by electrons, some 8 electrons evaporate for every atom.

Table I makes it apparent that an important factor contributing to the high velocity of the vapor stream which Tanberg calculated is a low value of the rate of evaporation. As I have pointed out,[5] the rate of vaporization for Hg found in the present experiment is consistent with the force on the cathode which has been observed. A potential maximum of about 3 volts above space, i.e., about 13 volts above cathode, in the cathode spot plasma with complete ionization of the vapor there would account for the observed force.

[5] Tonks, Phys. Rev. **50**, 226 (1936).

The smallest current maintained by a spot anchored on a tungsten "Schwamm" is given by von Engel and Steenbeck[6] as 50 ma. The smallest currents I have observed from a porous body of Mo saturated with mercury have been in the neighborhood of 0.5 amp. The present result shows that in these cases the vaporization was at the rate of 1.2 and 12×10^{-5} g/sec., respectively. It may be that vaporization rates lower than these would give a density of gas immediately above the cathode spot which is insufficient to establish the electron emission condition.

[6] Von Engel and Steenbeck, *Elektrische Gasentladungen*, Vol. II, p. 263.

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The Effective Cross Section of Positive Alkali Ions with Respect to Gas Molecules

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The absorption of positive sodium ions with velocities of 40 to 400 equivalent volts has been studied in hydrogen, nitrogen and oxygen. The nature of the collision processes has, in each case, been studied to determine the relative importance of neutralization, retardation or small angle scattering. The mean free paths and effective cross section of the sodium ions with respect to the gas molecules is found to be a function of the pressure of the gas, the velocity of the ion and the nature of the gas-ion combination. The effective cross section of each gas-ion combination approaches the kinetic theory value at low velocity of the ion while at high velocities it approaches a minimum considerably smaller than the kinetic theory value. At any given velocity over the range studied, the effective cross section of the gas-ion combination increases in the order hydrogen, nitrogen, oxygen. The values for nitrogen and oxygen are essentially, within experimental errors, equal. An improved furnace for the production of positive ions has been developed.

A NUMBER of investigations have been made on the absorption of slow positive ions in gases. The absorption may be due to small angle scattering, retardation or neutralization. The method of investigation generally used has been to bend a beam of positive ions in a magnetic field and measure the rate of absorption of the ions over a fixed length of path. The rate of absorption has been found to be a function of the pressure of the gas, the nature of the gas-ion combination and the speed of the ion. G. P. Thompson[1] found considerable small angle scattering of H^+ ions in H_2, He and A. Dempster[2] passed H^+ ions, accelerated between 14 and 1000 volts, into helium. Little, if any, retardation was observed, but considerable scattering of the bundle of protons was found at high pressures. Durbin[3] measured the rate of absorption of K^+ ions in He, H_2, A, N_2 and O_2. He found the absorption of the ions to increase with the pressure of the gas and with a decrease of velocity of the ions. In all cases, the mean free path was found to be greater than the kinetic theory mean free path, but it approached the

[1] G. P. Thompson, Phil. Mag. [7] **1**, 961 (1926); Phil. Mag. [7] **2**, 1076 (1926).

[2] A. J. Dempster, Phil. Mag. [7] **3**, 115 (1927).

[3] F. M. Durbin, Phys. Rev. **30**, 844 (1927).

latter at low speeds of the ions. Kennard[4] found the collisions of Cs^+ in A to result largely in neutralization, while with Cs^+ in H_2 and He the essential phenomenon was that of retardation. Cox[5] passed slow Li^+ ions through Hg vapor and measured the resulting mean free path. The collisions were found to result largely in small angle scattering of the Li^+ ions. Thompson[6] found collisions between slow Cs^+ ions and H_2 and He

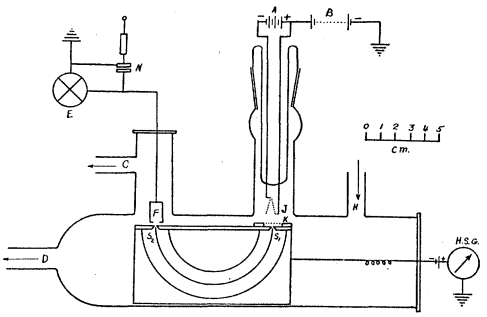

FIG. 1.

to result for the most part in retardation of the ions while for Li^+ in He, the chief factor involved was that of scattering. In a theoretical paper Beeck[7] concludes that the correction for the effective cross section of the gas-ion combination, due to the dimensions of the apparatus, varies with the angular aperture of the system of slits but is negligible for very small angular apertures. Holzer[8] found the absorption coefficient of H_3^+ in H_2 to be greater than that of H^+, but less than that of H_2^+.

The present investigation was undertaken to determine the mean free path and effective cross section of Na^+ ions in H_2, N_2 and O_2 and to determine, if possible, the type of collision occurring in each case.

APPARATUS

A modification of a Dempster mass spectrograph, Fig. 1, was chosen as the most suitable means of studying the phenomena involved. Before admission to the chamber at H, the pressure of the gas was reduced in a reservoir to a value only slightly higher than the working pressure of the gas in the analysis chamber. The gas was admitted by means of a fine capillary leak, so that a continuous flow was maintained throughout the system. Various pressures could be obtained by adjustment of the leak. The gas was pumped out at D through a liquid-air trap. Pressures were measured by a McLeod guage connected at C. Ions were produced in the furnace J which was heated by a 6-volt storage battery. The ions were accelerated to the pole shoe through a screen consisting of a brass ring having a hole 12 mm in diameter, across which were soldered fine parallel wires having a spacing of 24 to the inch. The armature, entirely enclosed in glass, contained an internal slot in the form of a semi-circular aperture of 4 cm radius. The width and depth of the slot were 0.3 and 1.7 cm respectively. After passing the slit S_1 of 2 mm width, the ions were bent in a semicircle and those passing through S_2, of 1 mm width, were captured by a Faraday cylinder connected to a Compton electrometer, adjusted to a sensitivity of 1120 mm per volt.

Let Q_0 positive ions be incident upon one end of a column of gas, and be moving parallel to the axis of the cylinder. In general, collisions will occur, and a reduction in the density of positive ions results. Let (R_i+R_m) be the maximum distance from center of ion to center of molecule, which results in a collision. Then $\pi(R_i+R_m)^2$ is called the effective cross section of the positive ion with respect to the gas molecule. The probability of collision is directly proportional to $\pi(R_i+R_m)^2$, to the number of molecules per cc, to the distance x traversed, and to the number of ions Q_0 incident upon the column. Let Q be the number of ions remaining after traversing a distance x. Then

$$Q=Q_0 \exp\left[-PN\pi(R_i+R_m)^2x\right]/760. \quad (1)$$

The quantity $N\pi(R_i+R_m)^2$ is the reciprocal of the mean free path L. Hence, at a pressure P_1 mm of Hg we have

$$Q_1=Q_0 \exp\left[-P_1x/760L\right].$$

With the same initial current Q_0 and a pressure P_2, we have

$$Q_2=Q_0 \exp\left[-P_2x/760L\right].$$

[4] R. B. Kennard, Phys. Rev. **31**, 423 (1928).
[5] I. W. Cox, Phys. Rev. **34**, 1426 (1929).
[6] J. S. Thompson, Phys. Rev. **35**, 1196 (1930).
[7] Otto Beeck, Zeits. f. Physik **61**, 251 (1930).
[8] R. E. Holzer, Phys. Rev. **36**, 1204 (1930).

Then

$$Q_1/Q_2=\exp\left[x(P_2-P_1)/760L\right]$$

and

$$L=x(P_2-P_1)/(760\ln Q_1/Q_2). \qquad (2)$$

Hence, by maintaining the emission current Q_0 constant and measuring the electrometer currents Q_1 and Q_2 of the ions passing through S_2, the mean free path L and effective cross section C may be computed at once.

The positive ions were obtained by heating an alkali-iron catalyst kindly supplied by Dr. Kunsman.[9] It was found that the materials, after being finely powdered and mixed with paraffin to act as a binder, would fuse nicely onto resistance wire. By winding the wire into a cone, it was possible to obtain a concentrated emission from a relatively large mass of material. After fusion to the coil, the catalysts were reduced in an atmosphere of hydrogen at about 400°C for a period of about five hours. Such a source was found to continue to emit very homogeneous ions after 200 hours of service.

The procedure in making measurements was as follows. The heating coil of the furnace was filled with material and reduced in hydrogen. The mass spectrograph was then evacuated, and after the impurities had been burned out of the furnace, the chamber was flushed with the gas to be studied. The chamber was then again evacuated, and the furnace heated to the proper temperature to yield a sufficient emission of ions, and run in this state for a number of hours before measurements were made. The rate of ion emission was measured by a galvanometer G, having a current sensitivity of 10^{-11} amp./mm. Eq. (2) depends upon the condition that the initial ion emission Q_0 remains constant. While this condition is difficult to obtain in practice, one may assume that, as long as the galvanometer current remains constant, Q_0 remains constant. This is true, provided the composition of the beam remains homogeneous, and if there is no spreading of the beam as the pressure in the chamber is raised.

After reducing the pressure to a low value, the magnet current was adjusted to bend the ions around the circle to S_2 and the rate of ion emission adjusted to give a large but readable electrometer current. After determining the electrometer current and corresponding pressure, the pressure was quickly raised to a higher value and the new pressure and corresponding electrometer current measured as before. In this manner, the electrometer and galvanometer currents were determined for from three to five different pressures. Several such runs were made for each accelerating potential. From each possible combination of two different pressures (P_2-P_1) in a given run a determination of the mean free path L was made. From the average L for a given accelerating potential, the effective cross section C was determined from the equation $C=1/(NL)$.

Discussion of Results

Kennard has pointed out that the type of collision between ion and molecule can, in general, be determined by the appearance of curves showing electrometer current against magnet current for various pressures. Three types of collision may occur. In case of pure neutralization, an ion is simply removed from the beam by collision; hence the maximum electrometer current occurs at the same field strength, but decreases in value as the pressure is raised, the base line remaining constant. In case of pure retardation, however, an ion is merely slowed up by collision, and may accordingly be brought back to the slit S_2 by weakening the field H. The maximum of the curve is thus shifted toward lower values of field strength without a decrease

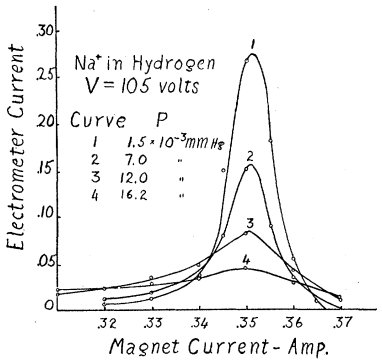

FIG. 2. Curves showing the relation between electrometer current and magnet current for 105 volt Na^+ ions in hydrogen. The essential factor involved is that of neutralization. The curves show, too, a small amount of retardation and small angle scattering.

[9] C. H. Kunsman, Science **62**, 269 (1925).

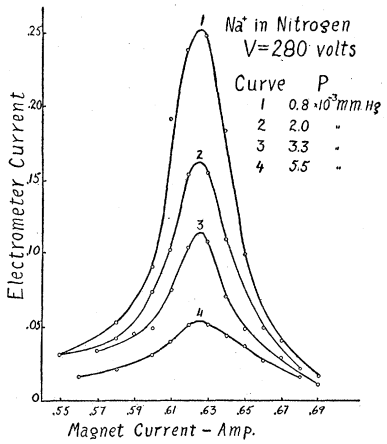

FIG. 3. The curves show the absorption of 280 volt Na^+ ions in nitrogen to be due to pure neutralization.

in area of the curve. If the collision results in scattering, however, there will occur a decrease in area of the curves and a symmetrical broadening of the base line to each side of the maximum, since the scattered ions may be deflected into the walls of the pole shoe. In case the collisions consist of two or more of these phenomena, the analysis of the phenomena is difficult to make. Fig. 2 shows such a set of curves for 105 volt sodium ions in hydrogen. From the appearance of the curves, it is apparent that the essential factor involved is that of neutralization. The curves show, too, a small amount of retardation and small angle scattering. This is in good agreement with a similar set of curves made by Kennard for the single accelerating potential of 455 volts. Fig. 3 shows a similar set of curves for Na^+ ions in nitrogen. Here we find a case of pure neutralization. In Fig. 4 we find the collisions between Na^+ ions in oxygen to result in both neutralization and small angle scattering.

Curves showing the variation of the mean free path of Na^+ ions in H_2, N_2 and O_2 are shown in Fig. 5. For 385 volt Na^+ ions in H_2, a mean free path of 15.8×10^{-5} cm was obtained. Kennard reports a mean free path value for 455 volt Na^+ ions in H_2 of 27×10^{-5} cm. Measurements made on his curves, however, show this value to be only 18.4×10^{-5} cm in excellent agreement with the determination made above. Unfortunately, Kennard's measurements were made for only one accelerating potential and his paper gives no data to support his measurement of 27×10^{-5} cm. It is probable, then, that his set of curves is correct but that his measurements, based upon the curves, are incorrect.

If the radius of the sodium ion be taken as that of the neon atom, data from viscosity measurements give $R_{Ne}=1.17\times10^{-8}$ cm and $R_{H_2}=1.09\times10^{-8}$ cm from which the kinetic theory mean free path L_0 is found to be 2.3×10^{-5} cm. From Fig. 5 it is seen that, as the accelerating potential decreases, the value of the observed mean free

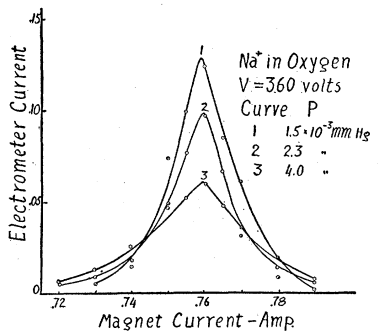

FIG. 4. The absorption of 360 volt Na^+ ions in oxygen is largely due to neutralization with some small angle scattering.

path also decreases, apparently approaching the kinetic theory value at zero accelerating potential.

The results for the mean free path of Na^+ ions in N_2 and O_2 for various accelerating potentials are also shown in Fig. 5. The closeness of the two curves came somewhat as a surprise to the author and, to make sure that avoidable errors in measurement had not been made, the curves were carefully rechecked, and found to be almost identical with the original ones. Care in obtaining pure gases was also observed. Oxygen and hydrogen were produced by electrolysis while nitrogen was obtained by heating a 10 percent solution of NH_4Cl and $NaNO_2$. The nitrogen gas was bubbled through NaOH before admission to the drying trains. The capillary leak gave continuous flow of the gases through the mass spectrograph, and the pressure was controlled by continuous pumping and adjustment of the leak. In this way, any foreign gas given off by the furnace was swept out as quickly as formed.

The closeness of the two curves is of special interest. Durbin, working with K^+ ions in H_2, N_2 and O_2, found the ratio of the observed mean free

path to the kinetic theory mean free path to decrease in the order stated, the values for nitrogen lying about halfway between those for hydrogen and oxygen. On the other hand, Ramsauer and Beeck,[10] working with the same combinations, report the absorption coefficients for the gases to increase in the order hydrogen, oxygen and nitrogen, the values for oxygen lying about halfway between those for hydrogen and nitrogen. These results for nitrogen and oxygen are, of course, contradictory. In the present work, it has been found that, within experimental error, the two curves for nitrogen and oxygen are practically identical. The present work supports the measurements of Durbin more than those of Ramsauer and Beeck. Perhaps the short life of the source of positive ions used by Ramsauer and Beeck and the necessity for rapid measurements mentioned in their paper is a cause of the discrepancy.

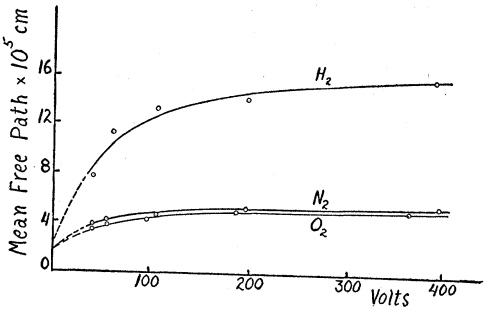

FIG. 5. The mean free path of Na^+ ions in the gases H_2, N_2, and O_2 decreases in the order stated for a given pressure and speed. The closeness of the two curves for N_2 and O_2 is of special interest. The mean free path for a given gas-ion combination decreases with an increase of the pressure of the gas and a decrease in speed of the ion. It approaches the kinetic theory value at zero accelerating potential of the ion.

[10] Ramsauer and Beeck, Ann. d. Physik **87**, 1 (1928).

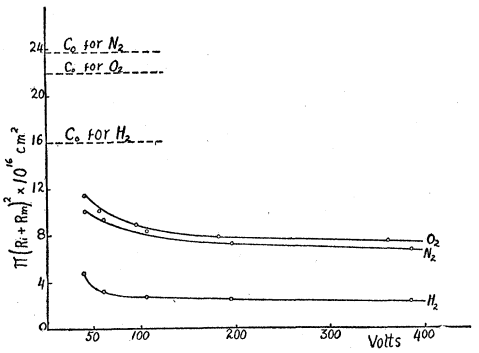

FIG. 6. The effective cross section of Na^+ ions with respect to H_2, N_2 and O_2. The curves turn sharply upward at speeds less than 50 volts and apparently approach kinetic theory values at zero accelerating potential.

Curves showing the variation of the effective cross section of Na^+ ions with respect to H_2, N_2 and O_2 are shown in Fig. 6. The effective cross sections were computed from the equation $C=1/LN$. It appears from the curves that the effective size of an ion depends not only upon its dimensions but upon its speed as well, and at high speeds it is capable of making many kinetic theory collisions without removal from the beam. Thus, 385 volt Na^+ ions are capable of making 6.8 kinetic theory collisions in hydrogen before being removed from the beam.

In conclusion the author wishes to acknowledge his indebtedness to Professor Mason E. Hufford under whose supervision the above investigation has been made and for his kindly interest and suggestions during the progress of the study.