Ionization of Helium, Neon and Argon under Impact of their own Atoms and Positive Ions[1]

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The number of electrons liberated from neutral rare gas atoms under impact of their own atoms and positive ions was measured as a function of the kinetic energy of the impinging particles. When the impinging beam is composed mostly of neutral atoms, it is found that helium is ionized at about 60 equivalent volts, neon at about 50 volts and argon at about 40 volts. If the impinging beam is composed of atoms and positive ions in about equal proportions, additional ionization is found to set in in argon at around 330 volts. No ionization by positive ions was observed in either helium or neon up to 500 volts. Curves are shown which indicate the efficiency of ionization of the rare gases under impacts of their own atoms and positive ions.

INTRODUCTION

IONIZATION by positive ions has been considered one of the processes necessary for the maintenance of a gaseous discharge. Earlier attempts made to detect this effect directly were inconclusive due to the difficulty of distinguishing electrons produced by ionization of gas atoms from secondary electrons which are emitted from metal parts under impact of positive ions.[2] However, the experiments of Sutton, Beeck and Mouzon[3,4] indicate quite conclusively that the rare gases are ionized under impact of the alkali positive ions, although the process is inefficient compared with ionization under electron impact. Beeck and Mouzon[5] have found definite values of the minimum kinetic energy which an alkali ion must have in order to ionize a rare gas atom. More recently Wolf[6] has reported that argon is ionized slightly by its own positive ions in the neighborhood of 300 equivalent volts. Still more recently, Beeck[7] has reported preliminary experiments on the ionization of argon and neon by slow argon atoms.

Attempts to find a theoretical solution of the problem have been made, among others, by Franck,[8] Joos and Kulenkampff,[9] and Zwicky.[10] About all

[1] This paper was presented before the American Physical Society at the New Haven meeting, June 23, 1932. The abstract printed in the program of this meeting should be disregarded.

[2] As a matter of fact, the skeptical may still claim with some justification that, even in the most recent experiments, the electrons are not products of ionization of gas atoms but are secondary electrons from the metal parts which are inherent in any experimental apparatus.

[3] R. M. Sutton and J. C. Mouzon, Phys. Rev. **37**, 379 (1931).

[4] O. Beeck and J. C. Mouzon, Ann. d. Physik **11**, 737 (1931).

[5] O. Beeck and J. C. Mouzon, Ann. d. Physik **11**, 858 (1931).

[6] F. Wolf, Zeits. f. Physik **74**, 575 (1932).

[7] O. Beeck, Proc. Nat. Acad. Sci. **18**, 311 (1932).

[8] J. Franck, Zeits. f. Physik **25**, 312 (1924).

[9] G. Joos and H. Kulenkampff, Phys. Zeits. **25**, 257 (1924).

[10] F. Zwicky, Proc. Nat. Acad. Sci. **18**, 314 (1932).

that can be said at present is that for central impacts between uncharged particles of the same mass, approximately one-half the kinetic energy of the impinging particle is available for ionization of the particle struck. Thus helium, neon and argon should be ionized under impacts of their own neutral atoms if the atoms have kinetic energy of approximately 49, 43 and 31 equivalent volts, respectively. Ionization of the rare gases under impact of their own positive ions might be expected at somewhat higher energies, for in this case the ejected electron escapes while in the field of force of two positive ions.

Apparatus and Procedure

The apparatus used in this investigation is a modification of that used by Sutton and is shown drawn to scale in Fig. 1. The experimental tube was divided into two parts by a glass partition which separated the discharge chamber from the chamber in which ionization of the gas by the impinging

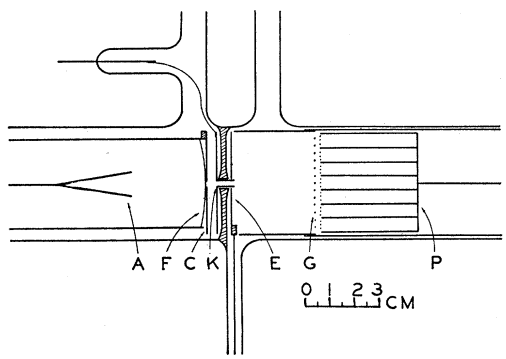

Fig. 1. Experimental tube.

particles was detected. A discharge was produced between the oxide-coated filament[11] F and the anode A. Positive ions of the gas are produced by electron impact and drift toward the filament. Since the voltage across the discharge, V_d, is concentrated at the filament, most of the positive ions that pass through the 2 mm hole in the virtual cathode C will have an energy of V_d equivalent volts. Between C and K they are further accelerated by an applied potential V_a so that most of the ions enter the canal K with an energy of V_d+V_a equivalent volts. The canal is 7 mm long and 2 mm in diameter. Emerging from the canal, the particles in the beam (now a mixture of positive ions and neutral atoms) enter the ionization chamber where they are free to collide with the atoms of the gas. The ionization chamber is 3.3 cm long. Its walls are of sheet nickel and the far end is closed by a large mesh fine wire grid G, both of which are at the same potential as the plate K. At the near end of the ionization chamber is the electrode E to which a positive potential is applied to collect any electrons resulting from the impacts. In general 15 volts were found sufficient to saturate the electron current to E. The positive ions in the beam continue through the grid G and are collected by P. The

[11] Kindly supplied by Dr. M. J. Kelly of the Bell Telephone Laboratories.

face of P is covered by a wire grid to give a more uniform field between G and P. The distance from G to P is about 2 mm and P is kept at a positive potential with respect to G in order to prevent the escape of any secondary electrons resulting from the impact of positive ions upon P. We might expect secondary electrons with velocities as high as 16 volts in helium, 13 volts in neon and 7 volts in argon.[12] However, it was found that only a few volts were sufficient to stop most of the secondary electrons emitted from P, but to be on the safe side the potential between G and P was kept at 15 volts for helium and 12 volts for neon and argon. The metal parts of the tube were made of nickel and were outgassed by an induction furnace. The rare gases were obtained spectroscopically pure and were used without further purification. The tube was completely evacuated and a fresh supply of gas admitted before each run.

Keeping V_d and I_d (the discharge current) constant, the accelerating potential V_a was varied and readings were taken of the electron current to the plate E and the positive ion current collected by P. The same galvanometer was used to measure each of these currents. It had a sensitivity of 2324 megohms.

It has been assumed that the moving particles enter the ionization chamber with a velocity of V_d+V_a equivalent volts. To check this, measurements were made of the positive ion current collected by P as the retarding potential between G and P was increased, for given values of V_d and V_a. It was found that the fastest ions reaching P did have a velocity of V_d+V_a equivalent volts.

We are quite certain that all the particles leaving the neighborhood of the filament are positive ions. Knowing the distance the ions go from the filament until they reach the ionization chamber (1.1 cm) and also knowing the mean free path of the ions for neutralization, we can compute the fraction of ions and of atoms in the impinging beam as it enters the ionization chamber. The most reliable value of the mean free path for neutralization of A^+ in argon, obtained from the work of Wolf,[6] is 1.6 cm at 0.01 mm pressure. For the mean free paths for neutralization of Ne^+ in neon and He^+ in helium we must make use of the more qualitative measurements of Kallman and Rosen[13] which yield values of 2.5 cm at 0.01 mm pressure in each case.

Results

If the discharge is operated at such a pressure that 95 percent of the particles entering the ionization chamber are neutral atoms, curves such as are shown in Fig. 2 are obtained. Here the electron current collected by the electrode E, I_e, is plotted against the energy of the impinging atoms in (V_d+V_a) equivalent volts. It will be noticed that in all cases the initial electron current is not zero but has a definite constant value. It is thought that this is due to secondary electrons ejected from the canal K by the impinging positive ions, and of course it is impossible to eliminate such secondaries.

[12] See for example Rev. Mod. Phys. **2**, 180 (1930) and references given there.

[13] H. Kallman and B. Rosen, Zeits. f. Physik **61**, 61 (1930).

When the impinging atoms have a certain minimum energy, ionization is observed to set in. This occurs in helium at about 60 volts, in neon at about 50 volts and in argon at about 40 volts. These values are in each case approximately 10 volts higher than we would expect theoretically. Further ionization also appears to take place in neon and argon at about 110 and 75 volts, respectively. Two possible explanations of these higher ionization potentials are suggested. They may represent the minimum energies which an atom must have in order to ionize successively two times. Or they may represent the minimum energy necessary to ionize one of the colliding particles and excite the other—a process which has been suggested in a recent paper by Weizel and Beeck.[14]

In order to increase the proportion of positive ions in the impinging beam, the tube was now operated at as low a pressure as possible. The minimum pressure was determined in the case of helium and neon by the lowest pressure

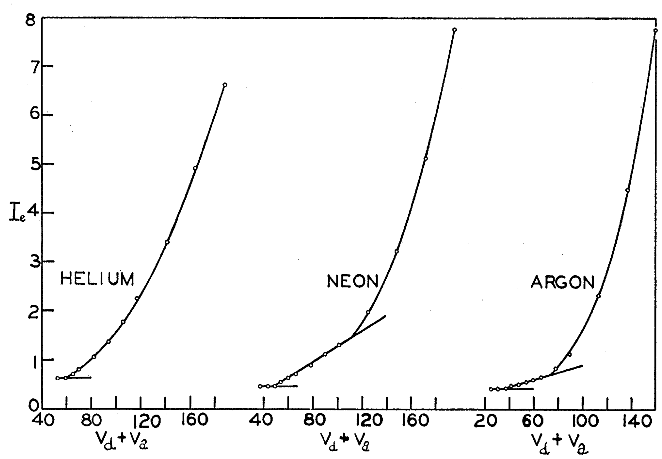

Fig. 2. Ionization of helium, neon and argon under impact of their own atoms. Helium: pressure $=0.07$ mm, $V_d=47$ v., $I_d=20$ m.a.; neon: pressure $=0.07$ mm, $V_d=31$ v., $I_d=20$ m.a.; argon: pressure $=0.036$ mm, $V_d=19$ v., $I_d=40$ m.a.

at which a discharge could be maintained; in argon by the lowest pressure at which there was an appreciable electron current collected by E. The results obtained under these conditions are shown in Fig. 3, where again the electron current collected by the electrode E, I_e, is plotted against the energy of the impinging particles in (V_d+V_a) equivalent volts. The impinging beam in argon on entering the ionization chamber is composed of 60 percent A^+ and 40 percent A° (neutral atoms); in neon 55 percent Ne^+ and 45 percent Ne°; and in helium 30 percent He^+ and 70 percent He°. As at the higher pressures, we again observe in neon and argon an increase in the ionization current (here at about 120 and 85 volts) due to successive impacts or to simultaneous ionization and excitation. No further abrupt increases in the ionization current are observed except in argon where further ionization seems to set in at about 330 volts. This is ascribed to ionization by argon ions and confirms

[14] W. Weizel and O. Beeck, Zeits. f. Physik **76**, 250 (1932).

Wolf's observation[6] that argon is ionized slightly by its own positive ions around 300 volts. If helium and neon are ionized by their own positive ions, the process must either be inefficient compared with the ionization of argon by its own positive ions, or it must take place at energies greater than 500 equivalent volts.

From the data used for Fig. 3 it is also possible to calculate roughly the efficiency of ionization of the rare gases under impact of their own atoms and positive ions. Knowing the number of positive ions collected by P,[15] the distance they have gone since entering the ionization chamber (3.5 cm) and also the mean free path of the ions, it is possible to calculate the number of initial positive ions entering the ionization chamber. Also, since the composition of

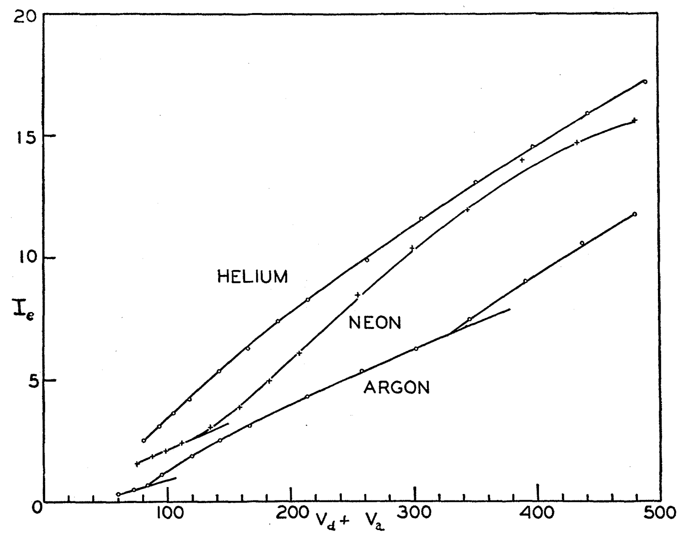

Fig. 3. Ionization of helium, neon and argon under impact of their own atoms and positive ions. Helium: pressure=0.028 mm, V_d=70 v., I_d=10 m.a.; neon: pressure=0.013 mm, V_d=65 v., I_d=10 m.a.; argon: pressure=0.0072 mm, V_d=26 v., I_d=20 m.a.

the beam on entering the ionization chamber is known, it is possible to calculate the number of atoms entering the ionization chamber. If now the ratio of the number of electrons produced (corrected for secondary electrons) to the number of initial atoms (or positive ions as the case may be) is divided by the gas pressure in mm and also by the length of the path of the particles in the ionization chamber (3.3 cm) we get N, the number of electrons produced per initial atom (ion) per cm path at 1 mm pressure. The variation of N with the kinetic energy of the impinging particles in $(V_d + V_a)$ equivalent volts is shown for helium, neon and argon in Fig. 4. These curves should only be con-

[15] If any of the ions produced by collisions in the ionization chamber had succeeded in reaching P, we would expect to observe a marked increase in the positive ion current collected by P after ionization set in. No such increase was detected except when argon was ionized by A^+. In calculating the efficiency of ionization of argon by A^+, an attempt was made to correct for these additional positive ions by neglecting the increase in the positive ion current after ionization set in.

sidered as accurate as the measurements of the mean free path of the ions; in other words, only qualitatively correct.

If these curves are compared with similar curves of Sutton[3] and Beeck[16] for the efficiency of ionization of the rare gases under impact of the alkali positive ions, it can be seen that the rare gases are considerably more efficiently ionized

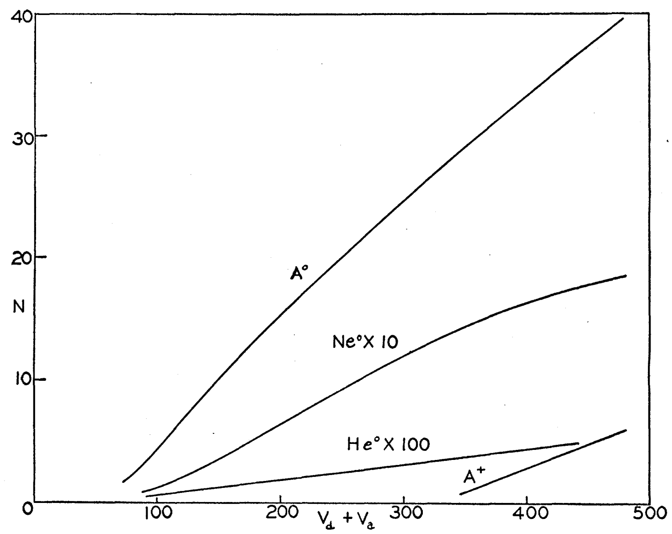

Fig. 4. Efficiency of ionization of helium, neon and argon under impacts of their own atoms (He^0, Ne^0, A^0) and positive ions (A^+). Ne^0 curve magnified 10 times; He^0 curve magnified 100 times.

by their own atoms (but less efficiently ionized by their own positive ions) than by alkali ions of approximately the same mass as the rare gas atom. As a matter of fact, in the case of argon and neon, the efficiency of ionization by their own atoms is comparable with the efficiency of ionization under electron impact.[17]

[16] O. Beeck, Ann. d. Physik **6,** 1018 (1930).

[17] K. T. Compton and C. C. Van Voorhis, Phys. Rev. **27,** 729 (1926).