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Absolute Values of the Electron Drift Velocity in Nitrogen, Helium, Neon and Argon

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The electrical shutter method for measuring electron mobility has been employed for measurements of the electron drift velocity in nitrogen, helium, neon and argon. The values obtained experimentally as a function of X/p are compared with those computed by theoretical equations and a discrepancy is shown to exist. In every case the deviation of the experimental from the calculated curves is explained by the hypothesis that the distribution of electron velocities is such that occasional inelastic collisions occur. Under such circumstances the energy losses are greater than those calculated, and the experimental values of the electron drift velocity are thus greater than predicted by theory. It is shown, in all cases studied, that electrons of sufficient energy are present to produce the postulated excitations. Assuming such inelastic collisions, a value for the probability of excitation of electronic levels in helium, neon, and argon is calculated. The probabilities so obtained agree in order of magnitude with those given by other experiments.

AN electrical shutter method for measuring the drift velocities of electrons in gases and its application to hydrogen gas have been described in a previous paper.[1] In this method, the shutters take the form of two fine wire grids, alternate wires of which are connected to a high frequency potential. Electrons pass through the grids only when the potential between adjacent grid wires is zero, and only electrons which cross the space in one-half cycle are received at the collecting electrode. This results in a sharp maximum in the electrometer current when the drift velocity of the electrons multiplied by the time of one-half cycle is equal to the distance between the grids.

In the present paper, measurements are reported on nitrogen and the rare gases. To facilitate the taking of data on the rare gases, the constant potential but varying frequency method of obtaining measurements was employed. The oscillator was so arranged that it would develop a nearly constant voltage over a wide range of frequency. The tube potential was then set at some fixed value and the frequency adjusted until a current maximum at the electrometer was observed. Various maxima at different frequencies, corresponding to electron groups taking one-half, one, or three halves, of a cycle to traverse the distance between the grids, appeared as in the previous method. Measurements of a few values over a wide range of X/p in hydrogen gave the same values for the drift velocity as those previously obtained, thereby justifying the method of correction used with the constant frequency method.

In the rare gases at high X/p, the grid efficiency became so low (due to the high random electron energy) that the maxima became too broad and flat for accurate measurement. In order to reach higher values of X/p, a new tube was therefore constructed. The principal changes in the second tube were: first, smaller size in order to require less gas for filling; second, a thermionic source of electrons consisting of a plane grid of tungsten filaments carefully outgassed; and finally, a reduction in grid wire spacing by fifty percent. These and minor improvements made it possible to reach values of X/p more than twice those obtainable with the first tube.

In helium and argon where values were obtained from each of the tubes, the overlapping points showed that within experimental error the two tubes gave the same values for the electron drift velocity. The gas pressure in the tube was measured at room temperature (20°C) when the filaments were cold. The heating of the gas by the filaments was investigated by a thermocouple mounted between the grids. The correction was found small enough to neglect.

Nitrogen was obtained from a commercial tank of the gas and purified by passing over finely divided hot copper and through a series of traps immersed in liquid air. The rare gases were obtained in glass flasks and stated to be of greater than 99.8 percent purity, the impurity being largely helium. These gases were in conse-

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[1] Bradbury and Nielsen, Phys. Rev. **49**, 388 (1936).

quence merely passed through liquid-air traps before using.

THEORY

In deriving the Compton equation for the drift velocity of electrons, a Maxwellian distribution for the electron velocities is assumed. This is an assumption which is valid only when the electrons are in thermal equilibrium with the gas molecules through which they move. However, the energy of the electrons in a gas in which there is an electric field, is very much greater than the energy of the gas molecules; and increases with the strength of the applied field. Assuming that the average electronic energy is such that the electrons lose no energy by inelastic collisions, Morse, Allis and Lamar[2] have derived expressions for the electron drift velocity, and for the velocity distribution function. For constant electron-molecular collision cross section, the equation obtained reduces directly to the Compton equation with a small difference in the numerical constant. In the Morse derivation, the collision cross section enters the integral equation in such a way that it is justifiable to remove it from under the integral sign before integrating. After performing the integration, varying values of the cross section, found experimentally by Ramsauer, Normand, and others, may be substituted into the expression. The effect of the changing cross section on the velocity distribution function and on the drift velocity may then be seen. A small cross section tends to flatten the distribution curve moving its maximum to higher values. A molecular cross section increasing with increasing electron energy, tends to sharpen the distribution curve by decreasing the number of both fast and slow electrons, resulting in an increase of the number of electrons in the region of the most probable energy. Similarly, a cross section decreasing with increasing electron energy tends to flatten the distribution curve, thus extending the allowed energy of the electrons to higher values. The magnitude of these effects depends of course upon the rapidity of the variation of cross section with the electron energy. For the case of constant collision cross section, the Morse equation for the distribution of electron velocities is symmetrical about its maximum. The velocities extend from zero to approximately twice the value at the maximum. Electron energies for the fastest electrons of which appreciable numbers exist, are therefore about four times the most probable electron energy.

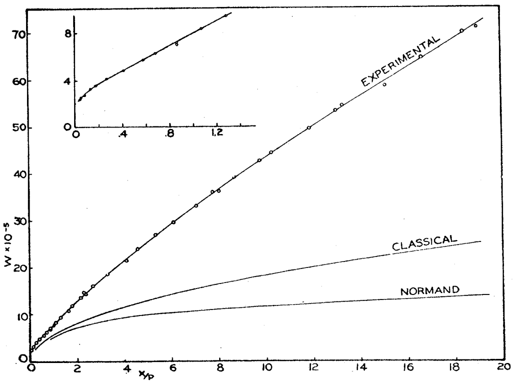

FIG. 1. Drift velocity of electrons in nitrogen as a function of X/p. Theoretical curves are shown for comparison.

Inelastic collisions, if they occur, will affect both the energy distribution function and the drift velocity of the electrons. The inelastic impacts will increase w, the drift velocity by increasing f, the average fraction of its energy which an electron loses at a collision, since w is proportional to $f^{\frac{1}{4}}$. Qualitatively this is due to the fact that inelastic collisions reduce the random energy of the electrons, thus permitting the applied electric field to be more effective.

EXPERIMENTAL RESULTS

Nitrogen

In Fig. 1 is presented a summary of the experimental values for the electron drift velocity in nitrogen as a function of X/p obtained by using the same method and technique as employed in making the measurements on hydrogen.[1] A comparison between theory and experiment is also shown. The curve marked "classical" is obtained by substituting into the Compton equation the ordinary kinetic theory value of the molecular cross section. If, instead of this cross section one uses the Ramsauer cross section for each value of X/p, as obtained from the experiments of Townsend[3] and of Normand,[4] the curve marked "Normand" is obtained. The

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[2] Morse, Allis and Lamar, Phys. Rev. **48**, 412 (1935).

[3] J. S. Townsend, J. Frank. Inst. **200**, 563 (1925).

[4] C. E. Normand, Phys. Rev. **35**, 1217 (1930).

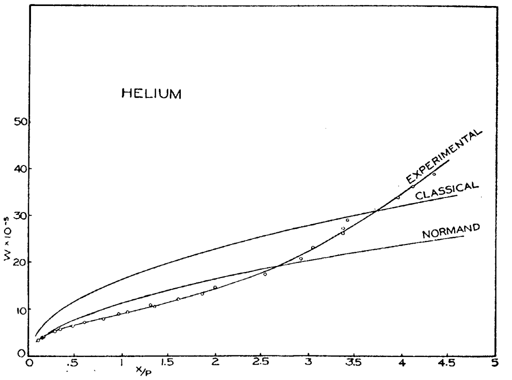

FIG. 2. Drift velocity of electrons in helium as a function of X/p. Theoretical curves are shown for comparison.

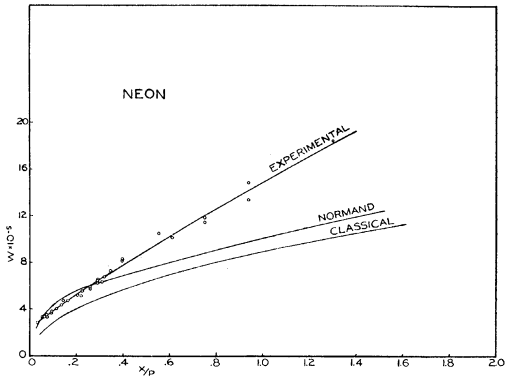

FIG. 3. Drift velocity of electrons in neon as a function of X/p. Theoretical curves are shown for comparison.

experimental curve is seen to lie above the calculated curves throughout the range of the experiment. This departure, as in the case of hydrogen[1] is ascribed to the energy losses of the electron in exciting the first level of the nitrogen molecule. At an X/p of 0.25, Townsend gives the average value of the electron energy as 0.29 volt, which is the energy of the first vibrational level in nitrogen. The experimental curve therefore should rise above the calculated ones at values of X/p greater than 0.25 due to the electronic energy losses caused by excitation of the first vibrational level in nitrogen. This is seen to be the case.

In hydrogen at an X/p of 19, where the electron energy is approximately five times the energy of the first vibrational level, the experimental drift velocity is greater than that calculated from the Ramsauer cross sections by a factor of 2.1. In nitrogen at an X/p of 4.0 where the electron energy is again five times the energy of the first vibrational level, the experimental value of the drift velocity is greater than that calculated from the Ramsauer cross sections by a factor 2.3. The correlation is good and indicates that the same process is responsible in both cases for the rise of the experimental curves above the calculated ones. At an X/p of 20 in nitrogen, the average electron energy is 2.2 volts. At this X/p, the fastest electrons in the velocity distribution may have energies greater than the excitation energy of the first electronic level of the nitrogen molecule at 6.14 volts. Energy losses from electronic excitations may therefore be a contributing factor in raising the experimental curve above the calculated ones at the high values of X/p.

To justify the assumption that the deviation of the experimental curve from the one calculated from the Ramsauer cross sections is due to the excitation of vibrational levels in the molecules, experiments were undertaken upon the rare gases where vibrational levels do not exist. Under these circumstances it is to be expected that the experimental curves will follow the calculated ones as long as energy losses do not occur as a result of the excitation of electronic levels in these gases. Since the electron is able to lose only the classical momentum transfer amount of energy at a collision, it will continue to gain energy from the field until the average energy loss per collision equals the average energy gain from the field in a mean free path. Thus, for the same X/p, the electron energy will be very much greater in the monatomic than in the diatomic gases since in the latter the electron energy is kept at low values by the inelastic collisions which excite vibrational levels.

Helium

In Fig. 2 are shown the experimentally determined values for the electron drift velocity in helium as a function of X/p. These values were obtained by the constant potential method. A comparison between theory and experiment is also given. The experimental curve is seen to follow the theoretical curve, obtained from Normand's values for the cross section, up to an X/p of 2.25 at which point it deviates markedly. The electron energy at this X/p is given by

Townsend as 4.25 volts. For constant cross section, according to the distribution function of electron velocities given by Morse, Allis and Lamar, the value of the energy of the fastest electrons is 16 or 17 volts. However, the cross section for helium[4, 5] in this range of X/p is decreasing with increasing electron energy. Therefore the distribution function will be flattened and elongated on the high energy side. Thus it may be assumed that the fastest electrons have energies of 19 or 20 volts which makes them energetically able to excite the first electronic level of helium at 19.77 volts. The rise of the curve at higher X/p is then due to the increasing number of electrons having suitable energy for such excitations.

Neon

In Fig. 3 the experimentally determined values for the electron drift velocity in neon are shown together with a comparison between theory and experiment. The experimental curve departs almost at once from the calculated curves and again this departure is ascribed to excitation. At an X/p of only 0.4 Townsend gives the electronic energy as 4.3 volts. The cross section of neon in this range of electron energy is slowly rising and leveling off at higher energies. One would therefore expect the fast electrons to have energies of the order of 16 volts. However, 16.58 volts is the first excitation potential of neon, so at this X/p inelastic collisions should begin to occur. At slightly higher X/p where the electron energy as given by Townsend rapidly increases, excitation will become much more probable. Thus the experimental curve lies increasingly above the calculated ones at values of X/p greater than 0.4.

Argon

In Fig. 4 the experimentally determined values for the electron drift velocity in argon are shown together with a comparison between theory and experiment. In the energy range of this experiment, the collision cross section of argon rapidly increases with increasing electron energy. This results in a distribution of electrons with energy very nearly that of the most probable value. The argon experimental curve follows the "Normand" curve quite well up to an X/p of about 1.75 at which it changes its trend by bending upward. Townsend gives the energy of the electrons at this X/p as 11.1 volts, which is nearly the excitation potential of argon (11.57 volts). At this X/p inelastic collisions should occur and produce the bending up of the experimental curve as is observed.

Discussion

From the above data it is seen that the experimental curves agree well with those calculated from the Ramsauer values for the molecular and atomic cross sections. Where deviations occur, they may in all cases be associated with electron energy losses greater than those given by classical momentum transfer. In every case studied it is shown that sufficient energy is available for inelastic collisions. These collisions produce excitations of the vibrational levels in the case of hydrogen and nitrogen, and excitation of the electronic levels in the case of the monatomic gases, helium, neon, and argon.

Loeb[6] and Wahlin[7] have measured electron mobilities in helium and nitrogen at $X/p=0.5$ using high pressures and the Rutherford alternating current method. These results are in good agreement with the data reported here over the narrow range where comparison is possible. Townsend[3] and his students have measured the random velocity of electrons by diffusion methods, simultaneously measuring the electron drift velocity by deflecting the moving electrons in a magnetic field. The apparatus of Townsend

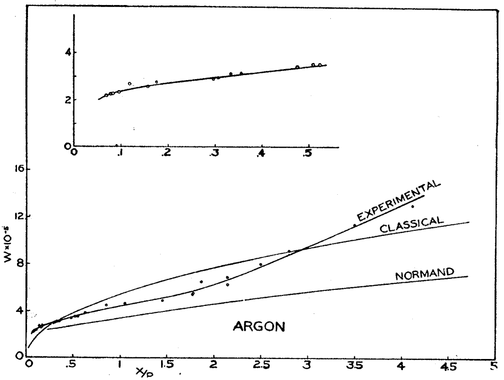

FIG. 4. Drift velocity of electrons in argon as a function of X/p. Theoretical curves are shown for comparison.

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[5] R. B. Brode, Rev. Mod. Phys. **5**, 257 (1933).

[6] L. B. Loeb, Phys. Rev. **19**, 24 (1922).

[7] H. B. Wahlin, Phys. Rev. **23**, 169 (1924).

and Bailey[8] could be evacuated only to a pressure of approximately 0.01 mm of mercury. This permits the presence in the gas of a considerable amount of impurity, small traces of which can produce effects greatly out of proportion to their concentration. Townsend's values for the electron drift velocity agree reasonably well with those here presented. Greater discrepancies exist in the case of the rare gases which may presumably be ascribed to the presence of impurity in their gas, inasmuch as Townsend and Bailey observed that the values which they obtained for the electron drift velocity in argon were strongly dependent upon the length of time of purification.

The only available experimental values of the random electron energy as a function of X/p are those of Townsend. These have been used in the above comparison of theory with experiment. It may be noted in justification of this procedure that first, Townsend's values for the electron energy agree reasonably well with those calculated where inelastic collisions do not occur; secondly, where inelastic collisions do occur, as in argon, the electron energy given by Townsend increases rapidly with X/p and then flattens off. The magnitude of the energy at this turning point is closely that of the first excitation potential of argon. Finally it may be noted that the collision cross section in many cases over these energy ranges is not strongly energy dependent.

Few measurements have been made upon the probability of electronic excitation at a collision.[9, 10] Various values have been obtained which give only the order of magnitude of the probability; in helium experimental values ranging from 0.03 to 0.001 are given. An order of magnitude value for the excitation probability in helium, neon and argon can be obtained from the measurements here presented. At an X/p of 1.2 in neon, the energy of the electrons is 8.75 volts, and f, the average fraction of its energy which an electron loses at a collision, as obtained from the curves in Fig. 3 is 5.7 $(2m/M)$. The classical value of the energy loss per collision is $2m/M$ times the average energy or for neon, about 4.8×10^{-4} volt. Inelastic collisions must therefore account for about 4.7 times this much energy loss or 22.6×10^{-4} volt. At an inelastic collision an electron must lose at least 16.58 volts. Let k be the fraction of the electrons having over 16.58 volts energy, and p be the probability for excitation at a collision; then $16.58\ kp=22.6\times10^{-4}$. Using the velocity distribution function of electrons as given by Morse, Allis and Lamar, it is seen that for the maximum of the distribution function at an energy of 8.75 volts, 0.11 of the electrons will have energy greater than 16.58 volts. This gives $p\sim0.001$. This calculation assumes a constant cross section for neon which is not greatly in error. If a slightly increasing cross section is used, the change in the percentage of electrons over 16.58 volts is small but will tend to increase p slightly. Performing a similar calculation in the case of helium for an X/p of 4.5 where the average electron energy is 6.1 volts and f is $7.35(2m/M)$, one obtains $p=5.47\times10^{-4}/k$. For constant cross section k is about 0.003 resulting in $p\sim0.2$. Actually the distribution curve flattens and extends to higher energies for cross sections decreasing with increasing electron energy (as in helium). More high energy electrons are thus available than given by the Morse, Allis and Lamar distribution function. At an X/p of 4.5 only a very small percentage of the electrons have an energy of more than 19.77 volts. Hence any change in the distribution function of the electrons greatly changes the percentage of electrons in excess of this value, and increases k accordingly. Therefore the above value of p is an upper limit, and more probably has a value ~0.01. Performing a similar calculation in the case of argon for an X/p of 4 where the average electron energy is 11.5 volts and f is $16(2m/M)$, one obtains $p=0.0004/k$. In argon at this X/p, k is ~0.5. Therefore $p\sim0.001$. It is to be noted that the p here considered is not the probability of excitation of only the first resonance level but is an integrated effect over all the levels that may be excited and over a comparatively narrow range of electron energy.

The experiments are being continued in other gases in some of which dissociation processes and negative ion formation are possible. The author desires to thank Professor N. E. Bradbury for his help throughout this research, and the Faculty Research Committee of Stanford University for a grant-in-aid.

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[8] Townsend and Bailey, Phil. Mag. **42**, 873 (1921); **44**, 1033 (1922).

[9] G. Hertz, Zeits. f. Physik **32**, 298 (1925).

[10] E. G. Dymond, Proc. Roy. Soc. **A107**, 291 (1925).