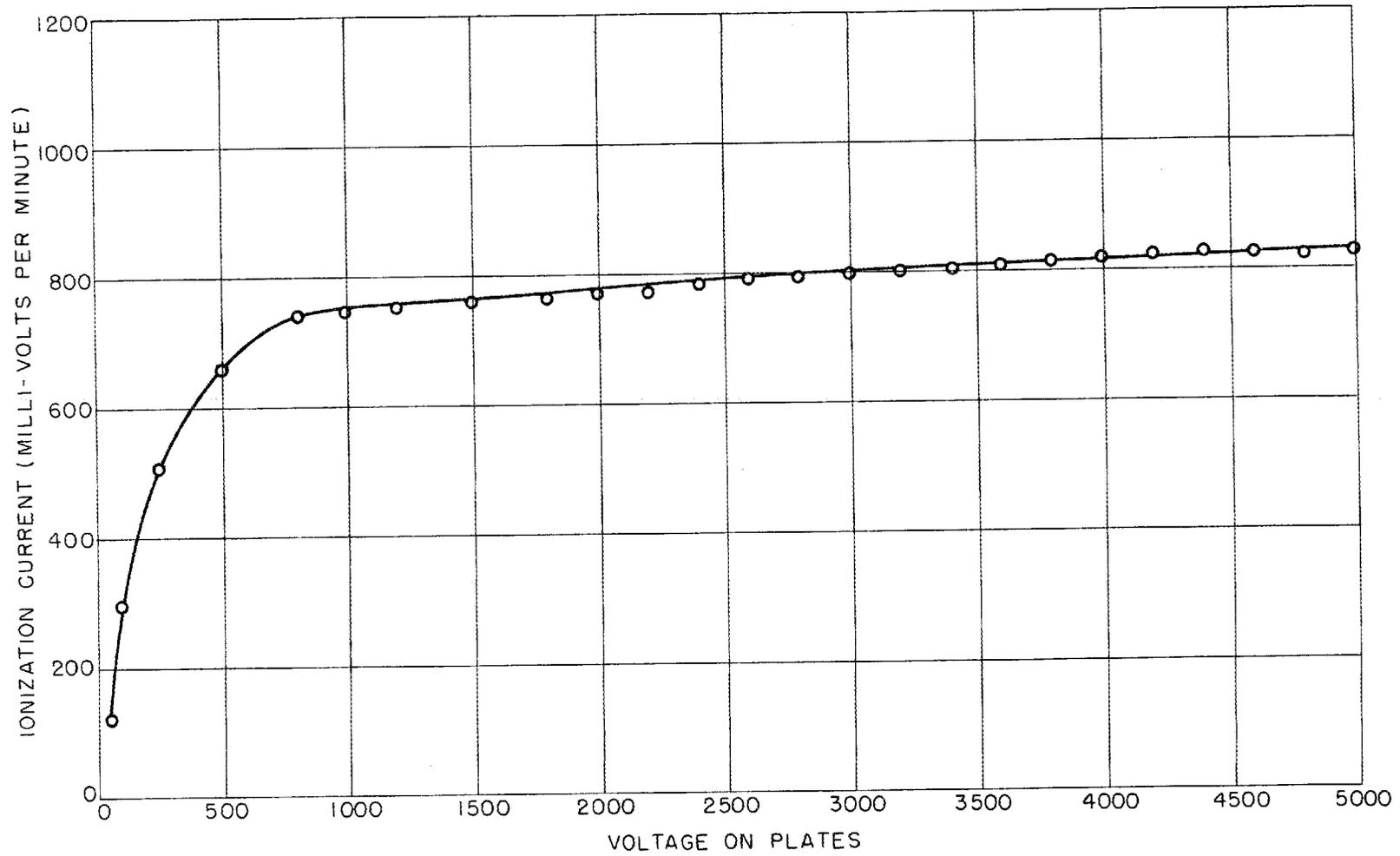


Fig. 16. Ionization Saturation Curve of Water Vapor for Second Determination.

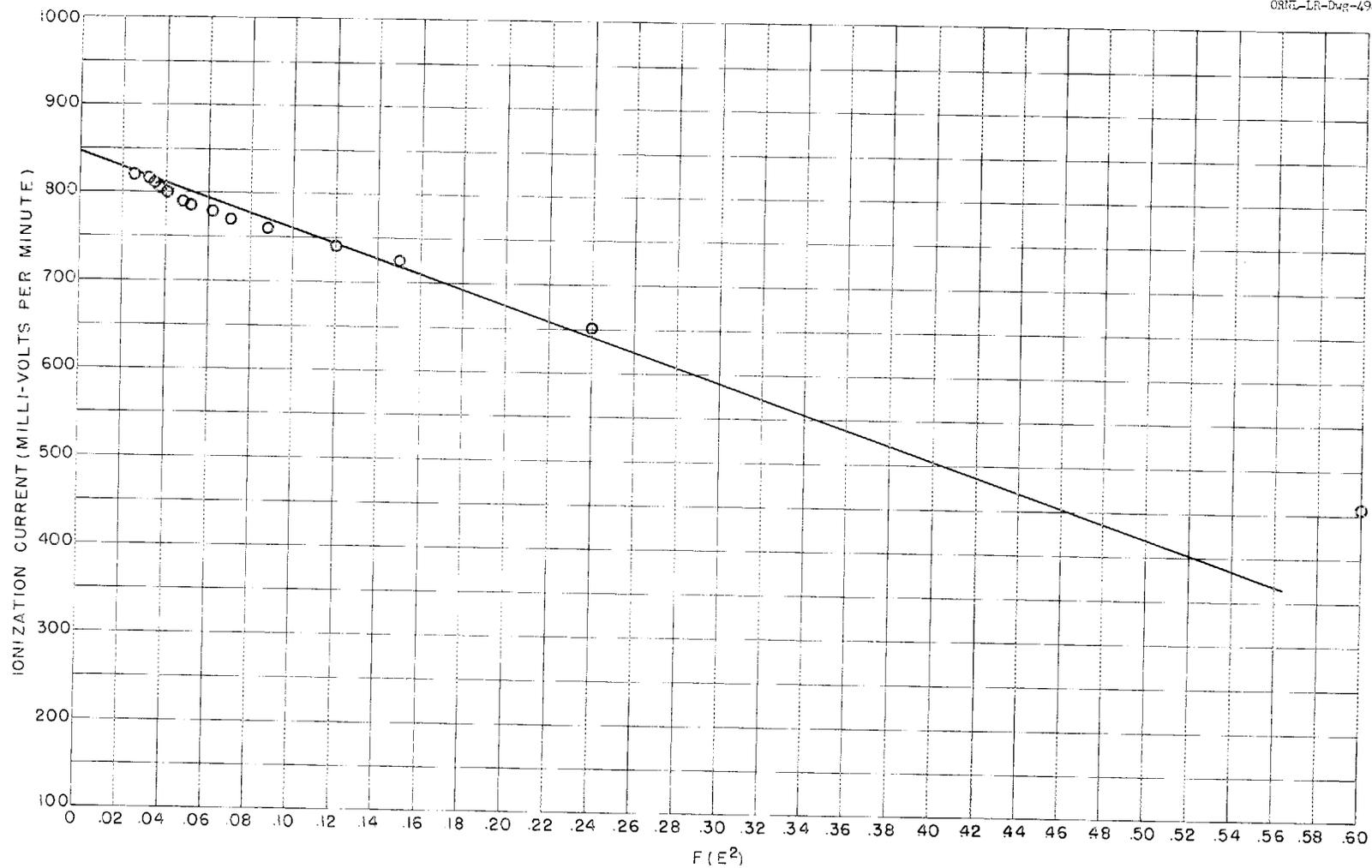


Fig. 17. Jaffe Extrapolation of Water Vapor Saturation Curve for Second Determination.

## V. DISCUSSION

An energetic heavy charged particle, in its passage through matter produces ionization contributing to its energy loss in two different ways. In the primary collision with the electrons in an atom, the most probable of the ionizing collisions are those in which a relatively slow secondary electron is ejected with kinetic energy smaller than the ionization potential. In a small percentage of the collisions, however, the secondary electrons are ejected at relatively high energies, the maximum being

$$E_m = 4mE/M ,$$

where

$E_m$  = maximum energy of secondary electron,

$m$  = mass of electron,

$M$  = mass of alpha particle,

$E$  = energy of alpha particle.

These high energy electrons, called delta rays go on to produce further ionization in the atoms of the stopping medium. Ions produced by these rays are visible in cloud chamber photographs and amount to a few ions per centimeter at the beginning of the path.

Total ionization is the sum of the primary and secondary ionization. It is an experimental fact that the average energy lost per ion pair formed is nearly the same regardless of the energy of the ionizing particle. It is also nearly the same for alpha particles, protons, electrons, etc. Furthermore, the energy lost per ion pair does

not vary greatly for the different stopping gases, varying from 25 ev per ion pair for butane to 46 ev per ion pair for helium.

These facts have been explained in a semi-quantitative theory by Fano.<sup>1</sup> Fano considers the total energy available for ionization regardless of whether it resides in the primary particle or in a delta ray. In a collision in which the atom is excited by either the primary particles or a delta ray, the available energy is reduced by the excitation energy. If the atom is ionized and the kinetic energy of the ejected electron is less than the ionization potential, the total energy given to the atomic electron is lost from the available energy. However, if a delta ray of kinetic energy greater than the ionization potential is produced, its kinetic energy is still available for further ionization, and the expenditure of available energy is considered to be only the ionization potential. The average amount of available energy is then

$$W = \frac{\sigma_e W_e + \sigma_{i1} W_{i1} + \sigma_{i2} I}{\sigma_{i1} + \sigma_{i2}},$$

where

$W$  = average amount of available energy,

$\sigma_e$  = probability that atom is excited by either primary particle or delta ray,

$W_e$  = amount by which available energy is reduced in excitation of atom by primary particle or delta ray,

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<sup>1</sup> Op. Cit.

$\sigma_{i1}$  = probability that atom is ionized and electron ejected with energy less than ionization potential,

$W_{i1}$  = amount of energy lost from the available energy when the atom is ionized and an electron ejected with energy less than the ionization potential,

$\sigma_{i2}$  = probability of an event where a delta ray of kinetic energy greater than the ionization potential,

$I$  = ionization potential.

The ratio of the various probabilities changes very little with energy. Also the average energy expenditures  $W_{e1}$  and  $W_{e2}$  are independent of the primary particle energy. Since the probability is small, this explains in a qualitative way the constancy of the  $W$  value with energy. The  $W$  value can be calculated to a first approximation by finding the total energy lost in all low energy collisions and the probability  $\sigma_{i1}$ .

Fano's<sup>1</sup> theory also explains the experimental result that the energy spent per ion pair is nearly the same for all substances regardless of their ionization potentials. To see this, consider first the rare gases with very high ionization potentials. Their excited states lie in a very narrow energy region close to the ionization potentials,

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<sup>1</sup> Op. Cit.

therefore the total transition probability to all discrete states,  $\sigma_e$ , is small and nearly every inelastic collision leads to ionization. Thus while  $W_{il}$  is large, the energy wasted in excitation  $\sigma_e W_e$  is small and  $W$  is only slightly higher than  $I$ . Conversely, for an alkali atom, for which the ionization potential is small, an overwhelming fraction of the collisions lead to excitation and a larger amount of energy is wasted in this process, therefore the  $W$  value is much greater than  $I$ .

Fano<sup>1</sup> made explicit calculations for hydrogen ( $I$  of 15.6) and helium ( $I$  of 24.5). He found a  $W$  value of 36 ev per ion pair for hydrogen, and 46 ev per ion pair for helium. Experimentalists find a value of 37.0 ev per ion pair for hydrogen, and 46 ev per ion pair for helium. The  $W$  value of hydrogen is very close to the experimental value while the value for helium is much too low. It appears that there is a fundamental process not considered in the theory of Fano.

Experimental evidence of a real variation of  $W$  value with the mass, energy or velocity of the incident particle is conflicting. Little more than qualitative results are available and no real conclusions can be made.

Hanna<sup>2</sup> has presented an argument based on a concept of a constant  $W$  value for incident particle energies above 4.0 Mev and a varying  $W$  value for particles with less energy. His reasoning is as follows,

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<sup>1</sup> Op. Cit.

<sup>2</sup> G. C. Hanna, Phys. Rev. 80, 530 (1950).

Let

- $W^*$  = the instantaneous  $W$  value of a particle,  
 $I$  = the ionization potential of a stopping medium,  
 $E$  = the energy of the incident particle,  
 $E_{\alpha}$  = the wasted energy.

Then

$$E = W^* I + E_{\alpha} .$$

At extremely low energies, all energy is expended in elastic collisions. In this case  $I$  becomes 0 and  $E_{\alpha}$  equals  $E$ . At higher energies, ionization is a progressively more probable event and  $E_{\alpha}$  increases with, but not as fast as  $E$ . At a sufficiently high energy, the fraction of energy used in ionization events becomes constant.

It was stated earlier that the energy lost per ion pair created is nearly independent of energy. Jesse, Forstat, and Sadauskis<sup>1</sup> have shown that the number of ion pairs formed in argon is proportional to the energy of the particle within 0.5%. The 0.5% discrepancy with energy showed no trend. Grey<sup>2</sup> deduced this independence in a survey article of old experiments of Gurney. From the experiments, it was concluded that  $W$  either varies in the same way for argon, helium, and neon or is constant for all three.

The discrepancy between the value of  $W$  calculated by the theory of Fano<sup>3</sup> and those determined experimentally is quite appreciable. This

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<sup>1</sup> Jesse, Forstat, and Sadauskis, Phys. Rev. 75, 1110 (1949).

<sup>2</sup> Ibid.

<sup>3</sup> Op. Cit.

discrepancy might be explained if the ion collection efficiency were not 100% as was thought to be the case. Some evidence is given for this by Kimura et al.<sup>1</sup> They repeated the experiments of Holloway and Livingston<sup>2</sup> and succeeded in raising the values somewhat.

Much of the experimental work in ionization has been done on argon. Work, currently being done at the Oak Ridge National Laboratory by Hurst and Bortner, indicates that minute amounts of impurities radically affect the electron drift rate and pulse heights produced by alpha particles in argon. It is hoped that when these data are analyzed, some facts pertinent to ionization theory may be disclosed.

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<sup>1</sup> K. Kimura, R. Ishiwari, K. Yuasa, S. Yamishita, K. Miyako, and S. Kimura, J. Phys. Soc. Japan 7, 111 (1952).

<sup>2</sup> H. Holloway and M. Livingston, Phys. Rev. 54, 18 (1938).

## CONCLUSION

The W value of water vapor has been determined as  $37.6 \pm 0.2$  electron volts per ion pair. Validity of these measurements is based on the assumption of 100% ion collection. This assumption is valid if all ions are collected before they recombine, but as mentioned in section V, this is still a point of controversy.

According to theory, recombination is a function of the angle at which the incident particle traverses the collecting field. Determinations of the W value of water vapor were made at angles of  $0^\circ$  and  $20^\circ$  with the same result. It is, therefore, concluded that ion collection was 100% and that the results are valid.

Although the W value of water vapor is higher than either hydrogen or oxygen, the value is not unreasonable since the W value is characteristic of the molecular structure. Since water vapor changes in molecular structure as the temperature varies, there is a possibility that the W value in water vapor may change, however no indication of this was observed in this study.