# The Total Ionization of Nitrogen by Electron Collisions

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Measurements of the total ionization produced in nitrogen by beams of electrons, whose homogeneity of velocity had been tested, have been taken for electron energies up to 1500 volts. The ionization was found to increase rapidly up to 75 volts, then less rapidly but linearly to 375 volts, for which there is a break in the ionization curve, indicating the onset of $K$ electron ionization; the ionization again increases rapidly near 750 volts and after 1200 volts is found to increase less rapidly but linearly with increased electron energies. From determinations of the critical pressures for some of the electron energies used, the mean effective ranges, the thicknesses of the absorbing gas layer, have been measured and found nearly to obey the equation, $R_e=0.07+1.88\times10^{-6}V^2$ cm at 1 mm pressure. By dividing the total ionization produced by electrons by their effective ranges as determined above the average total ionization per cm of absorbing gas layer has been calculated: the results show a maximum above 100 volts in the region found for primary ionization per cm by Compton and Van Voorhis and by Tate and Smith. The authors' curves show a second maximum at 750 volts, twice the ionization potential of the $K$ electrons of nitrogen, these characteristics being similar to those discovered by the senior author in an earlier study of the total ionization produced in air. None of these curves agree with the results of Lehmann and Osgoode in the same field, the discrepancies being ascribed to differences in the shapes of the ionization chambers used and in the fields within them.

SINCE the publication by the senior author[1] of determinations of the total ionization produced in air by electron collisions involving energies up to 2250 volts, a limited number of experiments in the same field and involving the same range of electron energies have been reported, principally those of Lehmann and Osgoode,[2] who used a method nearly equivalent to that of Anslow[1] and accelerating voltages up to 1000 volts, and those of Langmuir and Jones,[3] who used an entirely different method and voltages up to 100 volts. The best known experiments with voltages in excess of 1000 volts are those of Eisl[4] and Buchmann,[5] in which the total ionization produced by swiftly moving electrons was measured, and those carried out by Williams and Terroux,[6] who examined tracks of fast $\beta$ particles in a Wilson cloud chamber.

In general, ionization measurements have dealt with that portion of the ionization produced in the first fraction of the path of the moving electron, in which there is little chance of secondary collisions, some of the most outstanding measurements being those of Hughes and Klein,[7] Compton and Van Voorhis,[8] Smyth,[9] Bleakney,[10] and Tate and Smith.[11] Attention has been focused on this type of measurement largely because in comparisons of experimental results with the predictions of the collision theories of classical theory[12] and of wave mechanics[13] it has been difficult to evaluate the amount of energy lost in secondary and further collisions.

The necessity of examining the homogeneity of the velocity of the electron beam used in ionization experiments was pointed out and the homogeneity examined by Lehmann and Osgoode,[14] and later by Lawrence.[15] In the experiments, reported by the senior author[16] at the Washington meeting of the American Physical Society in April, 1934 and described in the present article, the homogeneity of the

[1] Anslow, Phys. Rev. **25**, 484 (1925).
[2] Lehmann and Osgoode, Proc. Roy. Soc. **A115**, 609 (1927); Lehmann, Proc. Roy. Soc. **A115**, 634 (1927).
[3] Langmuir and Jones, Phys. Rev. **31**, 357 (1928).
[4] Eisl, Ann. d. Physik **3**, 277 (1929).
[5] Buchmann, Ann. d. Physik **87**, 509 (1928).
[6] Williams, Mem. Man. Phil. Soc. **71**, 23 (1927); Proc. Camb. Phil. Soc. **24**, 315 (1928); Proc. Roy. Soc. **A125**, 420 (1929); **A128**, 459 (1930); **A130**, 310, 328 (1931); **A135**, 108 (1932); Williams and Terroux, Proc. Roy. Soc. **A126**, 289 (1930).
[7] Hughes and Klein, Phys. Rev. **23**, 111, 450 (1924).
[8] Compton and Van Voorhis, Phys. Rev. **26**, 436 (1925); **27**, 724 (1926).
[9] Smyth, Phys. Rev. **35**, 472, 478 (1930).
[10] Bleakney, Phys. Rev. **35**, 139 (1930); **36**, 1303 (1930).
[11] Smith, Phys. Rev. **36**, 1293 (1930); Tate and Smith, Phys. Rev. **39**, 270 (1932); **46**, 773 (1934).
[12] J. J. Thomson, Phil. Mag. **23**, 449 (1912); Bohr, Phil. Mag. **25**, 1 (1913); **30**, 581 (1915); Henderson, Phil. Mag. **44**, 690 (1922); Fowler, Proc. Camb. Phil. Soc. **21**, 521, 531 (1923); Phil. Mag. **47**, 257 (1924).
[13] Bethe, Ann. d. Physik **5**, 325 (1930); Massey and Mohr, Proc. Roy. Soc. **A132**, 605 (1931); **A139**, 187 (1933); **A140**, 613 (1933).
[14] Lehmann and Osgoode, Proc. Camb. Phil. Soc. **22**, 731 (1925).
[15] Lawrence, Proc. Nat. Acad. Sci. **12**, 29 (1926).
[16] Anslow, Phys. Rev. **45**, 750 (1934).

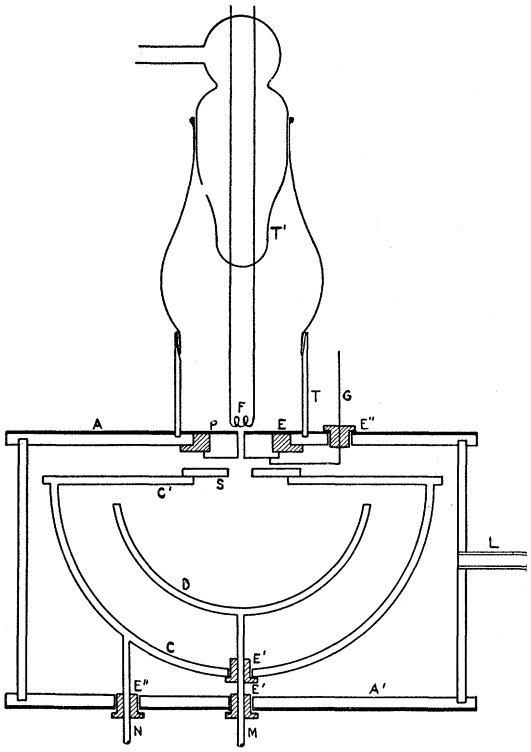


FIG. 1. The filament tube and ionization chamber.

electron beam was tested at various voltages and measurements taken of the total ionization in nitrogen produced by electron collisions with energies up to 1500 electron volts.

## EXPERIMENTAL PROCEDURE

The pure nitrogen used in the experiment was produced according to the method of Waran,[17] by the action of dilute bromine water on dilute ammonium hydroxide, and was stored over phosphorus pentoxide, being allowed to leak through a capillary into the ionization chamber at a rate which maintained a nearly constant pressure in the chamber.

The filament tube and ionization chamber are shown in Fig. 1, being the same as described in the earlier paper[1] with one alteration, necessary for the measurements of the homogeneity of the beam; the opening at the center of the hemispherical ionization chamber was decreased to 4 mm by attaching to its lid an aluminum plate, *s*, with this circular opening, taking care to center the aperture opposite the end of the capillary of the anode through which the accelerated electrons passed just before they entered the ionization chamber. The capillary was 1.1 cm long and 0.2 mm in diameter and the distance between the lid of the chamber and the anode was adjusted to 2 mm.

The ionization measurements were also taken according to the compensation method described in the first experiment, the accelerating potential applied to the electrons being taken in all cases as that between the midpoint of the filament and the anode.

### The homogeneity of the beam

To test the homogeneity of the electron beam the fraction of the electrons entering the ionization chamber with a velocity corresponding to the full drop of potential between the filament and the anode was determined by applying a retarding potential between the anode and the plate, *s*, of the ionization chamber, the pressure in the chamber being maintained by diffusion pumps at less than $10^{-4}$ mm before starting a run. In spite of the previous outgassing of the metal parts, the pressure usually rose during a run to about $2\times10^{-4}$ mm with a consequent production of ions, which had to be considered in the interpretation of the measurements. The fraction of the electrons emitted by the hot filament and accelerated to the anode, which enter the chamber through the aperture, *s*, with velocities equivalent to the full drop of potential, was determined in the following manner, the electrical connections being shown in Fig. 2. Connecting the rods and chamber together and

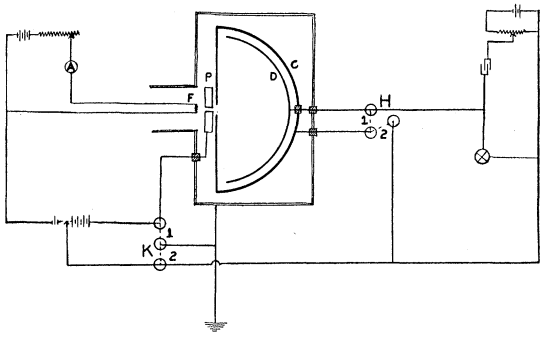


FIG. 2. Circuit used in homogeneity and ionization measurements.

[17] Waran, Phil. Mag. **42**, 246 (1921).

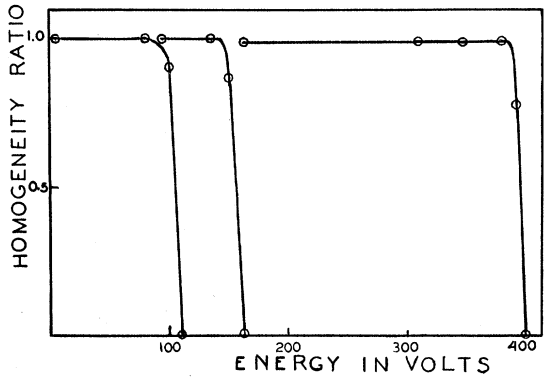


FIG. 3. The homogeneity ratio for 108, 165 and 400-volt electron beams.

to one pair of the quadrants of the electrometer by using the switch $H$ in the position 1 shown in the diagram, and applying an accelerating potential between the filament and the anode while the shielding cylinder and anode were connected to earth by switch $K$, used in position 1, the number of electrons reaching the rods and chamber in a given time interval was measured by the rate of charging of the electrometer. Then, with switches $K$ and $H$ in positions 2 and 1, respectively, a retarding potential was applied between the anode and the chamber by keeping the anode at a positive potential and connecting the chamber and the rods to earth through the electrometer; the latter collected both the total number of electrons which entered the chamber with velocities in excess of that corresponding to the retarding potential and also the positive ions produced by collisions with molecules of the gas in the chamber; the negative ions and any secondary electrons emitted by the walls of the chamber were attracted to the anode. Finally, with switches $K$ and $H$ in positions 1 and 2, respectively, an equal retarding potential was applied between the anode and the chamber with the anode connected to earth and a negative potential on the chamber which had been disconnected from the rods. The rods, connected to earth through the electrometer, collected the electrons which entered the chamber, the negative ions formed, and the secondary electrons produced, while the positive ions flowed to the chamber.

The Townsend null method was used in taking the measurements, by balancing in turn the currents flowing to the electrometer by opposing currents from a potentiometer system, which charged a standard air condenser shunted to the

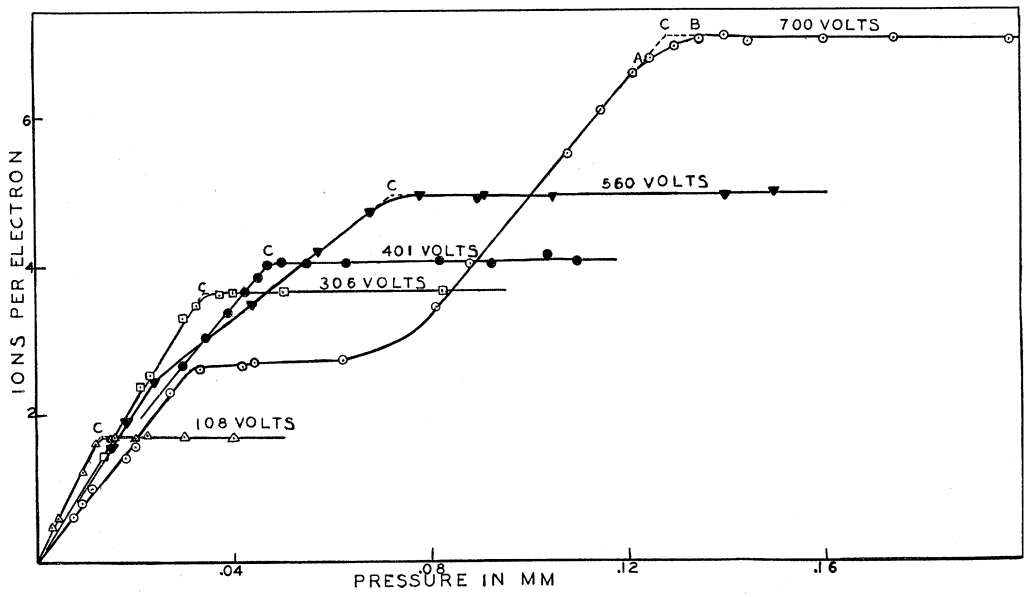


FIG. 4. Typical ionization-pressure curves. The ionization is proportional to the pressure up to a region of critical pressures, for which the thickness of the absorbing gas layer is nearly equal to the radius of the chamber. The pressure at $C$ in a curve is used to calculate the mean effective range of the electrons. Total ionization values for a given energy are taken as the mean of the values on the horizontal part of the curve.

TABLE I. *Test of homogeneity of electron beams.*

| Accelerating Potential | 400 volts | | | 165 volts | | |
|---|---|---|---|---|---|---|
| Retarding Potential | 310 volts | | | 152 volts | | |
| Pressure ($10^{-4}$ mm) | 1.2 | 0.8 | 1.5 | 1.8 | 1.1 | 2.0 |
| $r_1$ | 0.74 | 0.97 | 0.60 | 0.59 | 0.61 | 0.67 |
| $r_2$ | 1.24 | 1.00 | 1.44 | 1.17 | 1.16 | 1.06 |
| Homogeneity ratio | 0.99 | 0.98 | 1.02 | 0.88 | 0.88 | 0.86 |
| | mean 1.00 | | | mean 0.87 | | |

electrometer. Since the pressure on the chamber side of the anode rose slightly and the electron beam varied somewhat in intensity during a set of readings, the three measurements to be made were taken in order and then the first and the second repeated in reverse order. If $r_1$ represents the ratio of the current due to the retarded electrons and the positive ions within the chamber to the unretarded electron current, and $r_2$ the ratio of the current due to the retarded electrons, the negative ions and the secondary electrons to the same unretarded electron current, the homogeneity ratio may be taken as the mean of $r_1$ and $r_2$. Two sample sets of results are given in Table I, and the values of the homogeneity ratios for different retarding potentials are shown graphically in Fig. 3 for 108, 165 and 400-volt electrons. It is evident that these electron beams possessed a high degree of homogeneity.

## Ionization measurements

The ionization produced by electrons of a definite energy was measured exactly as in the previous experiment. For a number of voltages the ionization was determined for a series of gas pressures: typical ionization-pressure curves are shown in Fig. 4, and indicate that for small pressures a linear increase in ionization occurs with increasing pressure up to a region of critical pressures, for which the radius of the chamber is comparable with the mean thickness of the absorbing gas layer traversed; for still higher pressures the ionization is constant, this constant value giving the total ionization measurement. Determinations of the total ionization produced were made at frequent voltage intervals; the values obtained are given in the first two columns of Table II, and the results are shown in Fig. 5.

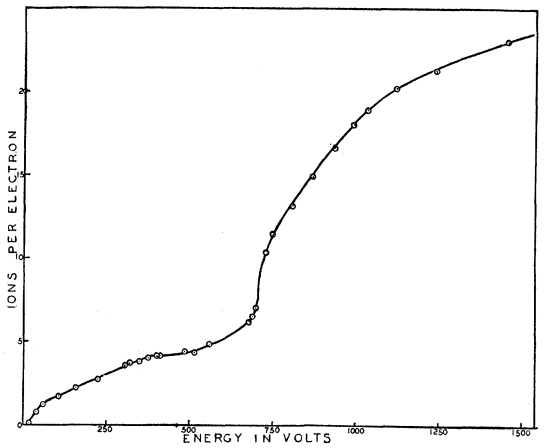


FIG. 5. Total ionization curve for electrons with energies ranging from 0–1500 volts.

It is evident that the total ionization produced is not a linear function of the energy of the colliding electron for energies less than 1000

TABLE II. *Measurements of total ionization produced by electrons of various energies in nitrogen.*

| Energy (volts) | Ions Per Electron | Effective Range at 1 mm Pressure | Ions Per Electron Per cm of Effective Range at 1 mm Pressure |
|---|---|---|---|
| 22 | 0.11 | *0.071 | 1.55 |
| 42 | 0.73 | 0.073 | 9.95 |
| 60 | 1.20 | 0.077 | 14.2 |
| 108 | 1.72 | *0.092 | 18.7 |
| 165 | 2.25 | *0.123 | 18.3 |
| 225 | 2.78 | 0.165 | 16.9 |
| 306 | 3.59 | *0.241 | 14.6 |
| 321 | 3.78 | 0.264 | 14.3 |
| 350 | 3.85 | 0.316 | 12.3 |
| 376 | 4.06 | 0.335 | 12.1 |
| 386 | 4.18 | 0.350 | 11.9 |
| 401 | 4.17 | *0.372 | 11.2 |
| 412 | 4.20 | 0.398 | 10.5 |
| 487 | 4.46 | *0.513 | 8.6 |
| 514 | 4.39 | 0.574 | 7.65 |
| 560 | 4.88 | *0.640 | 7.40 |
| 680 | 6.20 | 0.939 | 6.60 |
| 690 | 6.52 | 0.960 | 6.79 |
| 700 | 7.05 | *0.975 | 7.23 |
| 732 | 10.4 | 1.097 | 9.66 |
| 754 | 11.5 | 1.110 | 10.40 |
| 804 | 13.2 | 1.255 | 10.52 |
| 870 | 15.1 | *1.470 | 10.17 |
| 935 | 17.1 | 1.693 | 10.10 |
| 990 | 18.3 | *1.880 | 9.65 |
| 1030 | 19.2 | 2.053 | 9.36 |
| 1100 | 19.5 | 2.275 | 8.54 |
| 1120 | 20.0 | 2.348 | 8.52 |
| 1240 | 21.2 | *2.732 | 7.71 |
| 1460 | 23.1 | *3.618 | 6.36 |

*Note.* The values of the effective range marked * were obtained from the ionization-pressure curves, the others by interpolation from the range curve in Fig. 8.

volts, contrary to the results of Lehmann and Osgoode;[2] it is believed that this lack of agreement can be attributed to two important differences in the experimental conditions. Firstly, Lehmann and Osgoode used a cylindrical rather than a hemispherical ionization chamber. In the former type of chamber the electrons deflected in primary collisions may hit the sides of the vessel before their energy is exhausted, since their ranges at the pressures used are greater than the radius, though less than the length of the cylindrical vessel. In the hemispherical type of chamber these deflected electrons spend all their energy in collisions before reaching the sides of the chamber. Secondly, in the experiments of the authors the anode was kept at earth potential, thus maintaining a field free region within the ionization chamber; whereas, in the other experiments the filament was at earth potential and the anode at a positive potential, thus causing a retarding field between the anode and the ionization chamber, which decreased the energy of the electrons passing through it. It is believed that these variations in the shape of the ionization chamber and in the field within it are mainly responsible for the discrepancies between the total ionization and the range curves here reported and those of Lehmann and Osgoode.

Fig. 5 indicates that the ionization of nitrogen sets in at about 17 volts, the ionization potential of the nitrogen molecule,[18] increases rapidly to about 75 volts, then less rapidly but linearly up to 375 volts, the ionization potential of the $K$ electrons[19] of nitrogen, at which there is a sudden decrease in the number of ions produced because of the large amount of energy expended in releasing one of the $K$ electrons, leaving less energy available for the secondary collisions. The fact that a bend in the ionization curve is to be expected has been emphasized by Darrow,[20] and probably is more evident in total ionization measurements, which include the effects of secondary collisions, than in primary ionization experiments, in which these are eliminated. The break has never been recognized in any of the latter experiments.

[18] Smyth, Proc. Roy. Soc. **A104**, 121 (1923).
[19] Mohler and Foote, Sci. Papers Bur. Standards **17**, 471 (1922).
[20] Darrow, *Electrical Phenomena in Gases* (1932), p. 43.

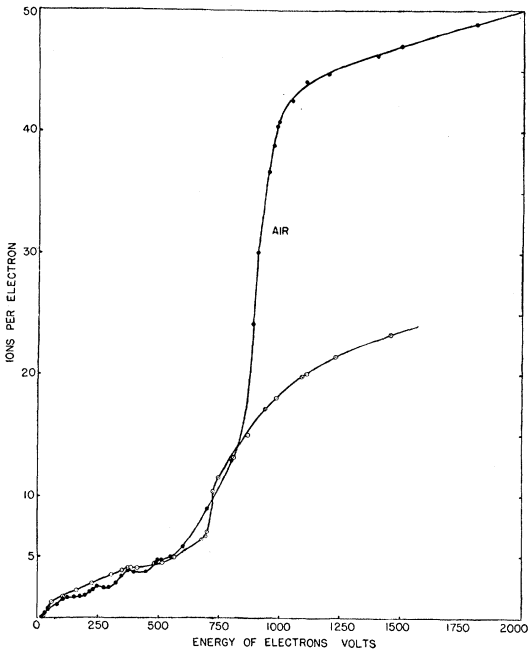


FIG. 6. Total ionization curve for nitrogen and air. Both show breaks at 375 volts and similar rapid increases in ionization near 750 volts.

As the energy of the accelerated electron approaches that equal to twice the ionization energy of the $K$ electrons, the probability of this type of ionization increases rapidly, and finally a second linearity is approached at and beyond 1200 volts.

It is interesting to note that these features were some of the characteristics of the total ionization curve for air given in the previous paper, and which is shown with the nitrogen curve in Fig. 6; the breaks at 250, 375, and 495 volts in the air curve were attributed to argon, nitrogen, and oxygen, respectively, since these are their ionization potentials.[21, 19, 22] The rapid increase in the ionization of air near 1000 volts was attributed in the earlier paper to the ionization of oxygen.

## Range calculations

Since the path of an electron which has suffered multiple collisions is tortuous and in three dimensions, the mean depth of the absorbing gas layer, known as the effective range, is consider-

[21] Int. Crit. Tab. **6**, 71–72 (1929).
[22] Kurth, Phys. Rev. **18**, 461 (1921).

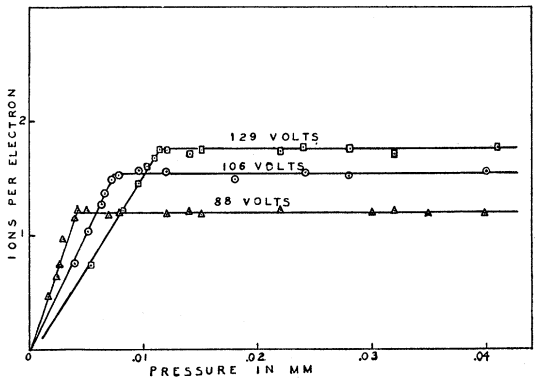


FIG. 7. Ionization-pressure curves for small energy electrons in air.

ably smaller than the actual length of path traversed by the electron. In a separate paper the senior author[23] has given the derivation of a formula relating these quantities, and reported numerical calculations of the actual ranges, made by suitably choosing constants which appear in Bethe's[13] equations for the scattering of electrons in both elastic and inelastic collisions.

In this experiment a mean value of the effective range of the electrons may be obtained from an examination of the region of critical pressures in their ionization-pressure curve. Those electrons, for which the fraction of energy lost in collisions is consistently large, are scattered most; when the pressure in the ionization chamber is such as that at the point $A$ in the curve for the 700-volt electrons in Fig. 4, the ends of their paths must be on the surface of the ionization chamber and the radius of the chamber will equal the effective range of these electrons. Similarly, the point $B$ on the same curve represents a pressure for which the radius of the vessel is very nearly equal to the effective range of those electrons and for which scattering is a minimum and straggling a maximum. For some intervening pressure the radius of the chamber must equal the mean value of the effective range of the electrons in the beam, such that half the electrons have effective ranges in excess of this value and the others less. Since the region of critical pressures is very narrow for the lower energy electrons and amounts to less than ten percent of the mean pressure within the critical region for the highest energy electrons used, a mean value of the effective range of the electrons in a beam may be obtained by calculating the pressure, $C$, at which the linear portions of its ionization-pressure curve intersect: multiplying this pressure in mm by the radius of the chamber gives the effective range in cm at 1 mm pressure. The error involved in such a determination cannot be large for energies somewhat in excess of those used in this experiment, for an inspection of the

[23] Anslow, Phys. Rev. **49**, 480A (1936).

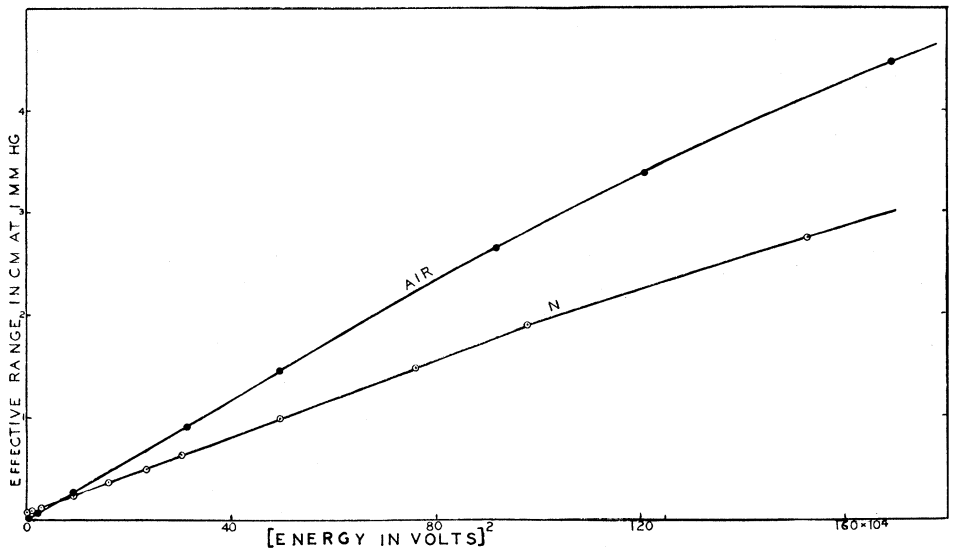


FIG. 8. Effective range *vs.* voltage relation for energies up to 1500 volts in $N_2$ and air.

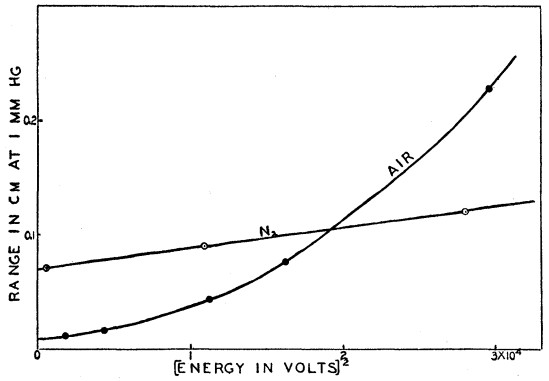


FIG. 9. Effective range *vs.* voltage relation for energies up to 175 volts in $N_2$ and air.

similar curves obtained by Buchmann[5] for electrons with energies from 4–13 kv and by Eisl[4] for energies from 9.8–3.6 kv indicate that the region of critical pressures remains narrow up to at least 20,000 volts. The region narrows down to practically a single pressure for beams with energies less than 150 volts, as can be seen in Fig. 7, where are plotted three of a series of curves obtained in a detailed study of the range of such electrons in air, measured since the publication of the previous paper. Since electrons with these energies have ranges scarcely twice the mean free path of electrons in the gas, they participate in only one or two collisions and those in a single beam must suffer practically equal scattering. Hence for these low energy electrons a single critical pressure should be anticipated.

The effective ranges thus obtained were plotted against the square of their energy in volts for energies up to 1500 volts, the results being shown in Fig. 8, together with the similar result obtained in the previous experiment for air. In Fig. 9 the same is shown for energies less than 175 volts. It is evident that there is a fair linear relation between the effective range of the colliding electron and the square of the energy expended for ranges less than 2 cm at 1 mm pressure, with a slight falling off in the range values for higher energies, and that there is a deviation from this linearity for small energy collisions in air. The empirical equation, derived from the lower portion of the curve in Fig. 8, between the mean effective range, $R_e$, measured in cm at 1 mm pressure, and the electron energies, measured in electron volts, $V$, is for nitrogen

$$R_e = 0.07 + 1.88 \times 10^{-6} V^2. \qquad (1)$$

The slope of this curve, $1.88 \times 10^{-6}$, decreases with the higher energies, and probably approaches the value obtained by Williams[24] for slow $\beta$-

[24] Williams, Phil. Mag. 2, 1109 (1926).

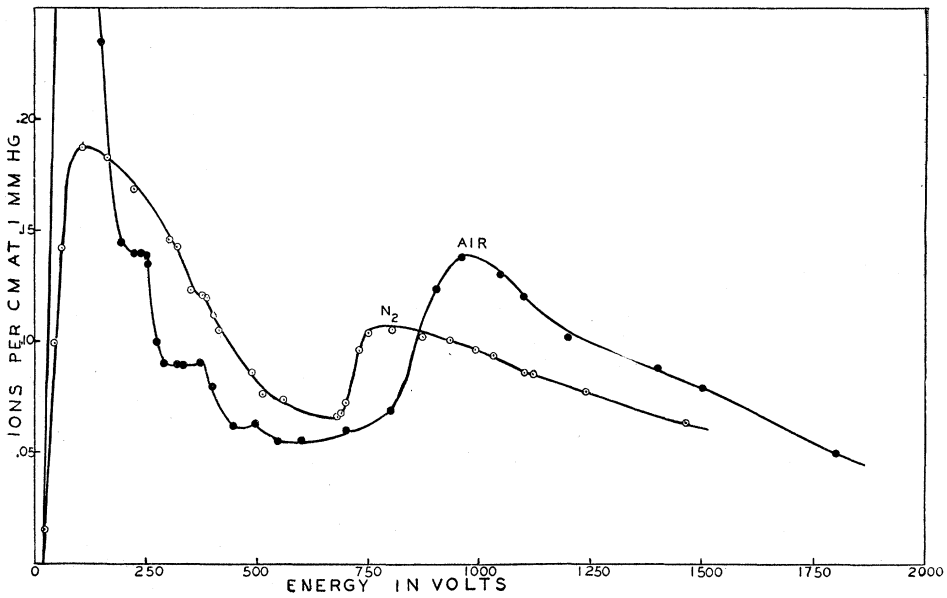


FIG. 10. Average total ionization per cm of absorbing gas layer for $N_2$ and air, calculated by dividing total ionization measurements by the mean effective range of the ionizing electron.

particles in nitrogen, which reduced to 1 mm pressure, is $1.54\times10^{-6}$. The effective ranges of the various electron beams, estimated from this curve, are given in the third column of Table II.

### Ionization per cm of absorbing gas layer

The average ionization produced per cm of the absorbing gas layer was obtained by dividing the experimentally determined value of the total ionization by the effective range of the colliding electron. The values obtained are given in the last column of Table II and plotted against the energy of the accelerated electrons in volts in Fig. 10, together with the same for air as given in the first paper, the results for small voltages having been calculated from the later determinations of the range in air. It is seen that in the curve for nitrogen a maximum value of the average ionization per cm of the effective range occurs between 100 and 150 volts, a break at 375 volts, and a second maximum at 750 volts, this latter maximum being at twice the ionization potential of the $K$ electrons of nitrogen. In the air curve this maximum came at twice the $K$ ionization potential of oxygen.[1]

In Fig. 11 the characteristics of the nitrogen curve are compared with the well-known curves for primary ionization per cm of Compton and Van Voorhis[8] and of Tate and Smith.[25] At the low pressure used in these experiments not more than one collision is probable in the electron path, and the thickness of the absorbing gas layer is identical with the actual distance traversed by the electron. In the figure there are also given graphs of the results obtained in Kossel's[26] early experiment and values calculated by the present authors from the total ionization and range curves published by Lehmann and Osgoode.[2] It is evident that both total and primary ionization measurements indicate a

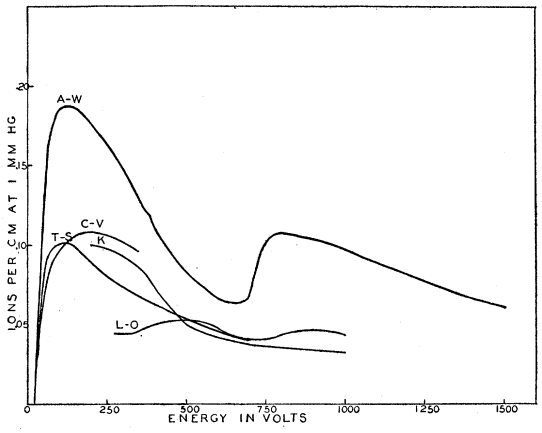


FIG. 11. Average total ionization per cm of effective range compared with primary ionization per cm results for actual range of Compton and Van Voorhis (C–V), Tate and Smith (T–S), Kossel (K), and average total ionization per cm of effective range calculated from Lehmann and Osgoode's determinations (L–O).

maximum probability of ionization for energies slightly in excess of 100 volts, but that the second maximum at 750 volts does not appear in any of the curves except that of the authors. In the experiments of von Hippel[27] with mercury and Funk[28] with sodium and potassium similar maxima have been located at approximately twice the ionization potentials involved. The form of the Lehmann and Osgoode curve is at almost complete variance with the general type of curve obtained in these experiments, and strengthens the belief of the authors that the Lehmann and Osgoode results were seriously affected by the shape and the field within their ionization chamber.

A reduction of the authors' results to the ionization per cm of the actual range, together with a comparison with the values predicted by Bethe's theory may be presented in a future communication by the senior author.

[25] Tate and Smith, Phys. Rev. **39**, 270 (1932).
[26] Kossel, Ann. d. Physik **37**, 393 (1912).
[27] von Hippel, Ann. d. Physik **87**, 1035 (1928).
[28] Funk, Ann. d. Physik **4**, 149 (1930).