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THE ANGULAR DISTRIBUTION AND POLARIZATION
OF AN ION-PAIR BY THE IONIZATION
OF 1000 VOLT ELECTRONS IN HBr

by

Frederick William Buchler

A THESIS

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
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THE AVERAGE ENERGY REQUIRED FOR THE FORMATION OF AN ION-PAIR BY THE TOTAL ABSORPTION OF 1000 VOLT ELECTRONS IN AIR

By

Frederick William Kuether

AN ABSTRACT

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

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THE AVERAGE ENERGY REQUIRED TO FORM AN ION-PAIR

OF LOW-ENERGY ELECTRON IMPACT

OF 1000 VOLT ELECTRONS IN AIR

Frederick William Gunther

An instrument has been constructed for the measurement of the ionization properties of slow electrons in gas. Preliminary measurements indicate that 1000 ev electrons totally absorbed in air produce 27.5 ± 3% ion-pairs on the average. This allows the determination of W, the average energy required for the formation of an ion-pair, to be 36.5 ev ± 4.5% for the particular case of 1000 ev electrons absorbed in air.

The method of measurement, which appears quite simple, consists of a comparison of the current due to positive ions removed from the ionization chamber by suitable electric fields with the current due to the electrons entering the ionization chamber. The ratio of these currents, which of course cannot be measured simultaneously, yields K, the average number of ion-pairs formed per initial low energy electron. If the low energy electron with energy L ev produces K ion-pairs per initial electron, W, the average energy required for the formation of an ion-pair is given by the ratio L/K.

The present instrument is capable of measuring R, the range of electrons, as well as W for electrons of energy between 200 ev and 2000 ev. With this information and the experimentally known specific ionization ion-pair formation per unit track length, the experimentally difficult to measure s, the total track length, may be determined as a function of initial electron energy.

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THE AVERAGE ENERGY REQUIRED FOR THE FORMATION OF AN ION-PAIR BY THE TOTAL ABSORPTION OF 1000 VOLT ELECTRONS IN AIR

IONIZATION PROCESSES

Various particles, such as alpha-particles, neutrons, protons, electrons, gamma-rays, x-rays, etc. are often thought of as possessing different over-all patterns of ionization as the particles fly through matter. The differences in these patterns are more frequently emphasized than their common features. As will be indicated in the following sections, a very significant fraction of the total ionization caused by the initial particle is due to delta-rays. Delta-rays are the low energy (a few hundred volts or less) electrons ejected by the initial particle from the molecules with which it collides.

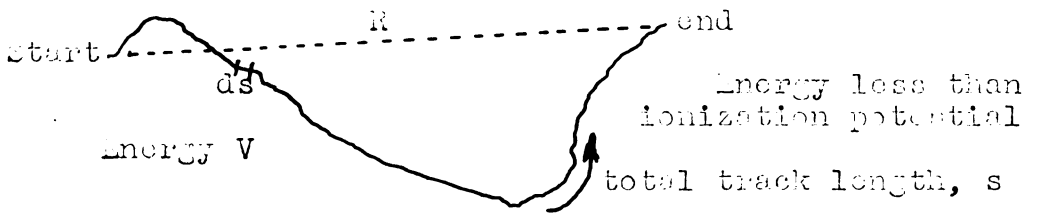
When the initial particle traverses a medium with energy equal to the ionization potential of the medium, there is a finite probability that the particle will yield all its energy by an inelastic collision and an electron will be ejected from the target atom or molecule with negligible velocity. It is vastly more probable that the atom or molecule is merely excited and later returns to its ground state by radiation. The atom or molecule may also have its kinetic energy increased by the collision.

As the energy of the particle is increased, the probability of ionization (electron ejection, ion-pair formation) increases greatly. When the energy is increased to twice the ionization potential it becomes possible for two ion-pairs to be formed by the initial particle. The initial particle is itself not necessarily involved in forming the second ion-pair, for the positive ion or more probably the electron of the first ion-pair may be ejected with sufficient energy to cause ionization by collision. Hence it is not only the behavior in collision of the initial particle but also those of the positive and particularly of the slow electron or delta-ray which contributes to the observed collision phenomena. As the energy of the incident ray or particle becomes large enough to form many ion-pairs, the possibilities for the sequence in ionization become very numerous. However the total ionization can only be due to the ionization caused by the components.

For an alpha-particle traversing air the ionization phenomena must be due to the alpha-particle, ejected electrons, positive ions, and negative ions. The negative ion is formed by attachment of an electron to a neutral molecule or atom. Since oxygen is electro-negative,[23] the negative ions in air would be O_2^-, etc. For some target atoms and molecules there are further complicating effects such as the creation of multiply charged ions of mercury, Hg^+, Hg^{++}, Hg^{+++}, Hg^{++++}, etc. which may be formed by relatively low energy collisions.

Ionization by electro-negative molecules, multiple ionization, dissociation of the target molecule, etc. are effects of secondary importance except in isolated cases.

Even in the absence of the secondary effects mentioned the collision phenomena remain complex. Hence we digress from the present account to sketch the physical situation and to present a goal for the instrument which has been constructed. The following remarks are confined to electrons as the incident particle. The behavior of other incident particles is quite similar.



The wavy track is characteristic of the path of an electron[38] starting with an energy of v electron volts and ending when the electron is no longer capable of producing ion pairs. The range of the electron, R, is taken as the linear distance between the ends of the track of the electron. The total length of the track of the electron, s, is always equal to or greater than the range of the electron. There is of course considerable statistical variation in both R and s for electrons of a given energy. Hence R and s are taken as the average range and average track length for many electrons of the same energy.

Experimentally it is much less difficult to measure R than to measure s for a particle of given energy. In fact at the present state of knowledge it does not appear possible to measure s. However, in an indirect manner some knowledge of the behavior of s can be obtained:

Let I be the ion-pairs formed per cm of the track of the electron, and let K be the total number of ion-pairs formed along the track. Then $dK = I\,ds$, or for a particle of energy V electron volts $K_V = \int_V^0 I\,ds$. The limits are given in terms of the energy of the electron.

The problem is to integrate this expression for K_V. This cannot generally be done because of the unknown track of the electron. However the specific ionization I can be determined with some experimental accuracy as a function of the energy and range of the electron, or we may write $I = f(V)$. Obviously some relation exists between s and the energy and range of the electron. Let $s = L(V) = J(R)$, then ds can be denoted: $ds = L'(V)\,dV = J'(R)\,dR$. Hence the integral for K_V can be stated in these forms:

$$K_V = \int_V^0 f(V)\,L'(V)\,dV = \int_V^0 f(V)\,J'(R)\,dR = V/W_V$$

where W is the average energy for the formation of an ion-pair. From the first integral above and a knowledge of f(V), V, and W_V, we ought to be able to deduce L(V). Further, with accurate measurements of the range, R, as a function of the initial energy of the electron, V; J(R) may be determined since

$$K_V = \int_V^0 f(V)J'(R)L'(V)\,dV$$

Providing we write R = L(V); dR = L'(V) dV

The goal of the equipment which is to be described is to measure both the average energy for the formation of an ion-pair, W, and the range, R, as a function of the initial energy of the electrons. The present work deals only with the aspects of the first problem, the determination of the energy for the formation of an ion-pair. The following discussion returns to the more general case of the ionization phenomena of a particle.

IONIZATION [illegible]

The average energy, W, for the formation of an ion-pair has often been assumed to be a constant independent of the energy of the incident particle. It is now known that this condition holds only as long as the velocity of the particle is comparable to or greater than the velocity of orbital electrons. In the case of air, this is about 6 x 10^8 cm/sec[18] which corresponds to 100ev electrons, 0.2 Kev protons, and 0.8 Kev alpha-particles. Williams[41] points out that the constancy of W is implied in the theoretical result that the relative numbers of excitation collisions and of light ionization collisions (in which the energy losses are of the order of the ionization potential) are practically independent of the nature and velocity of the moving particle. The frequency of more violent collisions will of course depend upon the particle velocity, but this is relatively unimportant as nearly all the energy is ultimately dissipated in light ionizing collisions. Below the velocity of orbital electrons there is no theoretical guide. However, experimental work with electrons, protons and alpha-particles indicates that W is not a constant but increases with decreasing energy.

Experimentally the determination of W requires the knowledge of the total energy dissipated by the moving particle for the number of ions formed. The determinations divide themselves into two groups. Absolute determinations

in which the number and energy of the moving particles are known from within the experiment and the number of ion-pairs formed per absorbed particle is observed directly (as in cloud chamber studies) or is an average of many particles (as in ionization chamber studies). Secondly, relative determinations in which for example, the effectiveness of an ionizing agent is compared with the Ra C' alpha-particle ionization.

The Ra C' alpha-particle is not suitable for absolute determinations. The accepted energy of the particle according to Lind[28] and Rutherford, Chadwick and Ellis[30] is accurately known to be 7.68×10^6 ev. The strength of a source may be measured accurately in terms of the gamma-ray activity of Ra (C + D) with which the Ra C' is in equilibrium, and the number of alpha-particles emitted per second per gram of radium is known to be 3.71×10^{10}. Hence when the ionization of Ra C' alpha-particles is measured, W may be calculated for a 7.68×10^6 ev alpha-particle. The variation of W with the energy of the initial particle is more easily measured when the initial particle can be generated over a wide range of energies, as in the case of electrons where monoenergetic electrons of the desired energy can be formed with considerable ease.

It should be emphasized that the initial particle must be totally absorbed if its initial energy is to be used as the sole criterion of the energy dissipated by the particle. If total absorption does not occur, some measurement of the

residual energy of the particle must be made to determine the energy expended in ionization. The latter procedure of course introduces error.

THE IMPORTANCE OF DELTA-RAY IONIZATION

In 1916 by photographing the tracks of alpha-particles in hydrogen at a low pressure in a Wilson cloud chamber, Bumstead[6] became the first to obtain definite evidence of electrons radiating from an alpha-particle track. Bumstead estimated 2000ev to be the maximum energy of these slow electrons or delta-rays. Only a few exceptional electrons had sufficient velocity to emerge distinctly, but there appeared to be large numbers of delta-rays with small velocities, which formed projections on the track giving it a ragged edge. In 1922 C. T. R. Wilson[42] studied the angular distribution of delta-rays as a function of their energy. In his experiments Wilson estimated that the delta-ray of maximum range had a velocity about twice that of the alpha-particle. It appeared; however, to be ejected nearly at right angles to the direction of motion of the alpha-particle, and not along the line of motion as the simple collision theory would indicate. In 1926 Chadwick and Emeleus[8] pointed out that the results obtained by Wilson were misleading since the first 0.2 mm of delta-ray track cannot be observed because of the ionization surrounding the alpha-particle track. In hydrogen at normal temperature and pressure they point out that the most probable number of deflections through an angle greater than forty five degrees in the first 0.2 mm of a 2 mm delta-ray is 0.7 and in the first 0.3 mm of a 0.6 mm

delta-ray, it is 5.4. Hence the longer tracks should have a forward direction. This was observed. Since in air the range of a delta-ray of a given energy is only one-fifth that in hydrogen; and the number of scattering electrons and the charge on the nucleus are roughly seven times as great, the chances of deflection through a large angle are so greatly increased that the delta-rays will emerge from the alpha-track at random. Chadwick and Emeleus conclude their study of alpha-tracks in hydrogen, helium, air, and argon with this summary:[9]

> "As far as our observations go, the results are in accord with the view that the delta-ray arises from the collision of the alpha-particle with an electron in the atoms through which it passes. We assume that, for the distances involved in these collisions, the alpha-particle and the electron behave as point charges, and that the law of force between them is that of the inverse square."

Hence it has been established that delta-rays are formed in a straight forward manner as the initial particle traverses matter. However the ionization phenomenon of particles cannot be properly understood until the magnitude of the ionization due directly to the delta-ray electrons has been established. The following sections will deal with this point.

There appears to be little question that a major portion of the ionization caused by the incident particle is due to the secondary ionization of the delta-ray. In an extensive series of experimental observations on the effects of radiation on living cells Lea[25] reports the following importance

TABLE I[36]

DELTA-RAYS EXCEEDING 100ev ENERGY PRODUCED BY ELECTRONS, PROTONS, AND ALPHA-PARTICLES

Electron Energy Kev	*Number of Ions Produced by Delta-rays per Primary Ionization
0.5	0.325
1.5	0.504
3.0	0.597
6.0	0.672
24.0	0.780
96.0	0.856
192.0	0.891
384.0	0.920
Alpha-particle Energy Mev	
1.0	0.718
4.0	0.907
5.0	0.925
6.0	0.939
8.0	0.959
Proton Energy Mev	
1.0	0.905
2.0	0.956
3.0	0.978
4.0	0.981
6.0	1.006
8.0	1.013
10.0	1.018

*Including tertiary electrons, delta-rays produced by delta-rays

of delta-ray ionization. The column at the left of Table I indicates the energy of the incident particle. The column at the right indicates the ratio of the number of ion-pairs formed by the delta-rays of greater than 100 ev energy compared to the number of ion-pairs formed directly by the initial particle. Hence for a 5 Mev alpha-particle 0.925 as many ions are produced by delta-rays of energy exceeding 100 ev as by the alpha-particle. At the same time many delta-rays are formed with less than 100 ev energy. These low energy delta-rays and their ionization products increase the overall number of ions created by delta-rays. C. T. R. Wilson[42] gives the following experimental data for a reasonably fast alpha-particle.

TABLE II

FREQUENCY OF ION-CLUSTERS CONTAINING VARIOUS NUMBERS OF IONIZATIONS

No. of Ion-Pairs in the Cluster	1	2	3	4	>4	Total
Frequency of Cluster of this Size	.43	.22	.12	.10	.13	1.00

Let us assume that ten is the average number of ionizations in the group having more than four ionizations. This should be adequately large for even the fastest initial particles because of the rapid decrease in the probability of high energy ionizations. One can then approximate the ionization yield of the various ion-clusters.

TABLE III

RELATIVE ION YIELD OF CLUSTERS

No. of Ion-Pairs in the Cluster	1	2	3	4	>4
Relative Ion Yield of this Cluster	.43	.44	.36	.40	1.30

Since a 100ev electron can on the average yield about three ion-pairs, approximately forty-two per cent of the ionization due to delta-rays is accomplished by delta-rays of 100ev energy or less. This is probably a lower limit of their importance. One can then show that 1.595 ion-pairs are formed by delta-rays for every ion-pair formed directly by the alpha-particle. Hence a little more than sixty per cent of the total ionization is due to delta-rays. For protons of the same energy this percentage is apparently somewhat higher. Thus the ionization due to moving electrons is an important fact in the total ionization of heavy particles.

EXPERIMENTAL OBSERVATIONS ON ELECTRONS IN AIR

A great amount of work has been done by many observers with considerable disagreement between them. Some of the investigators are: Johnson[21], 1917; Lehmann and Osgood[27], 1927; Schmitz[31], 1928; Buchmann[5], 1928; Lisl[14], 1930; Thomson[40], 1931; Freund[15], 1935; and Gerbes[16], 1935. Lehmann and Osgood proposed the following empirical relation for K, the number of ion-pairs formed in air by an electron of energy V electron volts.

$$K = 0.0225\ (V - 17) \qquad 200ev \leq V \leq 1000ev$$

The accuracy of the determination was probably of the order of ten per cent. In 1931 this relation was confirmed by Thomson for 50 to 270 ev electrons, as well as for high energy electrons. Thomson changed the constant to:

$$K = 0.0270\ (V - 17)$$

and upon the assumption that the linearity holds for electrons of all energies, W becomes:

$$W = \frac{37}{(V-17)/V} = \frac{37}{1-17/V}\ ev$$

These relations disagree with the observations of Freund. He found the energy for the formation of an ion-pair to be 57 ev for 10 ev electrons, however there is reason to question the validity of this result.

In 1935, Gerbes, a student of Lisl, proposed the following empirical relation for W:

$$W = 31.62 + 5.27\ (V-V_i)^{-\frac{1}{2}} \mp 0.08ev$$

V_i is the ionization potential in Kev. Gerbes based this relation upon the work of Lisl (9 to 60 Kev electrons) which he theoretically corrected for the unusually large collection potentials Lisl used, and upon the work of Rigge[16] with 200 ev to 1000 ev electrons in nitrogen. The plus or minus 0.08 ev can hardly be the accuracy of the absolute magnitude of W, for the individual determinations of W by Lisl vary by about five per cent. Further, the conversion of Rigge's work in nitrogen to the equivalent in oxygen is subject to least some error, if not serious error. The Gerbes' relation for W does not hold for the observations of Freund. Apparently W has not yet been determined with sufficient accuracy to determine a valid relation between W and V.

The work described in this thesis has established a value of W for 1000 ev electrons absorbed in air. With the many technical improvements since 1935 and the reports of earlier investigators as a guide, the present instrument has been so constructed that ultimately individual determinations of W as a function of V may be made with an accuracy of plus or minus one per cent. This accuracy will be adequate to ascertain the validity of the expressions which have been advanced by Gerbes and Lehmann and Osgood, for electrons having energies between 200 and 2000 ev.

METHOD OF DETERMINATION OF W

The method used in this work for the determination of W will first be explained in brief outline. Later, details of the construction will be given. The principle of the experiment, which appears very simple, can be seen readily from Figure 1. The beam of electrons formed in the gun chamber is sent through the orifice into an ionization chamber where the energy of the beam is dissipated in the formation of ion-pairs and other processes. The number of ion-pairs formed is measured and this is compared with the number of incoming electrons to determine the average number of ion-pairs formed per initial electron, K. With the knowledge of I and the energy of the initial electron V, the average energy for the formation of an ion-pair W may be calculated by the relation $W = V/K$.

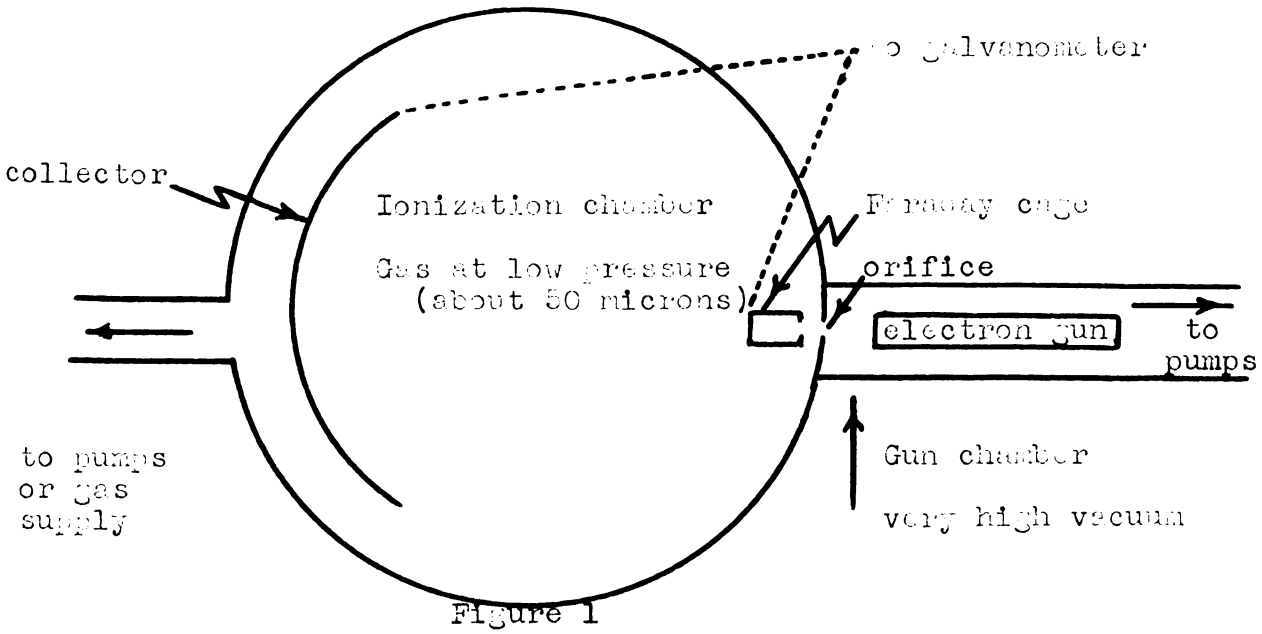


Figure 1

The source of the initial electrons was a conventional cathode ray tube from which the glass envelope had been removed. For the proper operation of the source, the gun chamber was operated at 0.05 microns or less. The initial electrons were directed by the electron gun toward the orifice so that they passed into the ionization chamber. The number of initial electrons was determined by trapping them in a Faraday cage. The Faraday cage was mounted so that it could be removed from the path of the incident electrons to allow these electrons to dissipate themselves within the ionization chamber. The number of ion-pairs formed was measured by applying small positive or negative potentials to force electrons or positive ions to the collector. Two steps were needed to complete one observation of K, the average number of ion-pairs formed per initial electron. First, the initial electron current was measured by the Faraday cage; second, the Faraday cage was removed and the current of ions formed by these electrons was measured by the collector. As these measurements could not be made simultaneously, care was taken to minimize the variation in the number of initial electrons entering the ionization chamber during an observation of K. The determination of K consisted of a comparison of two currents registered by a D'Arsonval wall galvanometer.

To apply the relation W = V/K to determine the average energy required in the formation of an ion-pair, two conditions must be satisfied. First, the initial electrons must suffer so many collisions within the gas of the ionization

chamber that the terminus of their track lies within the limits of the gas in the chamber. This condition, called total absorption, must apply as well to the delta-rays formed by the initial electrons. Second, the initial electrons which enter the ionization chamber through the orifice should be identical, mono-energetic. The first condition was satisfied mainly by adjusting the pressure in the ionization chamber. The details of this will be given in a later section. The second condition cannot be satisfied exactly. However, as will be seen later, it was possible to satisfy this condition to a good approximation. The energy distribution of the initial electrons was determined by applying retarding potentials to the Faraday cage to prevent the collection of electrons having an energy less than the retarding potential. Unfortunately these retarding potentials could not be applied with the gas in the ionization chamber at the normal pressure for total absorption, for a gaseous discharge was formed in this case. This is a source of error which cannot be removed from this method for the determination of W. The present work has done much to reduce this error; it is now believed not to be significant.

DESIGN CONSIDERATIONS

For the Ionization Chamber

The body of the ionization chamber illustrated in Figure 2 was fabricated from three-eights-inch boiler plate and the thirty-by forty-inch door from one-inch hot rolled steel. It was designed to withstand an external pressure of five atmospheres with safety. A twelve-inch spherical collector used in preliminary work is shown in position in Figure 2. The major dimensions of the ionization chamber were chosen to allow the tank to enter the laboratory without the removal of any walls. While it is desirable to have the tank as large as possible to reduce the pressure differential between the ionization chamber and the gun chamber, it did not appear feasible, for reasons of expense, to go beyond a volume of one hundred cubic feet. The useful volume of this tank is about fifty times as great as has been used in previous experiments. The shape of the ionization chamber was chosen to approximate the envelope of the furthest penetrations of the initial electrons. This envelope has an axis of symmetry along the line of flight of these electrons; its dimension should be greatest in the forward direction. For the large scattering angles expected, the forward portion of the envelope would be approximately a hemisphere.

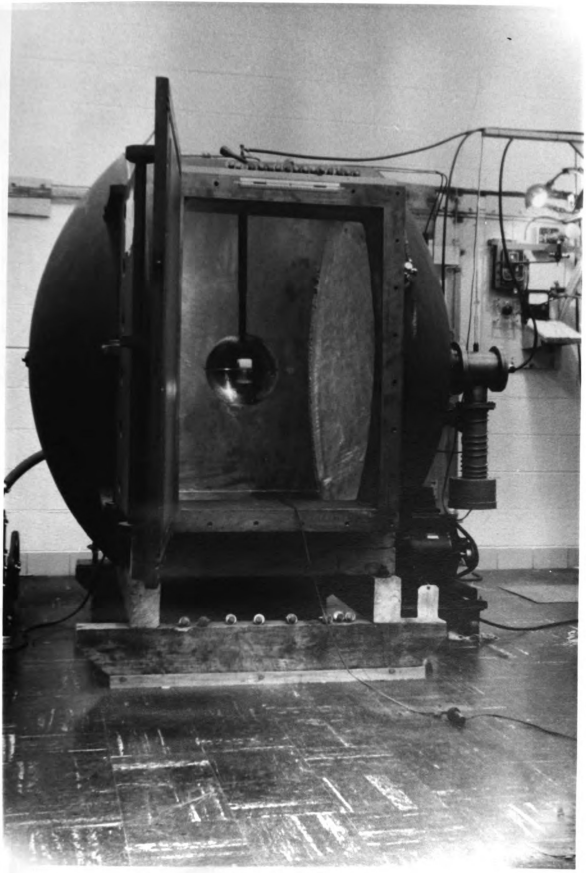


Figure 2. A General View of the Equipment

The twenty- by thirty-inch door illustrated in Figure 3 allows access to the interior of the tank for cleaning. This large door is particularly essential for the insertion of the large sheet metal plates used to collect ions.

Vacuum Requirements of the Ionization Chamber

To obtain a clean sample of air on which to determine W, it is necessary that the ionization chamber first be evacuated to at least one-hundredth of the operating pressure of fifty microns before the introduction of the air. Pressures as low as 0.05 microns can be obtained within twenty-four hours pumping time.

A potentially large source of leakage may be expected along the one hundred twenty inches of vacuum seal required for the ionization chamber door. The seal employed was based upon recommendations very willingly furnished by Radiations Laboratory, University of California. A section is illustrated in Figure 4. A comparison of Figures 3 and 4 indicates that the seal consists of two rubber gaskets mounted in grooves so machined into the door that the maximum squeeze applied to the rubber gasket is limited. The major portion of the eighteen thousand pound force exerted on the door by atmospheric pressure is supported by metal to metal contact. Pump-out holes A and B allow the evacuation of the volume between the two rubber gaskets if desired. The reason for the pump-out holes is two fold; first, in the event of leaks the pressure differential across the inner seal could

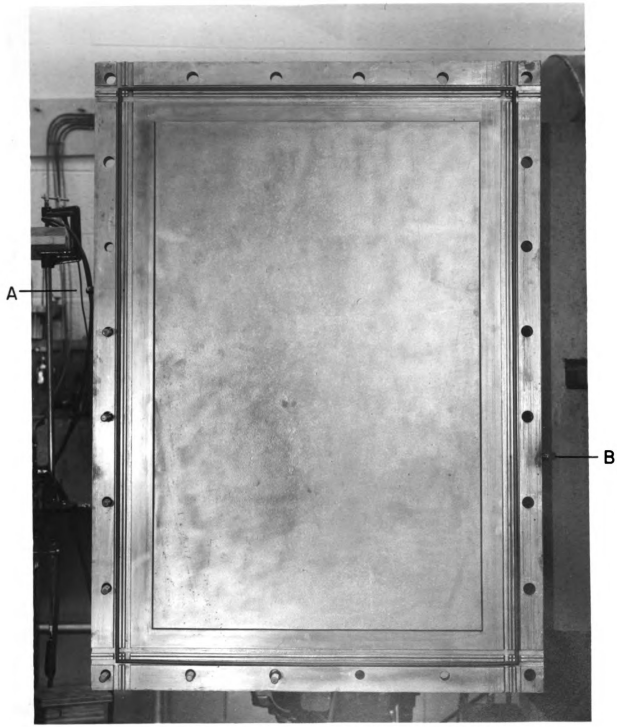


Figure 3. Interior Surface of the 20" by 30" Door

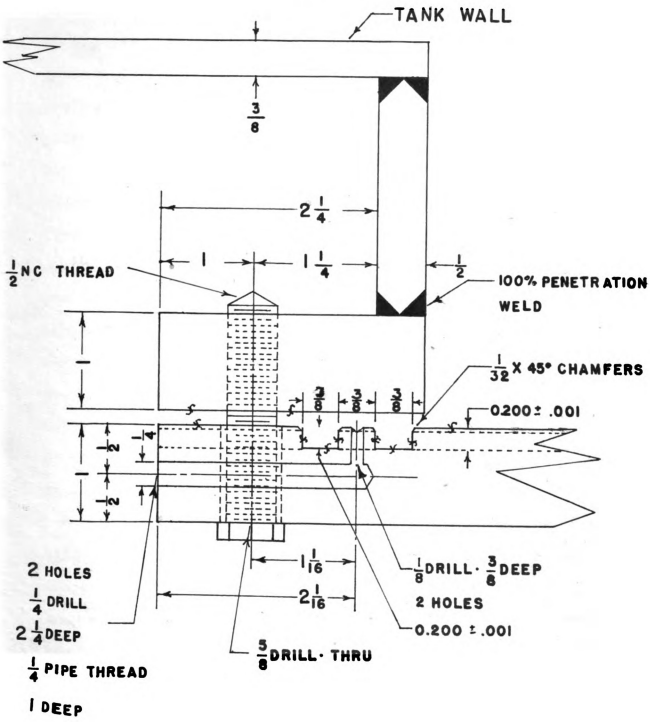


Figure 4

SECTION OF DOOR SEAL

be reduced and with it the magnitude of the leak; second, in the location of leaks it is reasoned that leaks in either of the gaskets may be located if the region between the gaskets can be evacuated and the exhaust of the pumpings analyzed. The door seal is so satisfactory that only one gasket is used and the pump-out holes have been sealed. The rubber gaskets are formed from sixty-durometer round quarter-inch Neoprene rope by cutting the rope at a forty-five degree angle and vulcanizing at the corners. The maximum squeeze on the gasket was intended to be twenty per cent of the diameter of the gasket, a factor of two greater than the ten per cent squeeze which is usually satisfactory for vacuum seals. It is fortunate that a twenty per cent squeeze was used, for in the process of vulcanizing the gasket at the corners, the diameter was reduced by about ten per cent, leaving ten per cent for an adequate seal.

Welds of the one hundred per cent penetration type which are indicated in Figure 4 were used throughout the ionization chamber with excellent results. For a one hundred per cent penetration weld, one or both of the mating pieces are ground to a "V" edge and the weld applied to both surfaces, thus greatly reducing the possibility that blow-holes extend through both welds to form leaks. Since considerable heat is generated in the welding operation, it is frequently difficult to prevent the warping of pieces that are being joined, particularly if their

thicknesses and hence their heat carrying capacities are quite different. The fabricator can overcome warping to a considerable extent by welding at numerous spots to join the two pieces with little heating and then proceeding with the running weld. Some welding strains are inevitable but the warping is usually not bothersome if the strains are symmetrical to the weld. The designer can do much to increase the symmetry of welding strains.

The twenty-four bolts at five and a half-inch intervals forced the door and the mating plate to yield to each other. The door and its mating plate are quite plane. However, in the unbolted condition, there was a wedge between them of about one-fourth inch at the greatest point. This was due to lack of alignment of the hinges of the door.

Vacuum Requirements of Gun Chamber

Upon the assumption that the dimensions of the small orifice connecting the gun chamber and the ionization chamber were small compared to the mean free path on either side of the orifice, one may calculate the net flow of gas from the tank into the gun chamber. This assumption was not strictly valid but could be relied upon to yield the order of magnitude of the effusive flow of gas. At fifty microns the mean free path of an electron is of the order of 1 mm. For a tank pressure of fifty microns opposed by the gun chamber pressure of 0.05 microns on opposite sides of an orifice 0.01 inches in radius, according to equations

developed by Dushmann, the "conductance" of the orifice was 20.1 cm^3/sec and hence the effusive flow into the gun chamber was calculated to be 1.0 micron-liter per second. (The choice of an orifice 0.01 inches in radius will be discussed later.)

To remove this gas at a large rate compared to one micron-liter per second a diffusion pump was chosen with a pumping speed of fifteen micron-liters per second at 10^{-15} mm. of mercury. A micron-liter is a unit proportional to the number of gas molecules; one micron-liter equals a liter of gas at a pressure of one micron, or ten liters of gas at one-tenth micron, etc. The Distillation Products Inc. VMF-260 three-stage oil diffusion pump was chosen because it had an adequate pumping speed. The choice of pumps is restricted to oil diffusion pumps because of the slow pumping speed of mercury diffusion pumps of comparable cost.

The VMF-260 requires a forepressure or exhaust pressure of one-tenth mm. of mercury or lower for satisfactory operation. The pumping action stalls if the pressure differential over the pump becomes too large. A Cenco-Hypervac-25 was chosen for this task. The Cenco-Hypervac-25 has a pumping speed of about twenty-five micron-liters per second at one-tenth mm. of mercury and hence it is capable of creating a sufficiently low forepressure for the VMF-260 diffusion pump. Sullivan[23] (1946) gives a fine account of modern pumping techniques.

The design of a vacuum pumping system is quite like the design of a plumbing system except for the complication caused by the compressibility of the gas. The tubing connecting the gun chamber, diffusion pump and forepump must be adequate to handle the expected flow. The gun chamber and diffusion pump were connected by four-inch tubing; because of the considerably higher pressure between the diffusion pump and the forepump a one-inch tube was adequate there. A vacuum valve was inserted between the diffusion pump and the forepump so that the forepump, when not in operation, could be returned to atmospheric pressure without bringing the rest of the system to atmospheric pressure. The gun chamber and pumping system are shown at the right of the tank in Figure 2.

Electrical and Electronic Components for the Electron Gun

The work of Misle[29] and particularly of Barnes[4] had indicated that the local facilities were not adequate to form highly uniform electron guns. This problem was eliminated by the use of the electron gun from a conventional 3JP1 cathode ray tube, a portion of whose glass envelope had been removed.

The 3JP1 tube with its original socket was inserted in an eleven-prong ceramic socket which was mounted rigidly on the endplate of the gun chamber. This is illustrated in Figure 5. The endplate seals the right hand end of the "T"

Figure 5. Electron Gun Mounted on Endplate

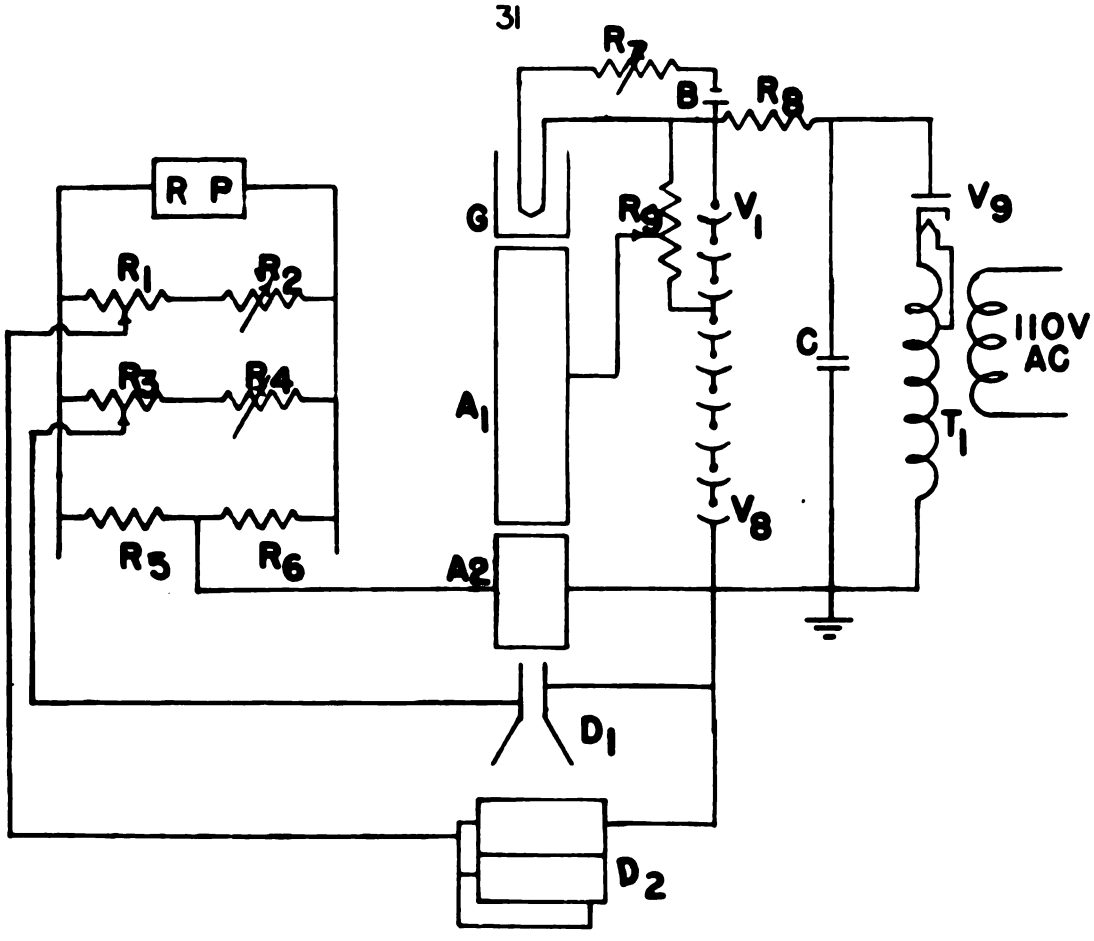
shaped pumping stem illustrated in Figure 3. The heavy conductor seen fastened to the endplate in the same figure is an eight-conductor cable delivering the electrical services necessary for the gun. An octal socket mounted from the outside of the end plate and an octal plug joined to the end of the eight-conductor cable allowed convenient connection and disconnection of the electrical services to the gun.

The electrical services were passed through the vacuum wall on eight copper buss wires which were insulated from each other by a quarter-inch disc of bakelite. Holes snugly fitting the buss wires were drilled through the bakelite and a ball of solder was placed on each of the buss wires so that the solder in contact with the bakelite supported the thrust of atmospheric pressure. The vacuum seal was made by melting Plicene to cover the points of contact of bakelite and metal. Bakelite was used rather than better insulators, such as polystyrene, for polystyrene will not stand up satisfactorily at the temperature needed for melting Plicene. Further, in this experiment, polystyrene showed a tendency to dry in vacuum and develop a cracking or crazing of the surface exposed to the vacuum. This was very troublesome as the quality of a vacuum seal depends upon the condition of the surface for sealing. The bakelite insulator has been in service for two years without signs of deterioration.

As is shown in Figure 5, the glass envelope of the cathode ray tube is broken at about the level of the

deflection plates. The remaining portion of the glass envelope serves as a support for the tube elements. The electron gun after removal of the glass envelope could be returned to a reasonable vacuum within five minutes. However, tubes which were open to the air of the laboratory for two weeks did not appear to be appreciably effected. Hence there was little reason to hurry the installation of a new tube. The author's results are in agreement with those of Bachman[2].

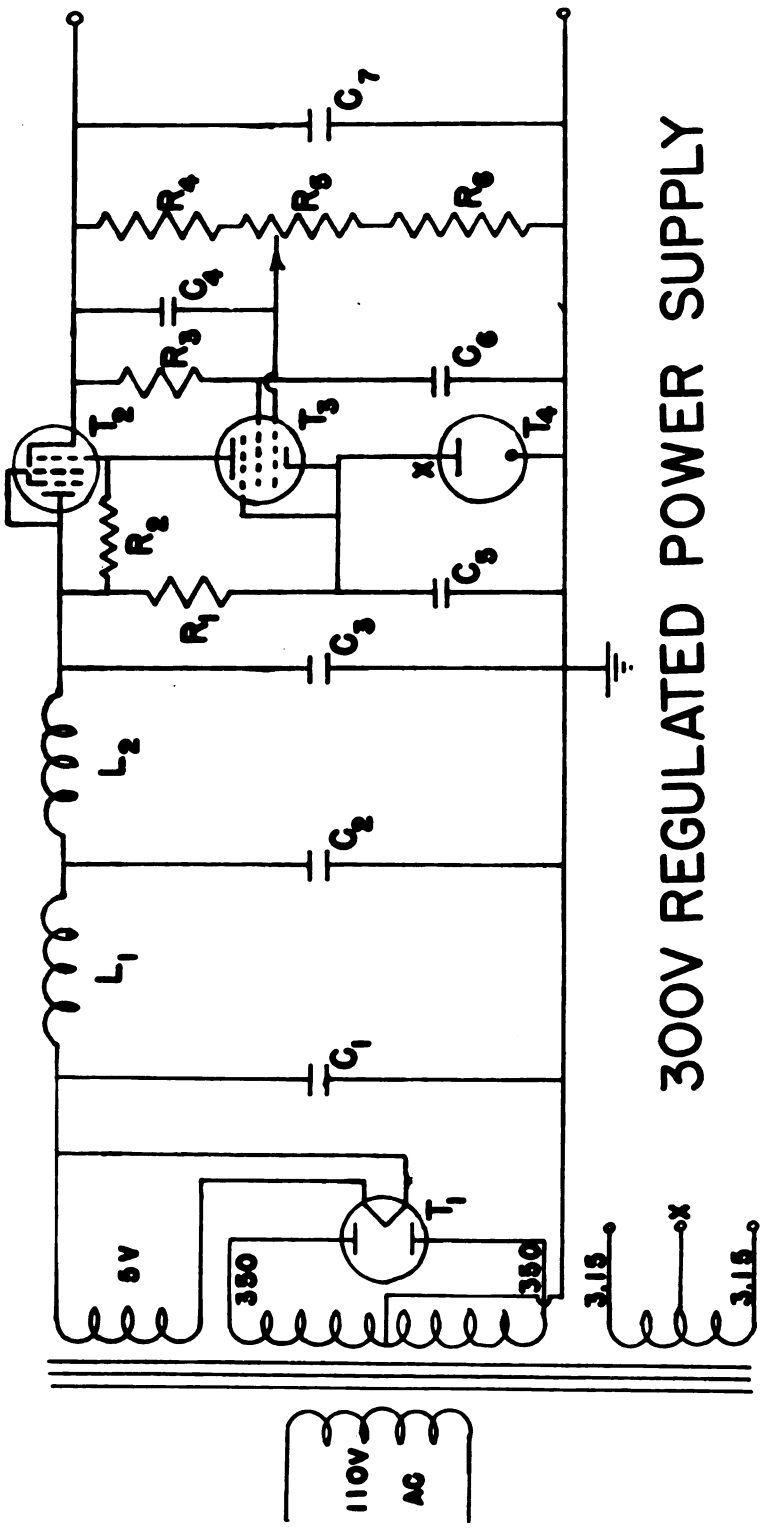
The electronic circuits employed to operate the electron gun are shown in Figures 6 and 7. A negative potential of 1000 v or less was stabilized in a straightforward way by a series of voltage regulating tubes. A well regulated voltage supply, capable of providing more than the necessary current can be obtained in this manner if the VR tubes are chosen carefully. About thirty per cent of new VR tubes are noisy; that is, their conduction pattern and hence their operating voltages change in a random manner. It seems that the discharge moves about within the tube causing the variation in voltage. If the VR tubes have been used before, their behavior is further complicated by their past operation. This difficulty can usually be avoided by operating the tubes at the desired level for a period of a week or so. Even new tubes should be operated at the desired level for several days to see if they will develop a stable mode of discharge. Best results were obtained if the VR tubes are kept in continuous operation.



R_1, R_3 - 500 K POT	V_1 - V_3 - VR 150	G - CONTROL GRID
R_2, R_4 - 50K POT	V_4 - V_8 - VR 105	A_1 - 1ST ANODE
R_5, R_6 200 K	V_9 - 2X2	A_2 - 2ND ANODE
R_7 - 20HM POT	RP - REGULATED	D_1 - DEFL. PLATE
R_8 - 135 K	POWER SUPPLY	D_2 - DEFL. PLATE
R_9 - 100 K POT.	C - 8 mf	T_1 - 2000V TRANSF.

ELECTRON GUN & VOLTAGE SUPPLIES

Figure 6



C_1, C_2, C_3 - 8mf 400V
C_4 - .1mf 200V
C_5 - .01mf 200V
C_6 - .1mf 300V
C_7 - 4mf 400V
L_1, L_2 - 12h

T_1 - 80
T_2 - 6Y6
T_3 - 6SJ7
T_4 - VR 105

R_1 - 15K 10W
R_2 - 470K 2W
R_3 - 10K 1W
R_4 - 100K 1W
R_5 - 100K POT.
R_6 - 100K 1W

Figure 7.

An excellent account of electronic voltage regulators is given by Hunt and Hickman[20]. For low current, high negative voltage, constant load the "mu" type regulation is exceedingly good. A "mu" type regulator was used in early work with good success. However, the method of voltage measurement which was used required currents of the order of 5 ma. The "mu" type regulation cannot deliver currents of this order because of excessive requirements on tubes. The VR tube network shown makes a somewhat inferior voltage regulator but has the necessary current capacity. Subsequent voltage measurements should be made with equipment of higher internal impedance, in which case the "mu" type regulation may be used, for the current requirements of the electron gun is of the order of ten microamps.

Figure 7 illustrates the regulated low voltage power supply used for the deflection voltages. This employed the gate-type regulation in which varying loads and varying line voltage are regulated. The output impedance of the power supply was three ohms at sixty cycles. The output impedance is frequency dependent because of the presence of the condensor C_4. A series of dry cells were sometimes used as a voltage supply for the deflection plates to avoid sixty cycle hum.

The great stability required in these two power supplies was necessary to obtain a sufficiently mono-energetic beam of constant magnitude. The accelerating voltage, of course,

had to be constant in time. The magnitude of the current entering the ionization chamber from the gun chamber depends upon the position of the beam with respect to the small carbon orifice. The position of the beam depends on both the deflection voltage and the acceleration voltage. The importance of the accelerating voltage in maintaining a constant initial electron current increases with increasing deflection voltage.

The deflection sensitivity of the 3GP1 at 1000 v accelerating potential is about forty volts per inch. The deflection is electrostatic. If the focus of the beam is sharp (of the order of the dimensions of the small orifice) the position of the beam may not vary by more than a few per cent of the diameter of the small orifice without a considerable change in the magnitude of the electron stream entering the ionization chamber. If on the other hand the focus of the beam is large compared to the small carbon orifice and if, as was found to be the case, the current density in the electron beam is approximately constant over the whole cross section of the beam, the position of the beam is a much less critical function of the current of initial electrons entering the ionization chamber. Finally, if the focus of the beam could be made small compared to the dimensions of the small orifice, the requirements on the position of the beam would be less than in the case of a beam having a focus comparable to the dimensions of the orifice. The electrons which were used were not capable of forming a focus small

compared to the dimensions of the orifice. This certainly was partly due to the quality of the electron optical system. However, it should be mentioned that charge concentrations could be formed in the beam of the gun such that mutual repulsion would prevent the formation of a focus small compared to the orifice. According to Bachman[2], the outward radial deflection of the outer electrons of a beam of radius r_o cm accelerated by V volts and carrying a current I amperes along a distance L cm is given by 0.76×10^4 I $V^{-3/2}$ L^2 r_o^{-1}. For 1000ev electrons, let I be 10^{-7} amperes, let L be 20 cm, and let r_o be 0.005 cm (one-fifth the radius of the small carbon orifice), then the outward radial deflection of the outer electrons becomes 0.002 cm, which is comparable to r_o. Therefore if a high quality electron optical system were used, for 1000ev electrons, currents less than 10^{-7} amperes should be used to prevent masking of the quality of the system.

If currents of the order of 10^{-9} amperes were used, at which mutual repulsion would no longer be a factor, this current must be read (for one per cent accuracy) to about 10^{-11} amperes. This in turn would require the insulation used in the isolation of the current carrying networks to meet more stringent conditions. For example in the Faraday cage network, where as high as 1000 v is applied to determine the velocity distribution of the electron stream entering the ionization chamber, a leakage current as small as 10^{-11} amp would require a correction of the observed data. To

obtain so small a conduction current the impedance of all the insulation required for the current carrying network must be 10^{14} ohms. In the region of 10^{14} ohms, the conduction of moist air becomes a factor, wood becomes a conductor, even glass conducts through a surface film of moisture.

For these reasons, instead of forming a high quality electron optical system and meeting the more stringent insulation requirements, a conventional electron gun was used at currents of about 5×10^{-8} amperes. The gun was usually operated with a broad focus to minimize deflection requirements.

It did not appear to be important whether the electrons moved in slightly convergent or divergent paths as they passed through the orifice. Without special study of the problem it would seem that a slightly convergent beam would be preferable, since scattering from the walls of the orifice would thereby be reduced.

As the energy of the incident electrons was reduced, the importance of the mutual repulsion of the electrons became greater. Fortunately another effect tends to cancel the difficulty one expects due to the spreading of the beam; that is, for lower energy incident electrons a lower tank pressure is required for total absorption of the beam; this in turn allows the use of a larger orifice connecting the ionization chamber and the gun chamber without increasing the effusive flow beyond tolerable limits.

The heater voltage for the electron gun was supplied by two Edison cell batteries. The voltage was available in 1.2 v steps with a two ohm adjustable resistance for adjustment within these steps. Edison cells retain their charge for a considerable length of time with the low current drain required by the electron gun (0.6 amps). A good quality lead storage cell would maintain a more constant voltage. The constancy of the heater voltage is important, for any variation in emission of the filament will cause a corresponding variation in the electron current passing through the small orifice.

The controls for the electron gun were centralized on a board illustrated in Figure 8. The functions controlled from this board include fine and coarse vertical and horizontal deflection voltages, control grid bias for the gun, etc. The 3GP1 cathode ray tube shown in Figure 8 was electrically in parallel with the unit mounted within the gun chamber. Its purpose was to simplify the problem of positioning the stream of electrons on the small orifice connecting the gun chamber and the ionization chamber. It was particularly useful to indicate the focus of the gun operating within the gun chamber. This condition was accomplished by placing the orifice in the gun chamber at the position formerly occupied by the fluorescent screen of the cathode ray tube. While the commercial cathode ray tubes vary slightly in operating conditions, they are amazingly identical, and one is never far from a sharp focus condition

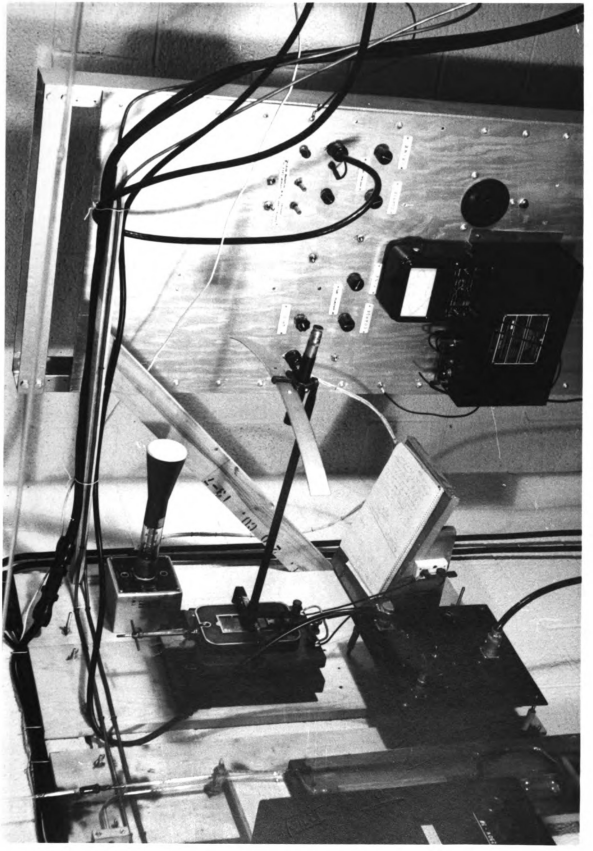


Figure 8. The Control Panel

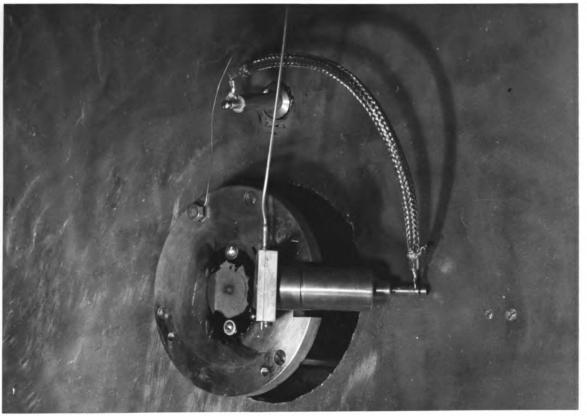
on the gun in the gun chamber if the monitoring tube is sharply focused. As long as the focus on the gun in the gun chamber was larger than the orifice, a sharper focus could be accomplished by minimizing the deflection voltage required for the electron beam to sweep the orifice. The Faraday cage or the collection plate was used as a detector.

The monitoring tube furnished a visual account of the deflections applied to the gun; this aided in locating the beam on the orifice. Once the orifice is located for a particular gun inserted in the gun chamber, the location of the image formed on the monitoring tube was used to return the electron beam to the orifice as long as the gun had not changed or been disturbed. To compensate for the deterioration of the emission of the gun in the gun chamber without burning the fluorescent screen of the monitoring tube, the monitoring tube was supplied by an independent filament supply consisting of 6.3 V transformer whose primary voltage was controlled by a variac. The emission of the monitoring tube was set to correspond to that of the gun in the gun chamber.

The use of the monitoring tube provided a means of visualizing the operation of the gun in the gun chamber without the need of more complicated measures which might be taken to view the operation of the gun directly. It was more satisfactory than a bank of meters indicating the voltages or currents delivered to the gun. The monitoring tube was placed in a location convenient for continual observation.

Other Electronic and Electrical Components

A Faraday cage, Figure 9, was used to determine the magnitude and the energy distribution of the electron stream entering the ionization chamber from the gun chamber. The dimensions of the entrance to the Faraday cage were such as to predict capture of 99.7 per cent of the charge entering the cage. The Faraday cage was adjustable from outside the vacuum system. Hence the electron stream entering the ionization chamber could be captured or allowed to spend itself on the gas in the ionization chamber. Further, the position of the Faraday cage for capturing the electron stream was exactly reproduceable. The Faraday cage and the electrical circuit removing the charge collected from the Faraday cage was shielded to prevent any charge from the gas of the tank to be included with i_e the current of the electrons captured by the Faraday cage as they entered the ionization chamber through the small orifice. The system satisfying these conditions is shown in Figure 9. The Faraday cage rotated about a vertical axis; motion was transmitted by a flexible solid spring brass rod. This motion was transmitted through the vacuum wall by use of an O-ring seal[24]. The large bearing surfaces and close tolerances used on the hinge on which the Faraday cage rotated maintained an accurate vertical and horizontal position of the Faraday cage with respect to the small orifice. Along the line of flight of the electron stream entering the ionization chamber, the separation of the small orifice and the Faraday cage was determined by a



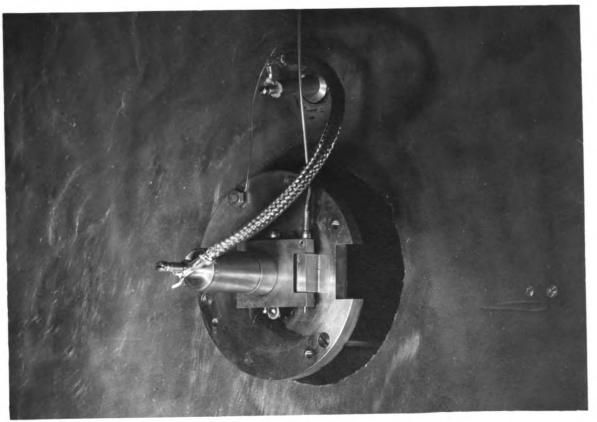


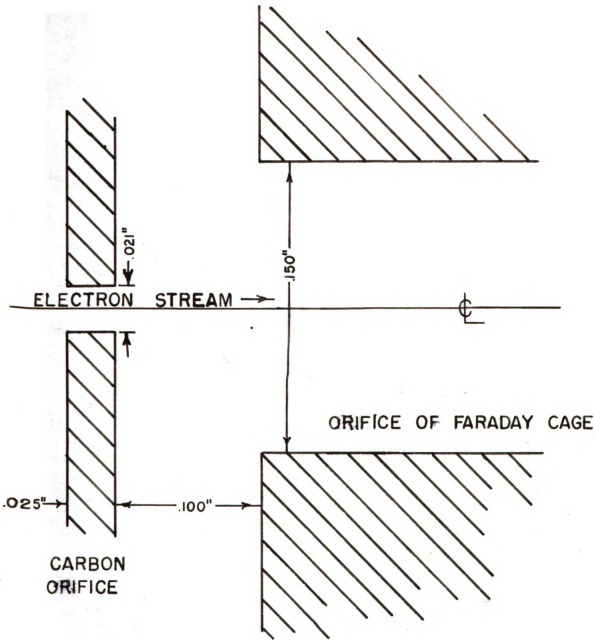
Figure 9. The Faraday Cage & Carbon Orifice

suitable stop against which the Faraday cage rested under tension from the spring brass rod.

The portion of the Faraday cage visible in Figure 9 is a shield which fitted over the Faraday cage to protect it from stray charge. The potential of the shield was that of the ionization chamber, ground. The conductor carrying the charge from the Faraday cage was also shielded from stray charge by a flexible tubular conductor at ground potential. The insulation inside the tubular conductor was small glass tubing broken in one-half inch lengths to give the necessary flexibility.

When the Faraday cage was in position to capture the electrons entering into the tank, the spacing of the small carbon orifice and the Faraday cage was as shown in Figure 10. The separation of the carbon orifice and the orifice of the Faraday cage was 0.100 inches. It is over this region that the retarding potentials were applied to the electrons entering the ionization chamber. It was of primary importance to capture all the electrons entering the ionization chamber; the certainty of doing this was increased if the angle subtended by the Faraday cage orifice was large. For a given size Faraday cage orifice the angle subtended increases as the separation of the small carbon orifice and the Faraday cage decreases.

Several types of collectors for the ions were used; two of the most useful are shown in Figures 10 and 11. The eleven-inch spherical collector illustrated in Figure 9



SCALE 1"= .050"=.127 cm

DETAIL OF VACUUM INTERFACE

Figure 10.

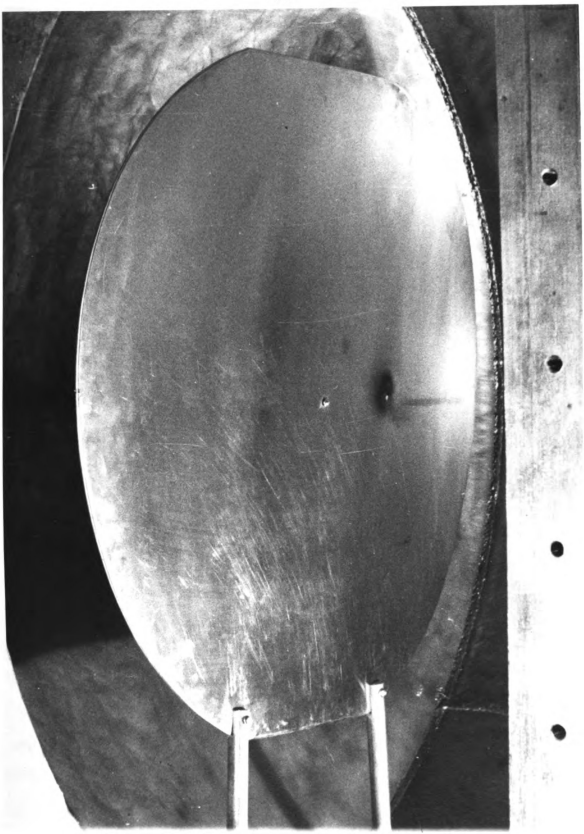


Figure II. An Ion Collector

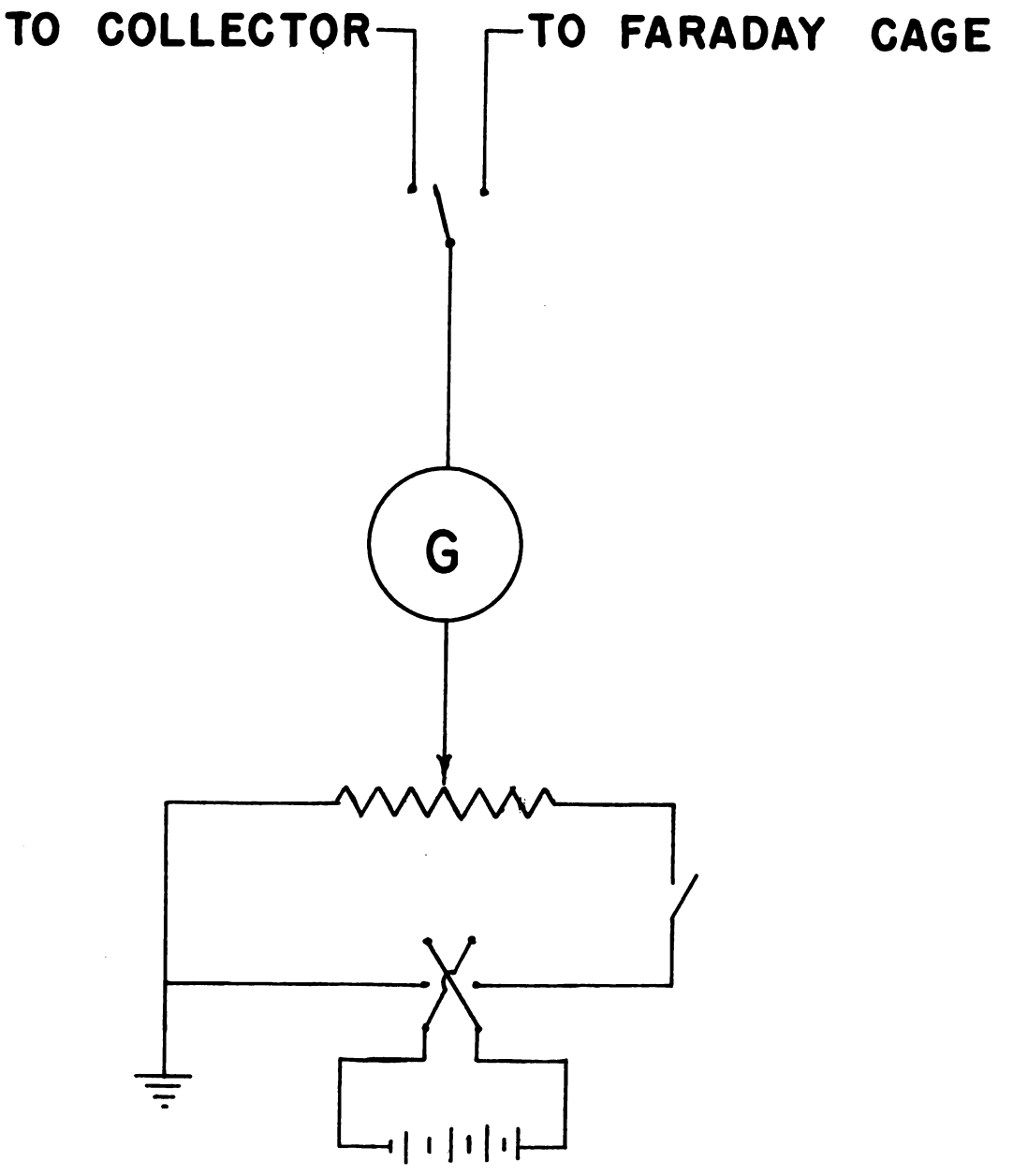
consisted of two stainless steel hemispherical collectors from which handles and base had been removed. They were supported by a rod insulated from the ionization chamber and extending through the ionization chamber wall to serve as an electrical connection to the sphere. This spherical collector was useful if mounted concentric with the roughly spherical shape of the ionization chamber. One could then calculate to a good approximation the electric fields existing in any portion of the ionization chamber. The collector illustrated in Figure 11 has a considerably larger surface area. It was insulated from the ionization chamber wall in a plane approximately normal to the direction of flight of the incident electrons

The collection of the ions formed in the ionization chamber must be at such a rate that none are lost by recombination (an electron recombining with a positive ion); and at the same time the ions must not be removed with such high electric fields that they are capable of forming more ions by collision with the gas molecules within the ionization chamber. J. J. Thomson[38] discovered that the strongest and weakest fields that satisfy both these conditions differed in magnitude by almost a factor of one hundred. Measurements with the spherical collector indicated that recombination losses became negligible for electrons at electric fields greater than 0.01 v per mean free path. This is calculated on the assumption that at 0.3 microns the mean free path of a 1000ev electron is twenty five centimeters. The product of the mean free path and the pressure is approximately a

constant, increasing slightly with the energy of the electron. The mean free path of an electron is approximately $4\sqrt{2}$ times that of an ion.

At a field of one volt per mean free path, a detectable number of ion-pairs were formed by the charge migrating to the collector. Since the fields developed in the ionization chamber were never uniform, the voltages applied to the collector could not be varied by a factor of one hundred and still collect all and only all the ions being formed. The electric fields <u>everywhere</u> in the ionization chamber must fall between 0.01 v and 1.0 v per mean free path. A usable collector is one which does not form fields in the ionization chamber which differ in magnitude by a factor greater than fifty and hence allows a factor of two variation in the collector potential. The sphere in Figure 2 formed fields differing by a factor of about thirty, the stainless steel sheet collector illustrated in Figure 11 formed fields differing by the same factor, mainly due to edge effects. To reduce these edge effects, the edges of the sheet were rolled over three-eighths-inch steel rods. The performance of these collectors will be described in the section on operation.

The measurements of the currents from the Faraday cage and the ion collector were made with D'Arsonval wall galvanometer. The galvanometer had a sensitivity of 10^{-9}amp, a full scale (25 cm) deflection for 10^{-6}amp read to $\frac{1}{4}$ mm. The electrical system used is indicated schematically in Figure 12.

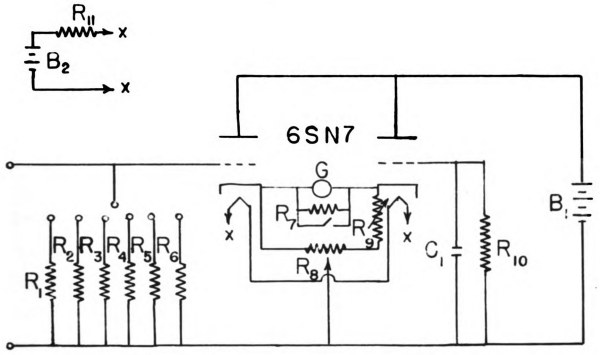


CURRENT MEASURING NETWORK

Figure 12.

The collector or Faraday cage and the galvanometer operated at the same potential. The insulation problems were simpler with this arrangement than with the potential applied only to the collector or Faraday cage. However, the latter more conventional orientation was tried in order to verify that no unusual effects exist due to the high potential of the galvanometer. Both positive and negative potentials could be applied for the collection of either electrons and negative ions or positive ions. Retarding potentials could also be applied to the Faraday cage.

To extend the sensitivity of the galvanometer to 10^{-11} amps, a DC amplifier was used. The circuit for the amplifier is shown in Figure 13. A series of five amplication scales, each differing by a factor of ten, permitted measurement of currents of a wide range. The scales were consistent with each other to one-half per cent. The calibration of the amplifier was accomplished by determining the deflection of the galvanometer as a function of the voltage applied to the grid of the first triode of the 6SN7. From this and the known grid resistances R_{1-6} the current generating a particular grid voltage and the accompanying galvanometer deflection, the gain of the amplifier was calculated. Because of the linearity of the response of the tube over the limited region of operation, small grid leakage currents caused no difficulty. Since in this experiment there is interest only in the ratio of the Faraday cage current to the ion collection current the accuracy of amplification



G - D'ARSONVAL WALL GALVANOMETER

R_1 - 98.94 Ω ± ¼ %

R_2 - 989.4 Ω ± ¼ %

R_3 - 9894. Ω ± ¼ %

R_4 - SHORT

R_5 - 98.94K Ω ± ¼ %

R_6 - 989.4K Ω ± ¼ %

R_7 - 484 Ω DAMPING RES.

R_8 - 10K POT.

R_9 - 400 Ω POT.

R_{10} - 100K Ω

R_{11} - 1 Ω

C_1 - 1000 μf, 15V DC

B_1 - 22½ V DRY CELL

B_2 - 6V STORAGE CELL

DC CURRENT AMPLIFIER

Figure 13.

required of the amplifier is satisfied by precision resistances R_1 through R_6, and the linearity of the amplifier. Variations from tube to tube and variations in the operation of a given tube during its life did not affect the proportionality of the scales of the amplifier, no matter how the gain of the amplifier changed except in case unusually large grid currents developed. Large grid currents were recognized by large changes in the "zero" of the galvanometer from scale to scale. It was easy to detect and remedy this disturbance.

Because of the high current sensitivity of the galvanometer, the amplifier was sensitive to microphonic noise. To reduce this, the amplifier was rather crudely shock-mounted. A more important means of reducing the microphonic sensitivity was to operate both tubes at conduction currents, about one hundred times as great as the galvanometer current required for full scale deflection. Microphonic noise acted as if it was an impedance adding to or subtracting from the plate resistance of the tube; so that if the conduction current of the tube was very large compared to that required for the galvanometer, the microphonic noise became excessive. On the other hand, the conduction current of the tube must be large compared to the currents supplied to the galvanometer if the operating conditions of the tube were not to change greatly with the galvanometer deflection (loss of linearity of the amplifier). Resistances R_9 and R_8 served as fine and coarse adjustments to zero the galvanometer. The amplifier was quite temperature sensitive; it required an hour to warm up.

Pressure Measuring Equipment

Pressures in both the gun chamber and the ionization chamber were determined with a McLeod gauge. A Pirani gauge was applied to either vacuum system to check for vapors and to serve as a leak-hunting device.[11] Acetone was sprayed on surfaces where leaks were suspected. Because of acetone's high molecular weight, it cooled the Pirani gauge filament at a faster rate than air and the gauge registered as if there had been a sudden increase in pressure. As acetone is a good solvent of glyptal; glyptal was not used in the system.

Vacuum Seals

Metal-to-metal vacuum joints were welded, silver soldered, or soft soldered. Demountable metal-to-metal joints were made using O-ring gaskets as described by F. H. D. Hurie[24] in a recent article. These gaskets proved to be exceedingly satisfactory though a vapor pressure of about one micron[7] is associated with the gaskets.

The metal-to-glass seals used consisted of ground glass parts mating machined metal counterparts. The seal was completed by wetting both surfaces with Flicone and allowing it to cool. This method was rapid and durable. Work by Cloud and Philip[7] indicates that vinyl acetate which is applied in the same manner as Flicone, has a lower vapor pressure. Fortunately no seals were required to operate at elevated temperatures, at which glyptal is a satisfactory sealant.

Vapor Traps

The oil diffusion pumps were equipped with "line of flight" vapor baffles. These were not adequate to remove all traces of oil vapor entering the vacuum system. An auxiliary baffle system was used to improve the performance of the pump.

For removal of vapors, the ionization chamber was equipped with a three liter stainless steel thimble suspended from the top of the ionization chamber. The neck of the thimble extended through the vacuum wall and served as a filling port. The thimble was usually charged with an acetone-dry ice mixture and, because of the large surface the thimble exposed to the gas of the ionization chamber, acted as an excellent vapor condenser. The gas which from time to time was caused to enter the ionization chamber either for the determination of W or to return the ionization chamber to atmospheric pressure for repairs, passed through a glass vapor trap immersed in a dry ice-acetone mixture. The ionization chamber was exposed to moist air as little as possible with quite marked improvement of the pump-down time (roughly five hours).

Cleaning of Vacuum Surfaces

The techniques which were used are essentially those recommended by J. D. Strong[35]. Metal surfaces were scoured with a wire brush or steel wool and then washed down with carbon tetrachloride and acetone, in that order. The final rinse was with acetone, as carbon tetrachloride leaves a

slight residue. Sandpaper was not used because the binder used to hold the grains of abrasive frequently has a high vapor pressure. The binder clings to the metal surfaces which have been sanded. Glass was cleaned with potassium dichromate cleaning solution, rinsed, and thoroughly washed with water. Frequently the glass was wet with alcohol to speed the drying. Rubber was washed with a solvent such as acetone unless more elaborate precautions had to be taken as in the case of rubber tubing to be used in contact with mercury.

It was found that considerably cleaner vacuums are obtained if the metal surfaces exposed to a vacuum were cleaned rather frequently (six months or so). The vapors that adhered or were loosely absorbed on fifty square feet of rough metal surface required considerable time to pump out (much longer than the rather tedious cleaning process required).

OPERATIONAL DETAILS

Evacuation of Ionization and Gun Chambers

The small carbon orifice, because of its thinness was quite fragile. Because of the leak through the small orifice, a large pressure differential did not develop between the two vacuum chambers unless the pressure was changed very rapidly. With the two-hour pump-down time for the ionization chamber, the pressure differential never exceeded 25 cm of mercury. When air was allowed to reenter the ionization chamber rapidly, large pressure differentials occured. As long as the air was allowed to enter the ionization chamber for fifteen minutes or longer, the pressure differential did not affect the orifice. If it was necessary to introduce air at a more rapid rate, some air was introduced to the gun chamber to equalize the pressure, using the McLeod gauge as a guide.

The usual technique in evacuation was to use only the forepump on the ionization chamber until the ionization chamber pressure had been reduced to 20 cm of mercury, then the forepump for the gun chamber was started. With the small volume of the gun chamber and the high speed of the pump, pressures of the order of ten microns were obtained in the gun chamber after ten minutes of pumping. If the operation of the gun was desired as soon as possible, the diffusion pump and the forepump for the gun chamber were turned on at the same time.

Care of the Forepumps and Diffusion Pumps

The VHF-280 required about 170 cc (300 gm) of Octoil-S pump fluid which was changed when the fluid discolored. The amount of fluid is not very critical for the operation of the pump particularly if a little more than 280 cc is placed in the pump. The oil increase is virtually wasted as it does not prolong the life of the fluid nor serve any useful function while in the pump. However, it gives a safety factor for, upon use, the level of the oil drops a little (mainly due to inefficient trapping and general cracking of the oil) and the oil discolors very rapidly if too thin a layer remains on the floor of the pump while it is in operation. The level of the oil was checked every six weeks to two months of continuous operation, by removing the pump from its mount and inverting the pump to drain it. The oil was changed completely approximately once a year.

The MB-100 Booster pump used on the ionization chamber pumping stem required 250 cc of butyl sebacate, diffusion pump oil. The same techniques apply to this pump as to the VHF-280. Butyl sebacate is relatively cheap fluid and the pump may be, at small cost, charged with a total of 300 to 350 cc of fluid rather than check the oil level frequently.

Each of the Hypervac-25 forepumps required about two quarts of light pump oil (Cenco 93050). The oil level indicator on the pump is not reliable. The indicator consists of a glass window positioned at the proper oil level; its purpose was defeated by a baffle which presumably prevented

the oil foam, which developed when the pump was operated, from reaching the indicator glass. Unfortunately this baffle also interfered with the movement of oil toward or away from the glass indicator. The level of the oil in the pump was adjusted satisfactorily by removing the cover plate of the Pressovac unit of the pump and observing the level of the oil directly while the pump was in operation. The servicing directions furnished by Central Scientific Company for the Hypervac-25 pump are apparently quite reliable.

Positioning and Focusing of Beam on Small Orifice

The electron gun was operated at pressures below 0.3 microns with reasonable results, though the operation of the gun improved considerably at lower pressures. Prior to the operation of the gun in the gun chamber, the monitoring tube was put in operation and observed for a while to check the operation of the electrical equipment. If the VR tubes in the accelerating voltage power supply had not been in operation for some time, a half hour "warm up" was required for stable operation. Whenever suitable operating conditions were attained, the electrical services were supplied to the gun in the gun chamber by connecting the eight-conductor service cable to the receptacle mounted on the endplate of the gun chamber.

If the gun had been operated previously, the electron stream from the gun was directed at the small orifice either

with the aid of an ink dot which had been placed on the face of the monitoring tube with a pen or more usually by the existing deflection potentials which were not changed unless necessary. If by accident or necessity the deflection voltage was altered, the ink dot served as a guide to return the beam to the proper location. As the magnetic field was approximately the same within the gun chamber and at the site of the monitoring tube, the ink dot located the small orifice quite independent of the accelerating potential. If a new tube was in operation, the gun was defocused to form an image 3 to 5 mm in diameter and then the beam was systematically swept over the area which included the orifice. The passage of electrons through the orifice was indicated either by collecting them in the Faraday cage, or by collecting the ion products formed by the electrons as they spent themselves in the ionization chamber. The latter method was more sensitive for a weak beam as each electron may form many ions. Once the approximate location of the orifice was found, the focus was sharpened until the location of the orifice was accurately determined. With experience the orifice can be located in several minutes.

It was advantageous to have the gun in the gun chamber directed quite accurately toward the orifice, for then the electron stream passed through the orifice with the least contact with the walls of the orifice, giving a better velocity distribution. On the other hand, if the electron stream was directed toward the orifice without the use of deflection

potential, one could not, as was convenient, remove the beam from the orifice and reinstate the beam to its former position by opening and closing a switch which completed a short between a pair of deflection plates. If the adjustment of the direction of the axis of the gun mounted on the endplate was made by eye, the probability that no deflection voltage was required was satisfyingly small. An auxiliary voltage could have been used equally sucessfully for the above purpose.

As mentioned earlier the focus conditions of the monitoring tube and the gun mounted in the gun chamber were nearly the same due to the location of the small carbon orifice in the plane formerly occupied by the fluorescent screen. The exact conditions for fine focus of the gun mounted in the gun chamber were determined by minimizing the variation of the deflection voltage required to deflect the beam across the orifice. This technique applies as long as the orifice is smaller than the cross section of the beam.

Determination of the Energy Distribution of Electrons Passing through the Small Orifice into the Ionization Chamber

The filament of the electron gun was operated at approximately 1000 v negative with respect to ground. The second anode of the gun was at the same potential as the ionization chamber, gun chamber, and orifice; namely, ground. Hence the electrons leaving the second anode of the gun traversed field-free space except for the small electric

fields due to the deflection voltages and the magnetic field due to the earth. As shown in Figure 10 the orifice of the Faraday cage was large enough so that the electrons could not escape entering the Faraday cage unless they were traveling at an angle greater than forty-five degrees with the axis of the system. This was exceedingly unlikely unless they suffered a collision with gas molecules between the small carbon orifice and the Faraday cage, or have been sharply scattered from the walls of the orifice. Such a wide angle deflection is very unlikely over the small distance of 0.100 inch with 1000ev electrons, even in a gas at a pressure of 50 microns. The mean free path of a 1000ev electron at 50 microns is approximately 0.1 inches.

The electron passes from the gun chamber, where its mean free path is of the order of 2.5 meters, to the ionization chamber where its mean free path is 0.1 inch. This transition is of course continuous, but one can with small error consider the transition to take place at the gun chamber side of the small carbon orifice. One may then reason that the average location of first collision of the electrons as they enter the tank lies about 0.05 inches within the ionization chamber. Of course some electrons do suffer collision within the orifice or just within the ionization chamber but most collisions take place further in the ionization chamber. If in these collisions the angle of deflection is greater than forty-five degrees, the Faraday cage will not register their entry into the ionization chamber. If the position of

the first collision occurred further within the tank, the angular deflection must be even greater to escape the Faraday cage. The experimental support for the acceptance of the Faraday cage as an effective trap for the electrons entering the ionization chamber was as follows:

During periods when the system is in unusually stable operation (after eight to ten hours of operation, usually after 11 p.m.) the electron current collected by the Faraday cage did not vary for periods of half an hour or longer. With the ionization chamber pressure adjusted to fifty microns for the total absorption of the electrons, the Faraday cage was swung into position to intercept the entering electrons. After the current collected was measured, the ionization chamber was evacuated to 0.1 microns as quickly as possible (about fifteen minutes) during which time the current being collected by the Faraday cage was observed. The pumping stem for the ionization chamber was then closed and a sample of dried air sufficient to raise the ionization chamber pressure to fifty microns was admitted. Frequently this test was interrupted by one of the many variables which cause the beam current to vary. However, many runs were obtained in which the current collected by the Faraday cage did not vary by one per cent of its original value. Furthermore, these variations did not show a pressure dependence for they appeared to be random fluctuations. This series of observations verified that the efficiency of the capture of electrons by the Faraday cage was not pressure

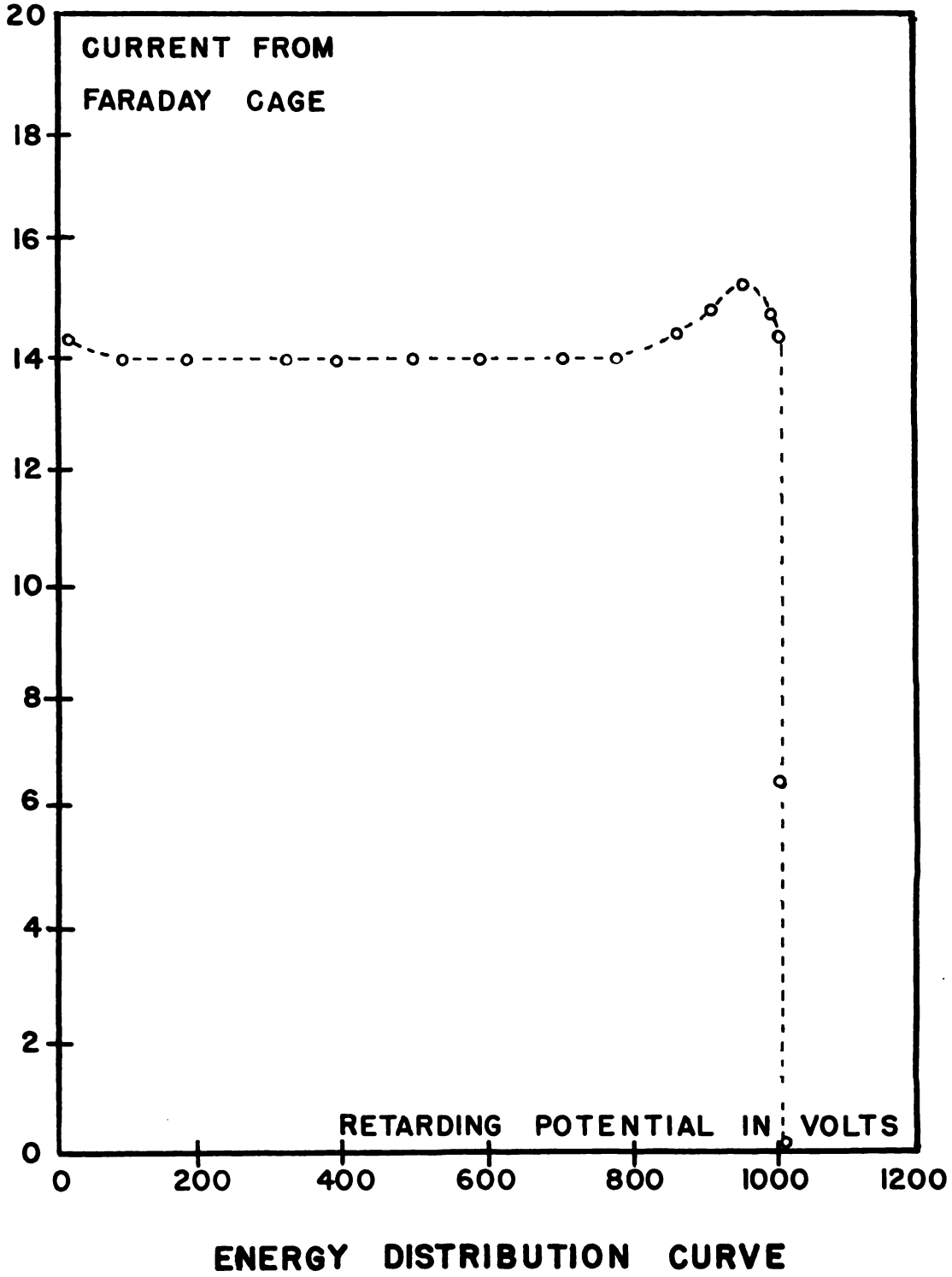
dependent over the region 0.1 to 30 microns. Hence it was legitimate to assume that not more than a few tenths of one per cent of the electrons undergoing collisions in the small carbon orifice and in the region between the orifice and the Faraday cage escaped capture by the Faraday cage.

If, after the evacuation of the ionization chamber, the pressure of the ionization chamber was not returned to fifty microns, but instead to two hundred microns, there was a very marked decrease in the current collected by the Faraday cage. Usually the current collected by the Faraday cage continued to decrease in a rather regular manner after the two pipettes began to leak air into the ionization chamber. After the ionization chamber pressure was returned to fifty microns, the current collected by the Faraday cage did not return to its original value. The current usually remained at the lowest value obtained while the ionization chamber was at two hundred microns. Occasionally, the current increased a little as the ionization chamber pressure was decreased, but in no case did it approach its initial value. Apparently the variation in current collected by the Faraday cage was due to variation in the emission of the tube probably caused by positive ion bombardment of the cathode. The tube was frequently returned to its original performance by "flashing" or by use of other activating techniques.

Although it has been shown that the efficiency of the Faraday cage's capture of electrons is not pressure dependent, this circumstance does not prove that all the electrons

entering the tank from the gun chamber are captured by the Faraday cage. On the assumption of random scattering and rather rapid absorption after striking the inside wall of the cage, about 0.3 per cent of the electrons which enter the Faraday cage do not remain there but scatter back out of the cage orifice. Further information concerning the effectiveness of the Faraday cage was obtained from the energy distribution curve shown in Figure 14.

The energy distribution curve was obtained by plotting the current collected by the Faraday cage at various negative potentials applied to the Faraday cage, all other variables being held constant. The current collected by the Faraday cage with 100 v negative potential consists of all electrons having a kinetic energy capable of overcoming the 100 v retarding potential required to enter the Faraday cage. As the currents collected by the Faraday cage at 100 v and 800 v negative potential were not significantly different, one may conclude that of the electrons captured with a retarding potential of 100 v, virtually none are lost due to the increase of the retarding potential to 800 v or for that matter to 800 v. In the first 50 to 100 v retarding potential applied to the Faraday cage there was a significant, but not large (two per cent), decrease in the current collected. This change may be due to slow electrons formed by the collision of the primary electrons with the carbon walls of the small orifice or with the gas molecules through



ENERGY DISTRIBUTION CURVE

Figure 14.

which the primary electrons traverse. These slow electrons appear to have less than 75ev energy along the direction of the electron stream. A small percentage of these low energy electrons may have considerably more than 75ev energy along a direction perpendicular to the line of flight of the electron stream.

These slow electrons considered as a group lose probably less than an average of 10 v to atoms in collision with the gas molecules in the tube. Hence the ion-pairs formed by them constitute considerably less than 0.1 per cent of the ion-pairs formed. This error was too small to be considered in the present work. Approximations for the ionization due to these low energy electrons can be made which are valid to ten per cent or so, leaving an absolute error of the order of 0.01 per cent. The electron current i_e entering the ionization chamber must be taken as the current with 100 v retarding potential, with zero retarding potential.

The increase in the current collected by the Faraday cage at retarding potentials between 600 v and 1000 v is not clearly understood. The effect might be variously described as an increase in the electron current collected, a decrease in the positive ions collected, a decrease in the electron current leaving the Faraday cage (secondary electron formation), or an increase in the positive ion current moving away from the Faraday cage (positive ions are formed within the Faraday cage and region between the Faraday cage and the small carbon orifice if the vacuum was

not sufficiently clean, particularly of oil and mercury vapors). As there could hardly be an increase in the electron current passing through the small carbon orifice as the retarding potential was increased, the effect was ignored as far as the results of the experiment were concerned. Unfortunately the energy distribution between 800 ev and 1000 ev was not accurately known. A few runs have been obtained for which the effect was missing.

The increase in current collected by the Faraday cage was not due to space charge though charge densities of the order of 10^9 electronic charges per cubic centimeter were formed with high intensity beams when they were strongly decelerated upon entering the tank. Energy distribution curves have been taken of beam currents differing by a factor of nearly one thousand in magnitude without a significant change in the curve. The change in the heating of the small carbon orifice due to a brome focus beam or sharp focus beam did not apparently change the shape of the curve in the 800 v to 1000 v region. It did not appear to matter whether the beam was convergent or divergent as it entered the orifice. Secondary electrons formed at the lips of the Faraday cage were not responsible for the effect as a change from brass to carbon lips produced no variation in the curve. The peculiar effect is not due to the current-carrying or current-measuring equipment for no "pip" is measured in the background current; the effect requires the presence of the beam. It appears likely that oil or mercury vapors may be

responsible for the unusual behavior. The large vapor condensor in the ionization chamber removed any vapors in the ionization chamber within a matter of minutes. If however the vapors were reabsorbed or absorbed in the region of the Faraday cage and evolved during the operation of the gun, the effect of the vapor in question would be seriously restricted. The present pressure-measuring, vapor-sensitive equipment did not have the sensitivity to indicate small variations in the vapor pressure. The presence of this "pip" in the energy distribution curve which was made on a 800 ev electron beam seems to indicate that the vapors present in the ionization chamber are probably responsible.

The cut-off of the current collected by the Faraday cage was exceedingly sharp (about five volts spread from maximum to zero current); this indicates that the majority of the electrons passing through the orifice are exceedingly mono-energetic. For purposes of calculation, the average energy of the incident electrons is taken as the potential necessary to reduce i_c to half its value at 100 v. As has already been mentioned, the electron current entering the ionization chamber, i_e, is taken as current measured with 100 v retarding potential.

The constancy of the electron current collected by the Faraday cage over the region 100 v to 700 v is taken as an indication of the satisfactory efficiency of the Faraday cage in the capture of the incident electrons. For if the Faraday cage were just capable of capturing electrons

scattering at wide angles, the application of retarding potentials would aggravate the situation and the current collected by the Faraday cage should decrease. Other factors could cause the same effect, but in the absence of a decrease in current all these conditions must have been simultaneously satisfied.

The measurements comprising the curve in Figure 14 (the energy distribution curve) were made by flipping the electron beam on and off the small carbon orifice for each retarding potential recorded. Hence effects due only to the presence of the beam were recorded. Frequent checks were made of the operation of the electron gun by returning to previous retarding potentials to check the consistency of results. The beam was flipped off of the small carbon orifice by grounding one of the deflection voltages of the gun.

The Addition of the Stopping Gas

The stopping gas used was dry air taken from the laboratory. The laboratory has an adequate circulation to reduce the possibilities of contamination due to common laboratory vapors such as oil, acetone, benzene, carbon tetrachloride, etc. The air was dried in a dry ice and acetone trap of such a volume, that the volume of the trap filled with gas at atmospheric pressure filled the ionization chamber to a pressure of seventy-five microns.

Liquid air or liquid nitrogen are not satisfactory as refrigerants for the trap for a goodly portion of the

nitrogen in the sample freezes out on the walls of the trap and the sample of gas introduced to the ionization chamber is not air. The necessity for careful control of this point was demonstrated by an incidental observation. When a sample of gas was introduced through liquid air (presumably at the oxygen temperature), a strikingly higher value of W, the energy for the formation of an ion-pair was measured. This value was approximately 1.4 times that of air.

Removal of the Ionization Products

As has been mentioned, electric fields were required to remove the ionization products at a rate such that few ions were lost due to recombination and yet none were formed by the too energetic movement of the ions toward the collector. The system used consisted of two electrodes; one, the ionization chamber at ground potential and the second, an insulated collector whose potential could be varied with respect to ground. The currents collected by the second electrode were registered by the wall galvanometer whose range was extended by the D6 amplifier. The current registered by the wall galvanometer is indicated in Figure 15 as a function of the potential of the collector with respect to ground. The upper curve, as indicated, gives the electron current (electrons and negative ions) collected; the lower curve, the positive ions collected. The ordinates of these curves differ by the magnitude of

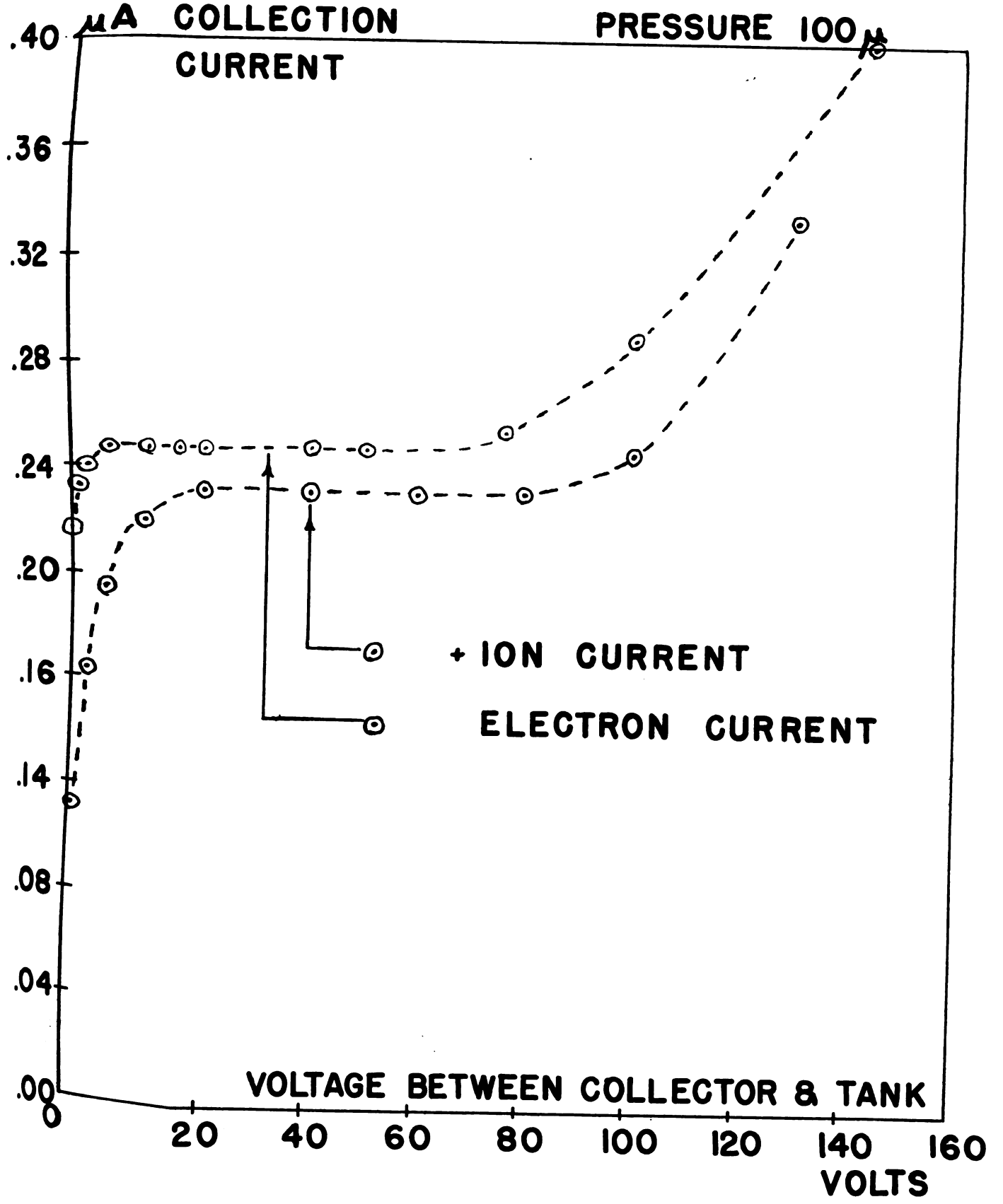

μA COLLECTION CURRENT
PRESSURE 100μ
.40
.36
.32
.28
.24
.20
.16
.14
.08
.04
.00
0
20
40
60
80
100
120
140
160
VOLTS
+ ION CURRENT
ELECTRON CURRENT
VOLTAGE BETWEEN COLLECTOR & TANK

Figure 15.

the initial electron current over the region of the plateau, where all and only all the ions formed by the initial electrons are collected.

At voltages below the "knee" of the curve (at the low voltage end of the plateau) a sufficient field does not exist, at least in some parts of the ionization chamber, to remove the ionization products without some loss due to recombination. At voltages above the plateau, at least some parts of the ionization chamber have fields which impart enough energy to the ionization products so that they may form ion-pairs by collision with the gas molecules. Ionization by collision in air requires about 17 v for unexcited molecules, and correspondingly less if the molecule is excited.

The measurements on which the ionization collection curves were based, were made in the same manner as the velocity distribution curves. To remove all effects which were not due to the presence of the initial electrons (background current, zero drift of the galvanometer and current amplifier, etc.) the beam of incident electrons was switched on and off the orifice separating the two chambers with a shorting switch connected between a pair of collection plates. Frequent checks were made to determine the satisfactory operation of the electron gun. Other methods of obtaining the same data were used to ascertain that this method, while convenient, did not introduce any systematic error.

With the aid of the collector shown in Figure 2, it was possible to calculate that a plateau should be obtained when fields everywhere in the ionization chamber were within the limits of 0.01 v and 1 v per mean free path. The smaller of these two fields was just capable of removing ions fast enough to prevent their recombination and the larger field was just weak enough to prevent the formation of a noticeable proportion of ion-pairs by the ions and electrons in the course of their migration to either collector. Notice that the electron collection plateau extends over a twelve-fold range from approximately 5 v to 60 v collection potential, the positive ion collection plateau from approximately 20 v to 80 v, a four-fold range.

Conditions easily occurred under which space charge concentrations developed potentials which were troublesome to the collection of the ionization products. Figure 15 illustrates this effect by showing the collection curve obtained if the magnitude of the electron stream entering the ionization chamber was increased ten-fold. This of course increased the collection current by a factor of ten. All other variables were kept constant. The plateau has disappeared, and one goes without pause from a region in which ions are lost by recombination to a region where ion-pairs are formed in the collection process. The regions do not join; they overlap. A collection current of two microamps represents a collection of roughly 10^{13} electronic charges per second. The surface area of the collector shown in

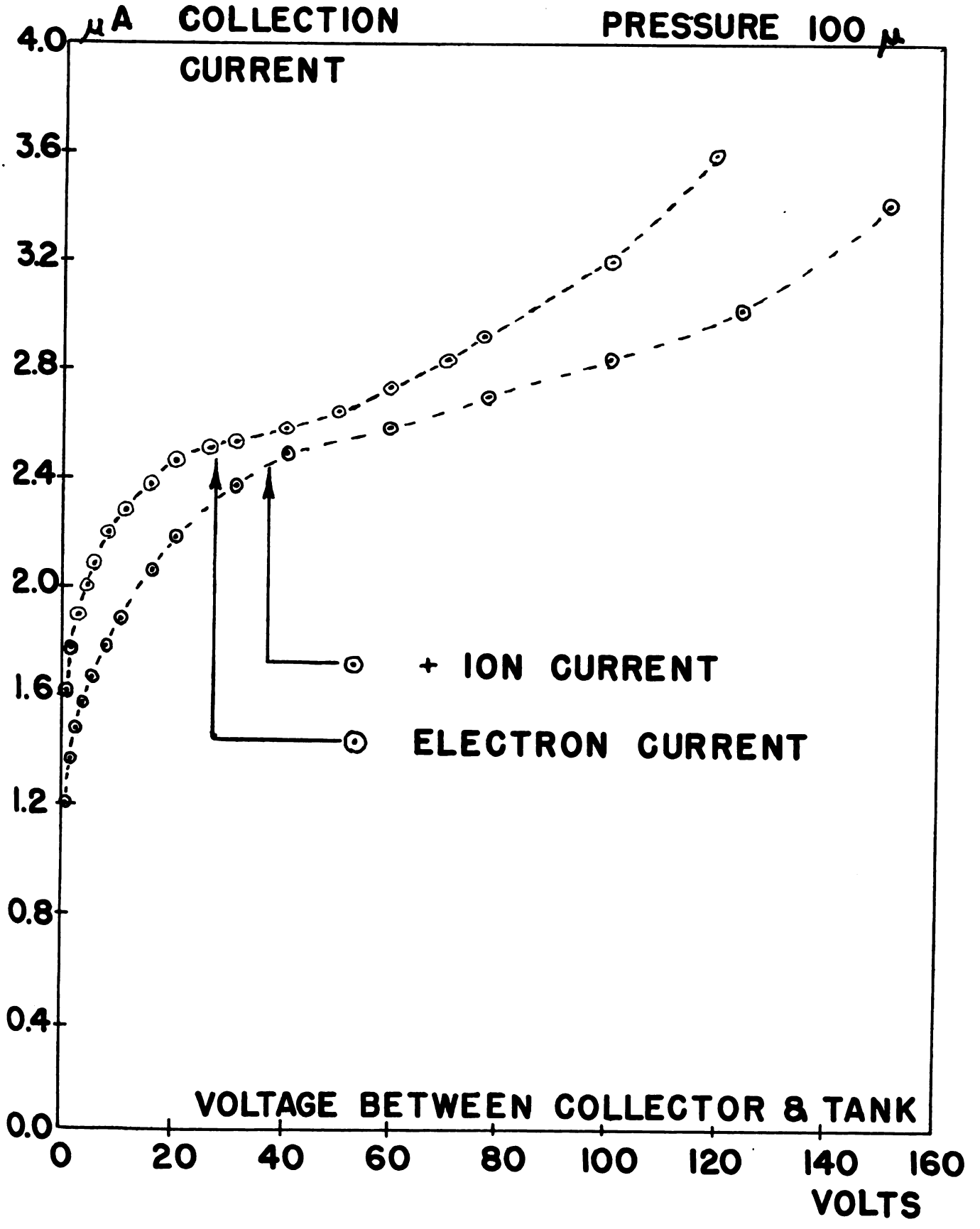

μA COLLECTION CURRENT
PRESSURE 100 μ
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
+ ION CURRENT
ELECTRON CURRENT
VOLTAGE BETWEEN COLLECTOR & TANK
0
20
40
60
80
100
120
140
160
VOLTS

Figure 16.

Figure 11 is of the order of 6000 cm^2, hence the charge collected per square centimeter is approximately 10^9 electronic charges per second. The mobility of a positive ion in a field of 0.1 v per cm is of the order of a few thousand centimeter per second. Assuming the charge to be transported as single electronic charges, the density of positive charges near the collector is of the order of 10^9 electronic charges per cubic centimeter. This high concentration gives rise to space charge potentials of the order of 1 v per centimeter which is more than sufficient to mask the fields generated by the potential of the collector. This difficulty is clearly demonstrated by Figures 18 and 19.

The collection curves shown in Figure 17 were taken with the collector visible in Figure 2. The initial electron current was reduced so that space charge conditions existed for positive ions, but not for electrons. As a result, an unmistakable plateau was formed for electrons, but when the positive ions were collected on the small surface of the eleven-inch spherical collector, space charge concentrations developed because of the low mobility of the positive ion with respect to that of the electron. The positive ions did not develop space charge conditions when the electrons were collected on the ionization chamber wall for the area of the ionization chamber wall was roughly twenty-five times that of the eleven-inch sphere. The electron collection and positive ion collection become more symmetrical to each other as the surface areas of the ionization chamber wall and the

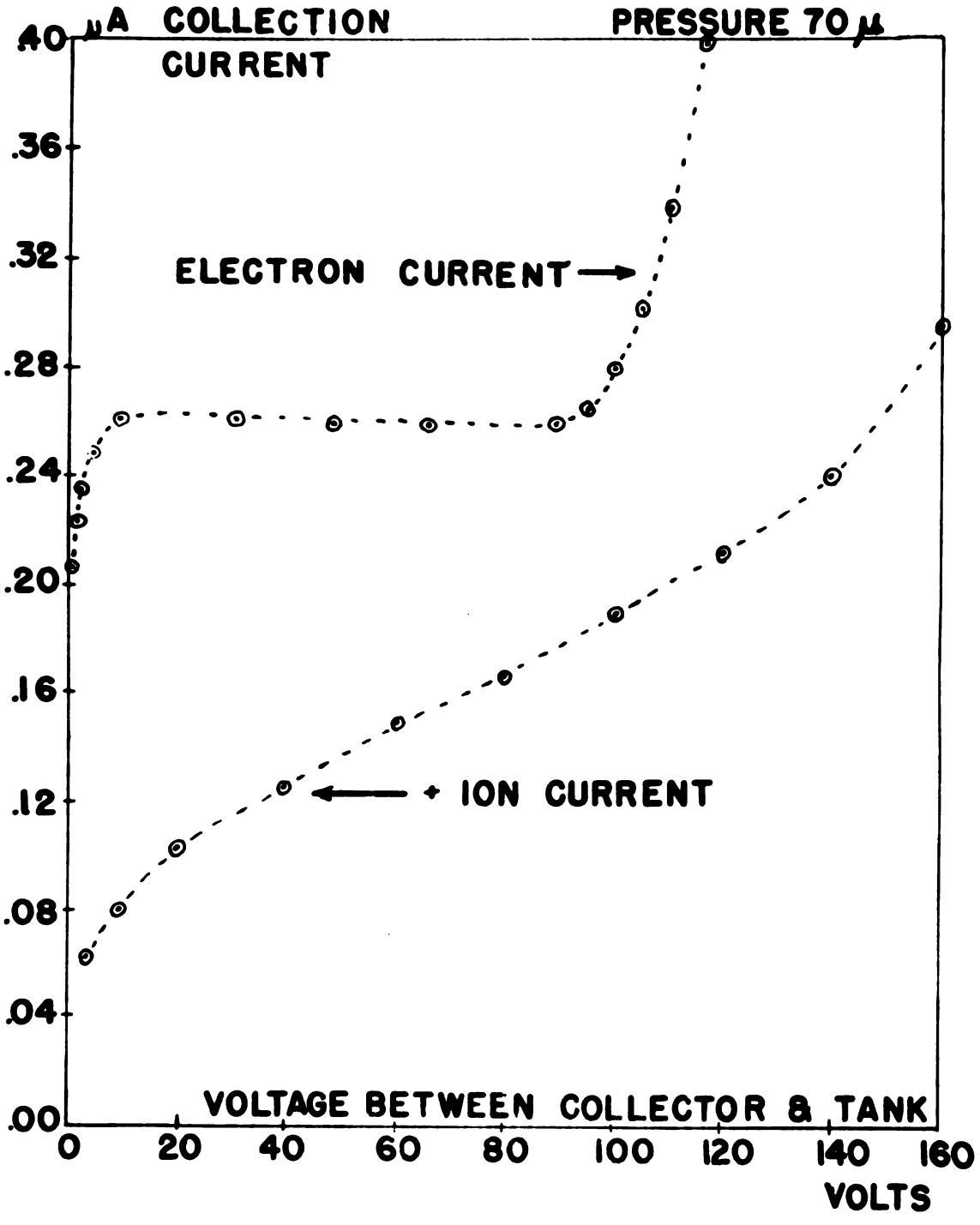

μA COLLECTION CURRENT
PRESSURE 70 μ
.40
.36
.32
.28
.24
.20
.16
.12
.08
.04
.00
ELECTRON CURRENT
ION CURRENT
VOLTAGE BETWEEN COLLECTOR & TANK
0
20
40
60
80
100
120
140
160
VOLTS

Figure 17.

collector become more nearly the same. It is generally advantageous to collect the electrons on the smaller surface and allow the positive ions to neutralize themselves on the ionization chamber wall.

As 1000ev electrons were stopped within the ionization chamber at pressures of the order of 50 microns, a satisfactory collection potential for saturation at this pressure was 10.5 v. This collection potential could be reduced by a factor of three and still remain on the plateau. So small a collection potential removed a treacherous source of error: the effect of the collection potential on the ionization field. For the present work, at the pressure required for total absorption of the initial electrons, the collection potential required was of the order of one per cent of the original energy of the electrons.

This result is in strong disagreement with Lisl[14]. The collection potentials which Lisl used were frequently ten per cent of the energy of the incident particle. As an example, the ionization products of 9000ev electrons absorbed in air were collected by a 1000 v potential. The author believes that Lisl may have been required to use these large collection potentials because of space charge conditions. The reasoning is as follows:

The number of mean free paths required for the stopping of an electron of a given energy is roughly a constant for a given gas, and the number of mean free paths over which the ionization products must be collected is approximately

the same number of mean free paths required to stop the initial electron. Hence for a given collection voltage per mean free path the ratio of the energy of the incident electrons to the collection potential for their ionization products should be approximately a constant, roughly equal to one hundred. Within broad limits this is independent of the energy of the particle and dimensions of the chamber (which affects the pressure required for total absorption). Therefore it is quite probable that Lisl's large collection potentials were not necessary by space charge conditions. Note that the "knee" of the positive ion collection curve shown in Figure 15 appears at considerably higher fields than were required for the electron collection "knee". As the space charge condition becomes more serious the "knee" apparently moves to the right (higher potentials) until the plateau finally disappears. It is probable that Lisl was driven to use high collection potentials for lack of consideration of space charge conditions. Whatever the validity of Gerbes'[16] theoretical correction for large collection potentials, the absolute error in the knowledge of W is reduced if lower collection potentials can be used. Gerbes' correction is small; that is, a correction of 3.6 per cent is required in W for 9000v incident electrons whose ionization products were collected with a potential of 1000 v. As Gerbes was apparently a student of Lisl, it is likely that Lisl was conscious of the objection to high collection potentials.

Determination of the Saturation Condition

To ascertain the pressure at which total absorption takes place, the following reasoning is used: At pressures well below that required to stop the initial electrons within the limits of the ionization chamber, the initial electrons will arrive at the ionization chamber wall or other limit without having spent all of their energy. The initial electrons coming in contact with the ionization chamber wall may be neutralized, may produce secondary electrons, may scatter, etc. with a net loss in the energy expended in the formation of ion-pairs in the gas. As the pressure in the ionization chamber is increased one expects the net loss of energy to be decreased and as a result a net increased number of ion-pairs formed per initial electron until the initial electrons are totally absorbed within the stopping gas. Beyond the pressure required for total absorption, the average number of ion-pairs formed per initial electron should not change unless secondary effects are produced by the elevated pressure.

The average number, K, of ion-pairs formed per initial electron is plotted as a function of the pressure of the ionization chamber in microns (Figure 18). The linear increase of K with the ionization chamber pressure is in agreement with the observations of Lehmann and Osgood[27] and others. As predicted, the value of K reaches a limiting value determined by the average energy of the incident electrons and does not deviate appreciably from this value with increasing ionization

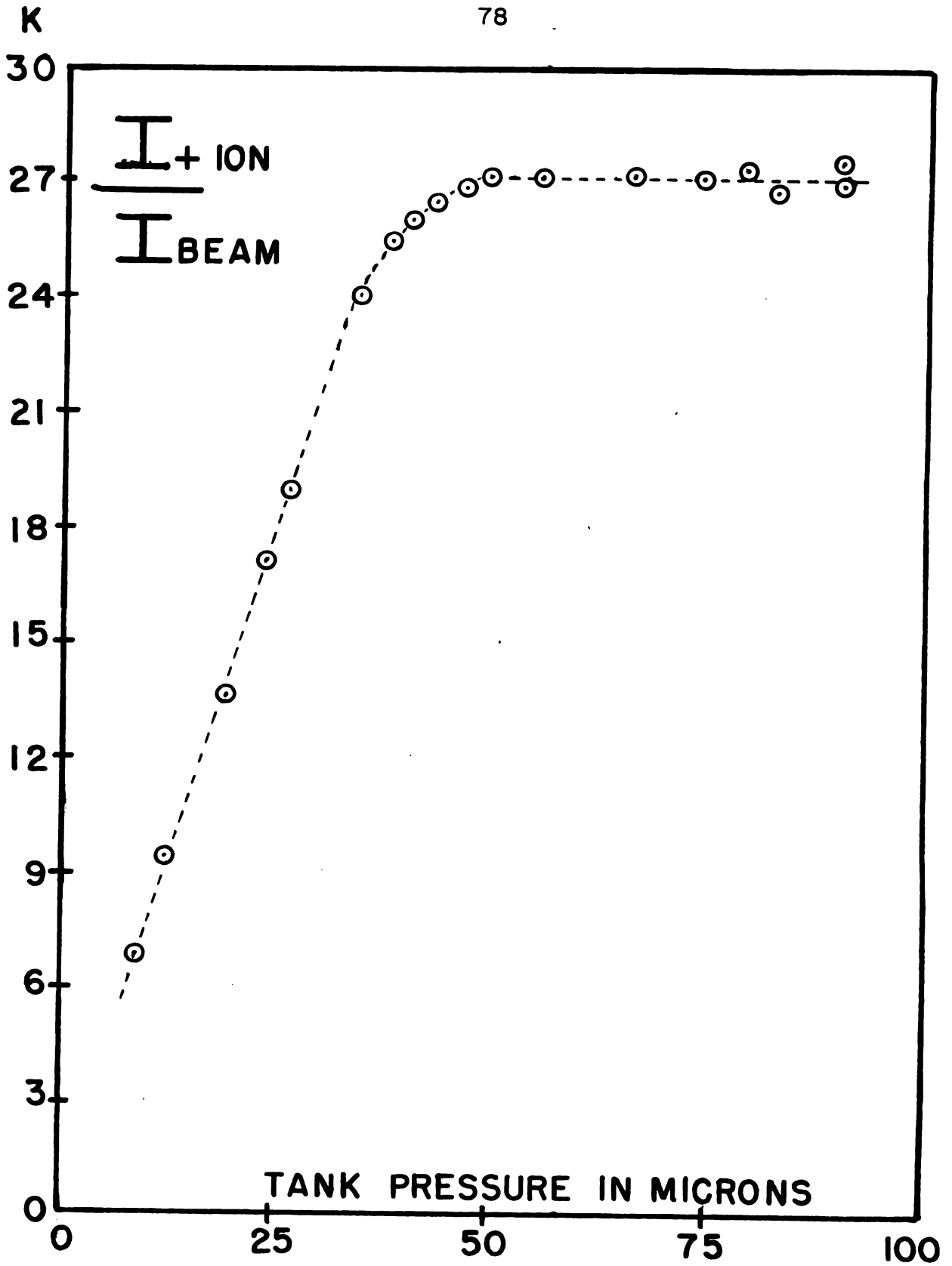

K
30
27
24
21
18
15
12
9
6
3
0
I+ ION / I BEAM
TANK PRESSURE IN MICRONS
0
25
50
75
100

Figure 18.

chamber pressure. Notice the apparent decrease in the accuracy of the determinations of K with advancing pressure. This scatter of observations resulted chiefly from the increased instability of the electron gun as the ionization chamber pressure becomes large. Since even with the increased effusive flow, the pressure of the gun chamber remained satisfactory, it is believed that positive ions formed in the region of the small carbon orifice follow the trajectory of the electron beam in the opposite direction to bombard the filament of the gun. If this difficulty cannot be removed in other ways, a magnetic ion ejector such as used in modern television tubes will certainly remove the bombardment. Within the accuracy of measurement, no variation has been found in the value of K with increasing pressure.

If the incident electrons were scattered upon entering the ionization chamber through such wide angles that an appreciable number of them collided with the ionization chamber wall near their point of entry the total ionization produced by the incident electrons should have decreased. This reduction in ionization should increase with increasing pressure. To visualize the situation, one can think of the envelope of the farthest penetration of the incident electrons as not only shrinking in size but also suffering a translation in the direction of the electron gun along the axis of symmetry of the system (the line of flight of the incident electrons). In the absence of any measurable change in the

value of K as a function of increasing pressure, one concludes then that few if any of the incident electrons are captured by the ionization chamber wall near their port of entry.

Diffusion and Recombination Effects

With the large volume used in the present work it was not surprising to encounter exponential decays due to diffusion and/or recombination of the ionization products.[34] Small effects were observed having a time constant of about two minutes. A careful study of this has not been made.

RESULTS

First it should be emphasized that the results to be given are not to be taken as indicative of the ultimate accuracy obtainable with the present equipment even over the highly restricted field of 1000 ev electrons totally absorbed in air. Improvements in the equipment and its operation, perhaps along the line of suggestions given in the next section, will increase the accuracy of the results and convenience of obtaining them. Quite arbitrarily the present report is considered the termination of the preliminary experiment.

Although the determination of W has already been discussed in considerable detail, it is essential to consider further factors emphasizing particularly the methods by which the various measurements are combined to yield an accurate value of W, the average energy for the formation of an ion-pair.

The current associated with the stream of initial electrons entering the ionization chamber was taken as the current collected by the Faraday cage minus the small number of electrons having an energy of 100 ev or less. As the area under the energy distribution curve is approximately proportional to the energy dissipated in the gas, the error involved in discarding the low-energy electrons was certainly less than 0.1 per cent. While the energy distribution is not known precisely for 800 ev to 1000 ev electrons, it is

believed, with the support of larger evidence, that few electrons with total energies between these limits pass into the ionization chamber. The above errors combined with the accuracy of the galvanometer yield an uncertainty in the determination of the initial electron current of plus or minus one half per cent.

Considerably more error was involved in the variation of the initial electron current during the period while it was compared with the ion current obtained when the initial electrons were totally absorbed. This variation in the initial electron current results mainly from the positive ion bombardment of the gun filament and the slow discharge of the batteries supplying the heater voltage for the gun filament.

The value of K was taken as the average of twenty sets of measurements. A set of measurements consisted of a measurement of the initial electron current, then the ion current, and then once again the initial electron current. To avoid a systematic error due to the steady decrease in the beam current with time, the current reading for each set were taken at constant time intervals. These intervals varied from thirty seconds to five minutes. This variation of the interval was chiefly caused by the microphonic sensitivity of the DC amplifier. The scale of amplification of the amplifier had to be changed between each reading; the switch noise resulting from the change of scale was the source of the difficulty. The data used in the determination

of K is shown in Table 4. Each set of data is represented by a horizontal line of numbers. In parentheses at the left of the column headed "Initial Electron Current" are the two initial electron current readings taken preceding and following the ion current reading given in the next column. At the right of the parentheses is the average of the two initial electron currents. As the ion current measured included the initial electrons as well as their negatively charged products, the ratio of the ion current to the initial electron current is K plus one. Each of the groups of four sets of data were taken on a fresh sample of air drawn from the laboratory through a vapor trap. There were intentional differences in the ionization chamber pressure and collection potentials used.

The values of K plus one in Table 4 are surprisingly consistent. The probable numerical error of the average of K plus one has been calculated to be 0.05 or 0.2 per cent of K plus one. The author does not believe this error to be indicative of the accuracy of the determination. The data was presented in the manner of Table 4 to emphasize the highly linear nature of the decrease of the initial current. This work has determined

$$K = 27.5 \pm 3,$$

ion-pairs per initial 1000ev electron.

The average energy of the incident electrons was taken as the potential required to reduce the Faraday cage current i_e to one-half the initial current. Because of the sharp

TABLE IV

EXPERIMENTAL VALUES IN THE DETERMINATION OF K

Initial Electron Current	Ion Current (Electron)		K + 1	Deviation from Grand Average
Ionization chamber pressure - 50 microns Positive collection potential - 4 v				
(13.7, 13.3)	13.5	376	27.9	0.0
(13.0, 12.4)	12.7	354	27.8	0.1
(11.3, 11.1)	11.2	309	27.5	0.4
(10.0, 9.4)	9.7	271	28.0	0.1
		Av	27.80	
Ionization chamber pressure - 50 microns Positive collection potential - 10 v				
(11.1, 10.9)	11.0	311	28.25	0.4
(10.6, 9.9)	10.2	281	27.55	0.4
(9.3, 8.4)	8.75	244	27.9	0.0
(7.85, 7.35)	7.6	211	27.8	0.1
		Av	27.87	
Ionization chamber pressure - 85 microns Positive collection potential - 40 v				
(13.9, 13.3)	13.6	380	27.9	0.0
(13.1, 11.9)	12.5	343	27.3	0.1
(11.7, 10.75)	11.2	307	27.4	0.5
(10.5, 9.3)	9.9	280	28.3	0.5
		Av	27.85	
Ionization chamber pressure - 50 microns Positive collection potential - 35 v				
(11.0, 8.5)	9.75	270	27.7	0.2
(8.2, 7.3)	7.75	215	27.75	0.2
(5.5, 4.7)	5.1	140	27.5	0.4
(10.05, 9.0)	9.53	260	27.3	0.6
		Av	27.61	
Ionization chamber pressure - 50 microns Positive collection potential - 40 v				
(15.0, 14.3)	14.65	400	28.7	0.2
(14.3, 14.5)	14.4	420	29.2	1.3
(14.7, 13.1)	13.9	387	27.8	0.1
(13.0, 13.4)	13.7	383	28.0	0.1
		Av	28.43	
			Total	5.7
	Grand	Av	27.91	

Grand average of K + 1 corrected for slow electrons = 28.5 ion-pairs per initial electron

$K = 27.5 \pm 3.7$

Probable Numerical error $= \frac{0.845\ \Sigma d}{n\sqrt{n-1}} = 0.15$

cut-off of the velocity distribution curve, little error is introduced by this assumption. The retarding potentials were measured with a voltmeter which had been calibrated with respect to a voltage-divider, potentiometer network, and also with the voltage-divider, potentiometer network. The average energy of the incident electrons was measured to be 1032 v ± 1%. With this value and K,

W becomes 38.5 ev ± 4.5% per ion-pair.

The actual value of W for 1000 ev electrons in air should lie between the limits of 33.8 ev and 40.2 ev per ion-pair.

The value of W for 1000 ev electrons in air from the formula proposed by Lehmann and Osgood[27] is 40.2 ev per mean free path. This result is corrected by Thomson[40] to become 37.3 ev per ion-pair for 1000 ev electrons absorbed in air. The relation advanced by Gerbes[16] sets W equal to 37.0 ev per ion-pair for 1000 ev electrons absorbed in air. The value advanced by Lehmann and Osgood lies outside the possible limits for W set by the present work. The results of Lisl[14] do not apply for his determination of W was made with 9000 ev to 60,000 ev electrons.

SUGGESTED IMPROVEMENTS

A major weakness in the present determination is the variability of the stream of electrons passing through the small orifice into the ionization chamber. It appears that the deflection voltage and the accelerating voltage for the gun were quite adequately regulated to exclude the probability that they were the cause of the variation. Unquestionably the regulation of the accelerating voltage would be improved by the "Au" type regulation. The discharge of the batteries supplying the heater voltage for the gun quite directly caused some of the variation in the initial electron current as the heater current noticeably diminished as time went on. This variation in heater current can be virtually eliminated if a high quality lead storage battery is used with a trickle charger delivering an appropriate current to offset the discharge due to the heater for the gun.

Variation in the emission of the filament of the gun was also caused by its bombardment by positive ions. Some of these ions originated from the effusive flow of gas from the ionization chamber, the remainder from the oil and mercury vapors of the diffusion pump and the McLeod gauge. A small fraction of the vapor may still be out-gasings from the vacuum walls. The effusive flow from the ionization chamber into the gun chamber is linearly dependent upon the pressure of the ionization chamber and hence the bombardment of the filament becomes serious at high ionization

chamber pressures. The positive ions may be removed by any of the several magnetic ejection systems. As an alternative, the oxide-coated filament may be replaced by a tungsten filament which is considerably less sensitive to bombardment. The high emission of the oxide-coated filament used was not exploited because of the space charge conditions which developed in the collection of the ionization products.

The following suggestions will reduce or remove the vapors which are responsible for much of the positive ion bombardment and when applied to the ionization chamber probably will remove the peculiar "pip" on the distribution curve. An additional trap for oil vapors should be inserted between the high vacuum volume and the diffusion pumps. There are many adequate types of traps for this purpose. The trap which is now in the gun chamber pumping stem has made a considerable improvement in the operation of the gun, but its effectiveness is limited by the lack of an adequate cooling system. The water lines which were used are too small and too long to deliver water adequately cold to the traps. To increase the effectiveness of the additional trap, the coils of the trap in the gun chamber pumping line might well be used as the expansion coils of a small household refrigeration unit. A trap for the ionization chamber pumping line could be served by the same refrigeration unit.

The mercury vapor can of course be removed by introducing a dry ice and acetone, or a liquid air trap into the lines connecting the McLeod gauge and the rest of the system. In addition it would be well to introduce a refrigerated trap of reasonable surface area into the gun chamber itself to rapidly remove the vapors evolved from the walls of the chamber.

Due to the long exposure to mercury vapor, there has been some amalgamation of the mercury and the walls of the gun chamber and the ionization chamber. To remove this from the vacuum surfaces, they should be scrubbed and rinsed in the manner indicated earlier. With the above measures the vacuum should be adequately clean. As a final safeguard, a vapor sensitive pressure gauge much more sensitive than the Pirani gauge should be used to monitor the vapor situation.

Despite some obvious failings, the DC current amplifier used to extend the range of the galvanometer has these merits: The amplifier is simple and straight forward in theory and construction, and with competent handling yields accurate results. The amplifier is by no means easy to operate but is rather temperamental. However, with experience the amplifier is reliable. Some optimum design conditions may be a factor of ten from the design actually used. One difficulty in arriving at a proper design is caused by the lack of published tube characteristics at the low operating level desired. Certainly the operation of the amplifier can be improved; however, it may be more rewarding to

use one of the more complex but stable amplifiers frequently described in the literature. As an alternative, the need of a current amplifier can be by-passed by the use of an electrometer. This will place a greater premium on the stability of the gun because of the integrating principle of the electrometer.

CONCLUSION AND ACKNOWLEDGMENTS

A new instrument has been constructed with which to determine the average energy for the formation of an ion-pair by electrons totally absorbed in gases. A preliminary value has been set for the average energy for the formation of an ion-pair by 1000 ev electrons totally absorbed in air at 33.6 electron volts. The experimental absolute accuracy of this determination is 1.1 per cent. At the present time it appears likely that certain changes may ultimately be made with an accuracy of one per cent or less.

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BIBLIOGRAPHY

1. Dushman, S. A. Scientific Foundations of Vacuum Technique. ed. 1, John Wiley and Sons, Inc., New York, 1949, 832 pp.

2. Dushman, S. A. reference 1, pp. 138-139.

3. Dushman, S. A. reference 1, page 139.

4. Barnes, J. L. A Compensated Electron Gun. Unpublished M.S. thesis, Michigan State College, 1950, 70 numb. leaves, 8 figures.

5. Buchmann, L. Über die Auslösung von Sekundärelektronen durch Electronen von 1-30 Kev. Ann. Physik, 87 (1928), pp. 809-838.

6. Bumstead, H. A. On the Ionization of Gases by Alpha rays. Phys. Rev., 8 (1916), pp. 715-730.

7. Cloud, R. W. and J. T. Philip Vacuum Tests of Rubber, Lead, Teflon Gaskets and Vinyl Acetate Joints. Rev. Sci. Instr., 21 (1950), pp. 741-743.

8. Chadwick, J. and H. S. Emeleus On the δ-rays produced by α-Particles in Different Gases. Phil. Mag. Ser. 7, 1 (1926), pp. 1-12.

9. Chadwick, J. and H. S. Emeleus reference 8, page 10.

10. Compton, K. T. and I. Langmuir Electrical Discharges in Gases Part I Survey of Fundamental Processes. Rev. Modern Phys., 2 (1930), pp. 123-242.

11. Daykendall, T. A. Use of Pirani Gauge in Finding Vacuum Leaks. Rev. Sci. Instr., 6 (1935), pp. 371-372.

12. Dushman, S. Scientific Foundations of Vacuum Technique. ed. 1, John Wiley and Sons, Inc., New York, 1949, 832 pp.

13. Dushman, S. reference 12, pp. 81-82.

14. Lisl, A. Über die Ionisierung von Luft durch Kathodenstrahlen von 10-30 Kev. Ann. Physik, 3 (1929), pp. 877-913.

15. Freund, L. Die totale Trägerbildung langsamer Kathodenstrahlen in Luft. Ann. Physik, 83 (1927), pp. 749-770.

16. Gerbes, W. Über die Ionisierungswirkung von Kathodenstrahlen in Luft. Ann. Physik, 83 (1927), pp. 848-884.

17. Gray, L. H. The Ionization Method of Measuring Neutron Energy. Proc. Cambridge Phil. Soc., 40 (1944), pp. 72-102.

18. Gray, L. H. reference 17, page 81.

19. Healy, R. H., and J. W. Reed. The Behavior of Slow Electrons in Gases, ed. 1, Amalgamated Wireless Limited, Sydney, Australia, 1941, 179 pp.

20. Hunt, F. V. and R. W. Hickman Voltage Regulators. Rev. Sci. Instr., 10 (1939), pp. 6-21.

21. Johnson, J. B. Total Ionization by Slow Electrons. Phys. Rev., 10 (1917), pp. 609-633.

22. Korff, S. A. Electron and Nuclear Counters. ed. 1, D. Van Nostrand Company, Inc., New York, 1946, 212 pp.

23. Korff, S. A. reference 22, page 83.

24. Marie, F. H. D. Vacuum Systems, Seals, and Valves. Rev. Sci. Instr., 19 (1948), pp. 480-493.

25. Lea, D. E. Actions of Radiations on Living Cells. ed. 1, The Macmillan Company, New York, 1947, 402 pp.

26. Lea, D. E. reference 25, page 28.

27. Lehmann, J. F. and F. K. Osgood The Total Ionisation due to the Absorption in Air of Slow Cathode Rays. Proc. Roy. Soc. (London) A, 115 (1927), pp. 609-634.

28. Mano, G. Recherches sur L'Absorption des Rayons-α. Ann. phys., 1 (1934), pp. 407-531.

29. Nisle, R. G. An Experimental Electron Gun. Unpublished M.S. thesis, Michigan State College, 1947, 18 numb. leaves, 6 figures.

30. Rutherford, E. K., J. Chadwick, and C. D. Ellis Radiations from radioactive substances, ed. 1, Cambridge University Press, 1930, 588 pp.

31. Schmitz, W. Die totale Tragerbildung langsamer Kathodenstrahlen in Luft. Physik Z., 39 (1938), pp. 848-849.

32. Stranathan, J. D. The "Particles" of Modern Physics. ed. 1, The Blakiston Company, Philadelphia, 1942, 388 pp.

33. Stranathan, J. D. reference 32, page 45.

34. Stranathan, J. D. reference 32, pp. 28-29.

35. Strong, J. et al Procedures in Experimental Physics. ed. 1, Prentice-Hall, Inc., New York, 1938, 628 pp.

36. Sullivan, A. H. Vacuum Pumping Equipment and Systems. Rev. Sci. Instr., 10 (1939), pp. 1-14.

37. Thomson, J. J. and G. P. Thomson Conduction of Electricity Through Gases, ed. 3, Vol. I, Cambridge University Press, London, England, 1928, 401 pp.

38. Thomson, J. J. and G. P. Thomson reference 37, page 17.

39. Thomson, J. J. and G. P. Thomson Conduction of Electricity Through Gases, ed. 3, Vol. II, Cambridge University Press, London, England, 1928, 703 pp.

40. Thomson, J. Ionizing Efficiency of Electronic Impacts in Air. Proc. Roy. Soc. (Edinburgh), 31 (1911), pp. 157-174.

41. Millikan, R. A. The Ionization of α- and β-Particles Through Matter by Lord's Theory of Collisions. Proc. Roy. Soc. (London) A, 106 (1924), pp. 187-191.

42. Millikan, R. A. and Bowen α-ray Tracks. Proc. Cambridge Phil. Soc., 21 (1923), pp. 109-119.

43. Millikan, R. A. and Ionization by X-rays and β-rays by the Cloud Method Part I X-rays. Proc. Roy. Soc. A, 104 (1923), pp. 1-30.

44. Millikan, R. A. and Ionization by X-rays and β-rays by the Cloud Method Part II β-rays. Proc. Roy. Soc. A, 104 (1923), pp. 188-212.