THE IONIZATION OF HELIUM, NEON, AND ARGON BY ELECTRON IMPACT

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Abstract

Quantitative measurements have been made of the total number of positive charges produced per electron per cm path at a definite pressure, in helium, neon, and argon, as a function of the energy of the impacting electrons out to 4500 volts. In helium the maximum efficiency 1.256 occurs at 110 volts, in neon 3.008 at 170 volts, and in argon 13.01 at 88 volts.

An empirical relation has been found which expresses the efficiency of ionization of helium within the experimental error for energies greater than 60 volts.

The data obtained differ considerably from that found by previous investigations, but because of the more precise length of path from which the positive ions were measured and the more accurate knowledge of the energy of the electrons as well as the elimination of secondary electrons, it is believed that the results presented here are the most accurate thus far obtained.

SEVERAL investigations have been made of the efficiency of ionization by electron impact in various gases.[1–9] Five different methods have been used, with results which are not in satisfactory agreement. The most extensive investigations were those of Hughes and Klein[3] and Compton and Van Voorhis.[1,2] After applying certain necessary corrections to the data of Hughes and Klein, Compton and Van Voorhis[2] were able to make these data qualitatively substantiate their own. Jones[4] and Bleakney[5] using a method suggested by Professor Tate measured the efficiency of ionization in Hg vapor with results which agreed only qualitatively with those of Compton and Van Voorhis.

Hummel[6] who studied Ne, A, and K by a method similar to that of Jones also agreed only qualitatively with Compton and Van Voorhis for Ne and A. The complicated effects present in the method used by Jesse[7] make it impossible to compare his results with those of the others. Finally the results of von Hippel[8] and Funk[9] cannot be reconciled at all with the results of the other observers.

Because of these discrepancies in the measured values of the efficiency of

[1] Compton and Van Voorhis, Phys. Rev. **26,** 436 (1925).
[2] Compton and Van Voorhis, Phys. Rev. **27,** 724 (1926).
[3] Hughes and Klein, Phys. Rev. **23,** 450 (1924).
[4] T. Jones, Phys. Rev. **29,** 822 (1927).
[5] W. Bleakney, Phys. Rev. **34,** 157 (1929); **35,** 139 (1930).
[6] A. D. Hummel, Thesis, University of Illinois (1928).
[7] Jesse, Phys. Rev. **26,** 208 (1925).
[8] von Hippel, Ann. d. Physik **87,** 1035 (1928).
[9] Funk, Ann. d. Physik **4,** 149 (1930).

ionization it was thought desirable to redetermine them by a method as free as possible from those sources of error which are inherent in most of the methods previously used and also to extend the work to higher voltages.

In this paper are presented the results obtained by using a method similar to that employed by Jones,[4] Bleakney[5] and Hummel.[6]

Apparatus and Procedure

The apparatus, Fig. 1, was made of copper with Pyrex insulation. It was baked out at a bright red heat before, and at about 400°C for two days after, it was placed in the tube. A Pyrex tube with no wax joints was used. It was surrounded by a solenoid to develop the magnetic field H which facilitated the separation of the positive ions from the electrons and also served to define the electron beam. The electron source was the filament F made of fine tungsten wire bent in the form of a hairpin about 1 mm wide. The holes

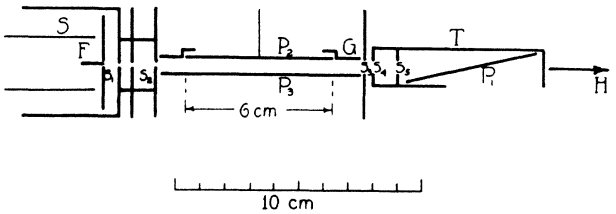

Fig. 1. Diagram of apparatus.

S_1 and S_2 were about 1.5 mm in diameter. This arrangement eliminated the presence of secondary electrons from the metal parts, since the magnetic field and not the slits defined the electron beam. Thus none of the electrons could collide with any metal until they reached the collecting plate P_1 which was connected to the grounded box T through a galvanometer G_1 (sensitivity 1500 megohms) and a set of B batteries (400 volts). S_3 was 5.5 mm in diameter while S_4 and S_5 were 5 mm in diameter.

The plate P_1 was covered with soot and, as stated above, maintained 400 volts positive with respect to T. Thus any electron which left P_1 would be in a field whose direction was nearly perpendicular to the axis of the tube and would have to go through a retarding potential of 400 volts before it could leave T. That P_1 collected all of the electrons is indicated by Fig. 2 in which the electron current to P_1, for various values of V_a, as a function of the potential of P_1 is shown.

The plate S_1, shield S, and the filament F (heated by the current from an insulated battery) were at the same potential $-V_a$ with respect to S_2 which was grounded.

The plate P_2, 6.05 cm$\times$2 cm was connected to the guard-ring G through the galvanometer G_2 (sensitivity 45,000 megohms) which measured the positive ions produced by the electrons in the 6.05 cm path directly below P_2. The positive ions were drawn out of the electron beam by an electric field between P_2 and P_3 which were 6 mm apart and maintained at 4 volts difference of potential. G and P_3 were connected together by a high resistance,

the midpoint of which was grounded, so that the speed of the electrons would not be appreciably altered after they left the last slit S_2 until they passed through S_4 which was at the same potential as S_2.

Compton and Langmuir[10] have pointed out that probability of ionization by an electron in terms of the total number of collisions made per unit path by the electron is not easy to measure nor to define accurately, and consequently it is better "to deal directly with the more accurately determined quantity, the number of new electrons produced by ionization per unit path at a specified gas pressure by an electron of given energy. This may be called

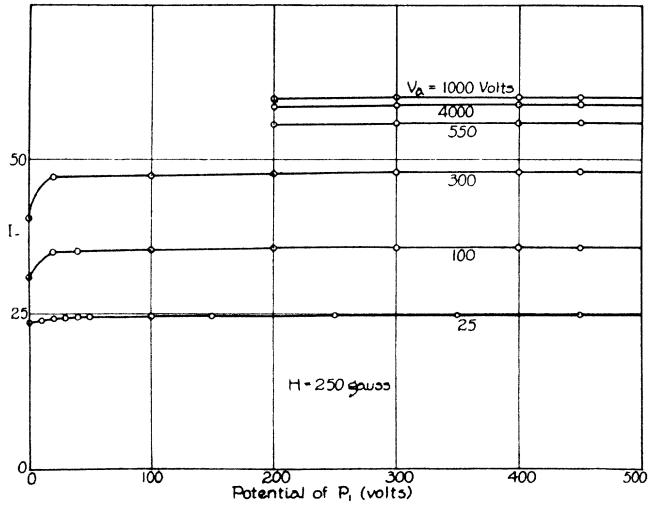

Fig. 2. Characteristics of electron trap.

the probability of ionization per unit path at unit pressure." In the present paper this quantity will be called the "efficiency of ionization," with the further specification that the temperature be 0°C.

The efficiency of ionization, ϵ, as defined above is given by the relation

$$\epsilon = (I_+/I_-)\,[(T_1T_2)^{1/2}/273lp]$$

where I_+ is the positive ion current collected by the plate P_2 and measured by the galvanometer G_2, I_- the electron current collected by P_1 and measured by the galvanometer G_1, T_1 and T_2 the respective absolute temperature of the McLeod gauge and apparatus, l the length of the plate P_2, and p the pressure of the gas in mm of Hg. T_1 was measured by a thermometer and T_2 by a thermocouple connected to the center of P_2 and at one edge, P_2 serving as one junction.

For He and Ne pressures from 1.0 to 1.6×10^{-3} mm of Hg were used. In argon the final results were obtained by using a pressure of 0.277×10^{-3}. At these pressures the ratio of the maximum positive ion current to plate P_2 to the electron current to P_1 was always less than 0.02, consequently the electron current could at the most not be more than 2 percent too high,

[10] Compton and Langmuir, **Rev.** of Mod. Phys. **2**, 129 (1930).

even though the new electrons from the positive ions were measured. At these pressures the chance of an electron colliding more than once before it reaches the electron trap T is small enough to be neglected.

The electron current[11] collected by P_1, which came from the ions formed within T, was smaller than the accuracy with which the total electron current could be measured.

Fig. 3 is a typical saturation curve for the positive ion current to P_2 The positive ion current to P_2 is shown as a function of the difference of potential in volts between P_2 and P_3, with the magnetic field H equal to 250 gauss, the field used throughout this investigation. Similar curves up to $V_a = 4500$

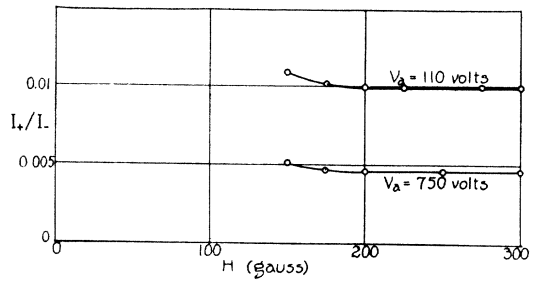

Fig. 3. Typical saturation curve for positive ions.

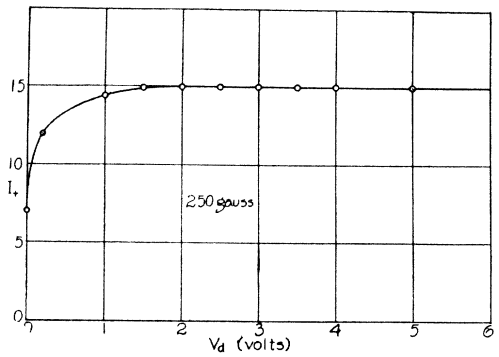

Fig. 4. The ratio of the positive ion current to the electron current as a function of the magnetic field.

volts were obtained. That none of the positive ions measured came from T was concluded, since no positive ions were collected when V_a was less than the ionization potential of the gas in the tube, with P_1 at a high potential.[12]

[11] The total current to T and P_1, was not measured by a single galvanometer, since such an arrangement would have required a well insulated set of "B" batteries which were not available. The electrical circuit was, however, arranged so that the current to either could be measured at any time without altering any of the conditions existing in the tube.

[12] The question as to whether any photo ionization might be present which would alter the values of ϵ was experimentally tested. P_2 was removed and replaced by a narrow plate to collect the ions formed by direct impact. On each side of this plate was a wider plate connected to an electrometer. The results showed that if any photo ionization did occur it was too small to effect the efficiency measurements.

Fig. 4 indicates that the ratio of the positive ion current to the electron current was independent of the magnetic field, near the value used when readings were taken. The higher ratio obtained with lower magnetic fields is explained by the spreading of the electron beam, since a negative current was collected on T with the lower fields. This current was just great enough to account for the increase in the ratio. With higher fields no electron current was collected by either S_3 or T.

The gases used were commercially pure. The helium and neon were further purified by connecting to the tube a charcoal trap immersed in liquid oxygen. The purity of the helium is indicated by the curve for helium in Fig. 7, that is, any appreciable amount of foreign gas would have resulted in ionization below the ionization potential of helium. Helium has the highest ionization potential and the lowest efficiency of any of the gases. Dr. Bleakney made an analysis with a mass spectrograph of the neon used and found a trace of helium present (not more than one percent). Helium is the only gas with an ionization potential higher than that of neon and consequently the curve in Fig. 8 would not show the presence of a small amount of helium. However the presence of one percent of He in Ne would not affect the results by more than 2/3 percent, since the efficiency is not very different for the two gases. Charcoal absorbs a little more neon than helium but the results are probably not off by more than one percent due to the presence of the helium. Bleakney found no impurities at all in the argon for which CO_2 snow in acetone was used in place of the liquid oxygen.

The pumps were sealed off from the tube by a mercury trap. (The mercury vapor was frozen out by a trap immersed in liquid oxygen.) The gas to be studied was allowed to leak into the tube through a small capillary until the desired pressure was obtained, after which the flow was cut off. No ionization could be detected before the gas was admitted, although an electron current four or five times that used in taking the readings was employed. The tube was allowed to stand for about two hours after the gas had been admitted, to be sure that a pressure equilibrium had been established between the charcoal and the gas. It was found that the variations in the pressure were less than one percent over a period of 12 hours. After a complete set of observations had been taken, readings were repeated at intervals over the entire range of accelerating potentials used. Any observation could be checked to within one percent. Curves obtained on different days checked very closely except at the highest potentials where variations of several percent occurred.

In the calibration of the McLeod gauge, etc., an attempt was made to reduce all constant errors to a minimum.

Result

Fig. 5 shows the results obtained for He, Ne, and A up to 1500 volts, (readings were taken up to 4500 volts). The efficiency of ionization as defined above is shown as a function of the accelerating potential of the electrons.

The break in the curve for argon at about 57 volts was at first hard to

account for, since the energy necessary to form A^{++} as a primary product is 43.51 volts.[13] The results of Bleakney[14] however indicate that this would be expected, due to the peculiar form of the efficiency of ionization curve for A^{++}.

Professor Tate has derved the empirical relation

$$\epsilon = 3.383(V_0/V_a)^{1/2}[1 - e^{-54V_0/V_a}]^{1/2}[1 - e^{-(V_a-V_0)/2.28V_0}]$$

which expresses the efficiency of ionization of helium within the experimental error for $V_a > 60$ volts out to 4500 volts. Below 60 volts this formula yields values of ϵ which are higher than the observed values, since the observed values approach a linear function of V_a near the ionization potential while the above formula does not.

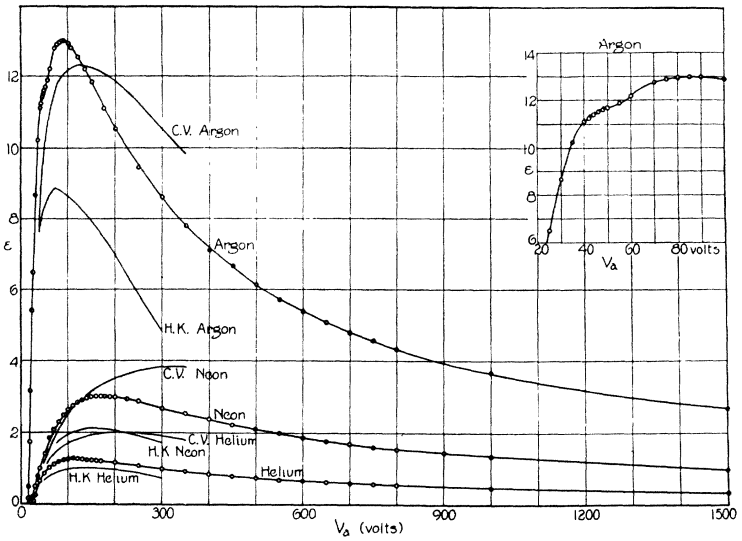

Fig. 5. The efficiency of ionization of He, Ne, and A as a function of the energy of the impacting electrons in volts, reduced to 1 mm pressure at 0°C.

It would seem that the above expression is more than a mere empirical formula, since there are in it only two constants which determine the shape of the curve, the constant 3.383 being only a scale factor.

These results were obtained with electron currents of from 1 to 3×10^{-7} amperes for $V_a < 2000$ volts, beyond which the currents used were from 8 to 10×10^{-7} amperes. For $V_a > 100$ volts the efficiency of ionization was independent of the electron current over the range 5×10^{-8} to 10^{-6} amperes, but for $V_a < 100$ volts it was found that the form of the curves began to change appreciably with electron currents greater than about 5×10^{-7} amperes. This could be accounted for by the increasing space charge at higher current densities which would decrease with increasing V_a, causing

[13] K. T. Compton, J. C. Boyce, and H. N. Russell, Phys. Rev. **32**, 179 (1928).

[14] W. Bleakney, see the following paper in this issue.

the voltage correction also to decrease with increasing V_a. In the results given here, the current density was always low enough so that this effect was not appreciable.

The temperature of the tube, about 87° C, was the same as the temperature of the solenoid and consequently the whole apparatus inside the tube came to the same temperature.

The same data are given in Fig. 6, but in order to show the results out

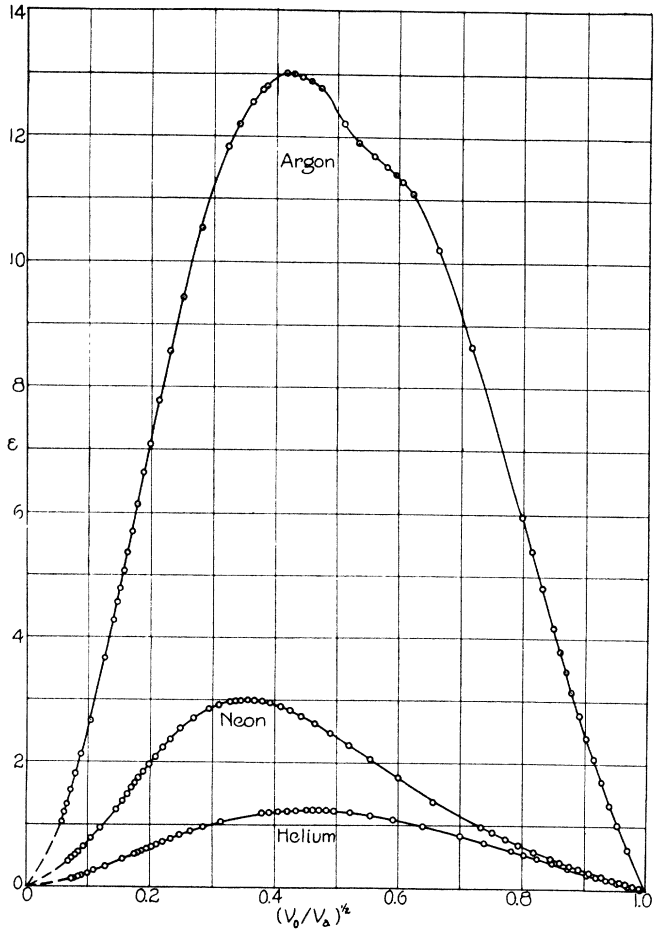

Fig. 6. The efficiency of ionization of He, Ne, and A as a function of $(V_0/V_a)^{1/2}$, reduced to 1 mm pressure at 0°C.

to 4500 volts the efficiency is shown as a function of $(V_0/V_a)^{1/2}$ when V_0 is the ionization potential of the gas and V_a the accelerating potential of the electrons.

The results are also given in the following table. The efficiency of ionization as defined, represents the average total number of positive charges per electron per cm path at 1 mm pressure and 0° C. The values of V_a have been corrected for contact e.m.f.'s initial velocity, etc., in the following manner.

To obtain a correct voltage scale the curves in Fig. 7 were drawn.[15] The extrapolated straight lines were assumed to be the correct curves, the curved part being due to the velocity distribution of the electrons. All of the

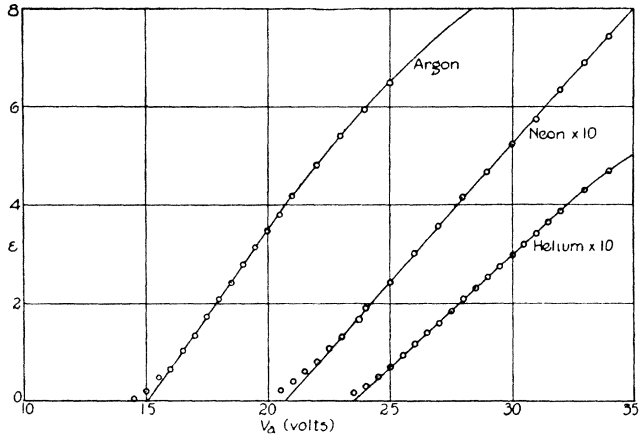

Fig. 7. The efficiency of ionization as a function of the energy of the impacting electrons, near the ionizing potential. The ionization potential of helium was assumed to be 24.48 volts, that of neon 21.47 volts, and that of argon 15.69 volts.[15]

curves do not show the same correction since the apparatus was changed several times and new filaments inserted.

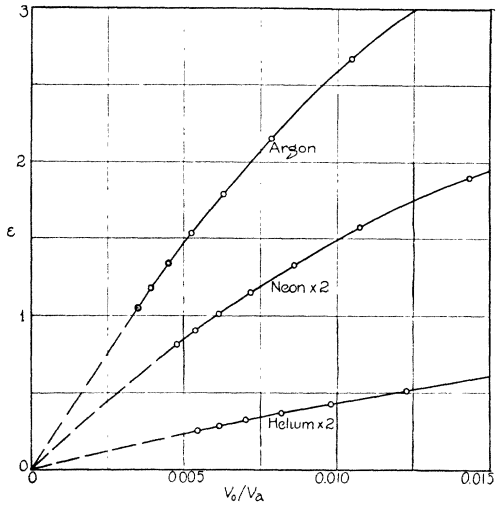

Fig. 8. The efficiency of ionization as a function of (V_0/V_a) for large values of V_a.

The curves in Fig. 7 also indicate that the efficiency of ionization is a linear function of the energy of the impacting electrons near the ionization potentials of the gases studied, whereas at higher velocities, Fig. 8, the

[15] The values of ionization potentials were obtained from the Int. Crit. Tables, Vol. VI, p. 70.

efficiency apparently becomes inversely proportional to the energy. This was found to be approximately true with beta-particles in an article by W. Wilson.[16] J. J. Thomson[17] theoretically arrived at a formula which represents the efficiency of ionization as being inversely proportional to the energy of an impacting electron with energy much greater than the minimum ionizing energy. The formula does not, however, at all represent the observed data at lower energies and yields values much too low at higher energies. Bohr[18] was able however partly to account for this discrepancy by considering the ionization due to the secondary electrons emitted in the process of forming the ions. In the present investigation this factor

TABLE I. *Efficiencies of ionization expressed as numbers of positive charges per electron per cm path per mm pressure at 0°C for various electron velocities.*

V_a	He	Ne	A	V_a	He	Ne	A
16.0			0.22	70	1.110	2.110	12.75
16.5			0.58	75			12.87
17.0			0.93	80	1.178	2.340	12.95
17.5			1.29	85			12.98
18.0			1.65	90	1.220	2.520	13.00
18.5			2.00	100	1.245	2.660	12.90
19.0			2.35	105	1.251		12.80
19.5			2.70	110	1.256	2.770	12.75
20.0			3.07	115	1.255		
20.5			3.40	120	1.250	2.860	12.53
21.0			3.75	130	1.247	2.930	
22.0		0.032	4.65	135			12.20
22.5		0.057		140	1.241	2.964	
23.0		0.087	5.12	150	1.228	2.987	11.83
23.5		0.118		160	1.216	3.000	
24.0		0.142	5.62	170	1.200	3.008	
25.0	0.022	0.198	6.16	175			11.10
25.5	0.045			180		3.005	
26.0	0.069	0.253		190		2.998	
26.5	0.092			200	1.149	2.988	10.53
27.0	0.114	0.307		225		2.935	
27.5	0.138			250	1.060	2.867	9.43
28.0	0.161	0.365		300	0.971	2.710	8.58
28.5	0.184			350	0.902	2.541	7.78
29.0	0.207	0.420		400	0.836	2.367	7.08
29.5	0.229			450	0.778	2.199	6.64
30.0	0.251	0.476	8.43	500	0.728	2.081	6.13
32.0	0.340	0.588		550	0.685	1.950	5.73
34.0	0.431	0.699		600	0.643	1.840	5.37
35.0			10.08	650	0.612	1.740	5.07
36.0	0.515	0.803		700	0.584	1.664	4.78
38.0	0.583	0.903		750	0.558	1.580	4.55
40.0	0.633	1.000	10.93	800	0.530	1.517	4.32
42.0			11.18	900		1.390	
44.0			11.39	1000	0.448	1.290	3.66
45.0	0.760			1500	0.328	0.950	2.67
46.0			11.52	2000	0.260	0.788	2.15
48.0			11.61	2500	0.215	0.663	1.79
50.0	0.860	1.470	11.68	3000	0.183	0.575	1.53
55.0	0.940		11.87	3500	0.162	0.510	1.34
60.0	1.025	1.830	12.15	4000	0.142	0.455	1.18
				4500	0.127	0.407	1.05

[16] W. Wilson, Proc. Roy. Soc. **85**, 240 (1911).
[17] J. J. Thomson, Phil. Mag. **23**, 449 (1912).
[18] N. Bohr, Phil. Mag. **30**, 581 (1915).

however would be negligible, since the number of secondary electrons would be of the same order of magnitude as the positive ion current. A beam of electrons of this magnitude could not produce an appreciable number of ions, no matter what their energy might be.

The writer hopes in the near future to study the efficiency at higher energies since the present apparatus was not suitable for potentials greater than 4500 volts.

Discussion

A comparison of the results of the present investigation for Ne, He, and A is shown in Fig. 5. The results of the other observers have been reduced to the same temperature and pressure conditions. The corrections which Compton and Van Voorhis[2] applied to Hughes' and Klein's data have not been made, although the temperature of their tube was assumed to be 60° C.[2]

Because of the definite length of path from which the positive ions were measured, and the more accurate knowledge of the energy of the impacting electrons as well as the elimination of secondary electrons, it is believed that the results presented here are more accurate than those of the previous investigations.

Although Hummel used the same method, the distorted fields in the ionizing chamber and the presence of secondary electrons from the slits which defined his electron beam, makes a comparison with his data difficult.

It is a pleasure for the writer to express here his gratitude to Professor John T. Tate, who suggested the method used and under whose guidance this work was carried out. Thanks are also due to Dr. Walker Bleakney for his constant interest and many suggestions.