MOBILITY OF THE IONS IN THE CORONA DISCHARGE

By W. M. Young

Abstract

The mobility of the ions generated in the d.c. corona discharge have been directly measured. Gas, moving with a uniform velocity, was ionized in a cylindrical corona tube and then passed into an ion chamber consisting of a hollow cylinder with electrodes along the axis. The ion current to the last electrode, when plotted as a function of the cylinder potential, exhibited maxima which indicated the presence of groups of ions. Calculation revealed a large number of groups whose mobilities, for oxygen, nitrogen, and carbon dioxide, were all less than .716 cm/sec per volt/cm, ranging down to 10^{-5} cm/sec per volt/cm. Nearly all mobilities were found below 10^{-2}, the ions apparently being generated in equal numbers, except now and then a greater number of a certain mobility were formed. The fact that the ions all possessed small mobilities seems to indicate that J. Kunz made the correct assumptions when he calculated the average value from the experimental determination of the pressure increase in the d.c. corona.

Introduction

VARIOUS pressure effects have been observed and measured for the a.c. and d.c. corona, among which is a pressure increase in the d.c. corona which appears about 1.5 seconds after the discharge is applied and which may easily amount to 3 cm of water. This pressure has been ascribed to the presence of ions of small mobility. The generation of these ions and the continual repulsion of them from the wire of a cylindrical corona tube necessarily cause an "ionic expansion" of the gas. The pressure observed, then, is due to these ions striking the walls of the corona tube.

J. Kunz,[1] from the experimental determination of such pressure increases in different gases has calculated the average mobility of the ions, his results for the gases H_2, N_2, CO_2, and O_2 being respectively: 15.1, 5.05, 1.61, and 0.23×10^{-3} (cm/sec per volt/cm). This, however, gave no information as to whether more than one type of ion was present. O. Blackwood[2] and P. J. Nolan[3] have studied the ionization produced by water spray and Erikson[4] that produced by radioactive materials. Contradictory results have been obtained on the question of whether or not groups of ions were formed. It is the purpose of

[1] J. Kunz, Phys. Rev. **19**, 169(1922).
[2] O. Blackwood, Phys. Rev. **16**, 85 (1920).
[3] P. J. Nolan, Phys. Rev. **18**, 185 (1921).
[4] H. A. Erikson, Phys. Rev. **21**, 720 (1923).

these experiments to determine the mobility of the ions formed in the corona discharge and to find out whether or not ions exist of the low mobility which Kunz has assumed in his explanation of the corona pressure.

Method

Gas free from moisture and dust was passed at a uniform rate through a short corona tube, the central wire of which was positive. The gas there ionized was passed into a tube maintained at some positive potential. The positive ions were driven toward the axis of the tube and the charge on some removed by an electrode connected to earth. The current due to other ions was measured by a quadrant electrometer connected to a second electrode. By varying the cylinder potential it was possible to obtain the electrometer current as a function of that potential and the graph of the results showed maxima which indicated the ionic

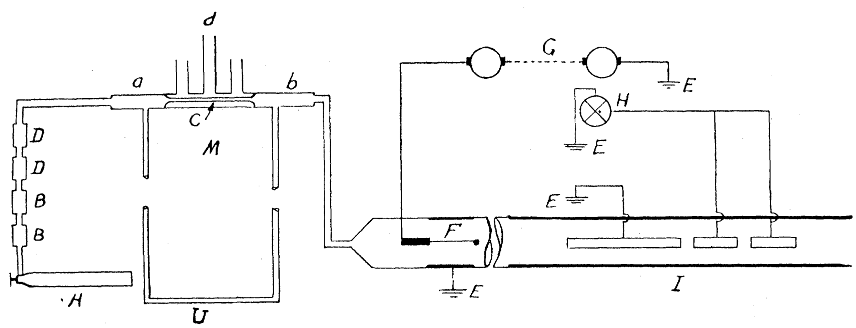

Fig. 1. Arrangement of apparatus.

mobility of certain groups. The curves contained maxima of varying magnitude. If but one mobility was present, only one maximum would be formed, but if two groups of ions existed the resulting curve would show a maximum for each group. It was not necessary to know the absolute value of the electrometer current as the mobility was determined by an equation which required only that the current reach a maximum or peak value.

Apparatus

The gas from commercial steel tanks *A* (Fig. 1) was passed through two tubes of $CaCl_2$ *B*, and two of P_2O_5 *D*, to remove moisture. Glass wool was used to remove dust particles. The gas flow was measured by a gas meter *M*, constructed on the Venturi principle, consisting of two tubes *a* and *b* of 1.3 cm internal diameter. The capillary tube *c* of 2 mm internal diameter, was surrounded by a water jacket so that constant temperature could be maintained and measured by a thermometer at *d*. The use of the water jacket was not imperative, however, as the capillary temperature varied at most by 3°C and since the capillary was made of Pyrex glass, little change in tube diameter resulted. The *U* tube was half filled with Stanolax, a light oil practically non-volatile at room temperature. The capillary was calibrated by means of a standard gas-meter. Two capillaries were used for the various gas flows, one of diameter 1 mm and the other of diameter 2 mm. In using the gas-meter care was exercised to maintain gas velocities through the capillaries which were below the critical velocity at which turbulent flow began. The gas-meter was calibrated with air, therefore in using it for nitrogen, oxygen, and carbon dioxide it was necessary to introduce correction factors in accordance with Reynold's equation.

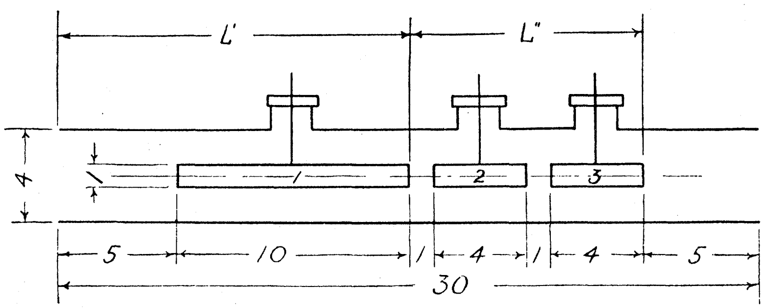

Fig. 2. Details of small ion chamber. All dimensions are in cm. The electrodes are brass tubes with closed ends.

It was desirable to have the ions generated in a small volume so that all would have approximately the same age. To this end a short corona tube *F* was used which had a length of 4 cm and internal diameter of 4.1 cm. The corona wire was always of brass, .4 mm in diameter, and had an exposed length of 4 cm. A ball of sealing wax on one end prevented the formation of a point discharge. The remaining length of corona wire was encased in hard rubber so that only the vertical portion of the lead-in wire (2 mm in diameter) and the corona wire actually within the corona tube were exposed. Corona wire and ion chamber were placed close to each other and arranged so that the gas flow through them would be in stream lines, and as uniform as possible.

A shunted D'Arsonval galvanometer was placed in the low voltage side of the corona circuit to indicate the corona current. The potential for the corona discharge was furnished by 38 d. c. shunt generators *G* of .25 kw capacity, rated at 500 volts each, connected in series. Their field currents were so controlled that the corona potential could be established and maintained at any value.

A preliminary experiment suggested the use of the Zeleny method; accordingly two ion chambers were built which differed only in dimensions. Fig. 2 illustrates the form of the chamber. The insulators were constructed of a sulfur plug 1 cm in diameter and 1.5 cm high, separated from a hard rubber plug 1.5 cm in diameter and 1.5 cm high, by a tinfoil guard-ring connected to earth. They were supported in brass collars in the long tube. The brass rods, 2 mm in diameter, passing through the insulators were fastened by taper joints to the electrodes and served as electrode supports and connecting wires.

The second ion chamber had a total length of 112 cm and an internal diameter of 4.8 cm. The electrodes were 50, 25, and 25 cm in length respectively, and of 2 cm diameter. They were spaced 1 cm apart and 5 cm from the ends of the tube. In future work the left ends of the electrodes will be so shaped that stream line flow of the gas is preserved. With square ends on the electrodes there is a chance for turbulence.

If uniform gas velocity across the tube be assumed, then for the Zeleny apparatus the mobility K of the ions is given by

$$K = Q\log_e(b/a)/2\pi E'(L'+L'') \qquad (1)$$

$$= Q\log_e(b/a)/2\pi E''L' \qquad (2)$$

where Q is the quantity of gas passing any cross section per second, b and a are the radii of cylinder and electrode respectively. L' is measured from the left end of the cylinder to the right end of electrode 1, and L'' is measured from the right end of 1 to the right end of 3. E' and E'' are the voltages necessary to produce maximum ion current to $(L'+L'')$ and L' respectively. Only equation (1) was used in these measurements.

The positive potential for the cylinder of the ion chamber was furnished by flashlight and "B" batteries. To exclude electrostatic effects, the ion chamber was inclosed in a metal box and the wire leading from the ion chamber to the electrometer in a shielded glass tube. It was also necessary to shield the quadrant electrometer by a metal box, which also served to retain a rather dry atmosphere about the instrument, calcium chloride being placed in the box.

In making the measurements electrode 1 was connected to earth, 2 and 3 were connected to the electrometer. The potential necessary to cause maximum current to 2 and 3, then, was the same as that required to give a constant current to $(L'+L'')$. For one group of ions the curve between electrometer current and cylinder potential would increase to a maximum and then decrease to zero as the cylinder potential increased. If two groups of ions were present two maxima would exist etc.

Several curves were taken with air merely to ascertain the form of the curve to be expected and to adjust the apparatus, but no curves are here reproduced. Suffice it to say, however, that an extremely large number of maxima were obtained in these rough measurements.

In all cases of the pure gases, every curve taken was duplicated two or three times so that the existence of the maxima was definitely established. The mobilities listed below are labeled S (strong), F (fair), W (weak). Only such mobilities are listed as were well defined on at least two curves.

The electrometer deflection due to the ion current in the ion chamber was generally small, of the order of 10^{-2} mm per second except for a small region of the nitrogen curves where it mounted up as high as 14 or 16 mm per second. It was practically impossible to repeat any curve point for point. Even if two curves were taken consecutively it was generally found that all deflection velocities would be increased or decreased. This was not due to leakage over the insulators in the ion chamber because the electrometer was tested before and after taking a set of readings, for insulation leakage, and in all cases this leakage was negligible, either zero or about .1 mm in 60 seconds. Calcium chloride was frequently used to produce a dry atmosphere within the ion chamber shield but it was found that the guard sleeve and sulfur plug were sufficiently effective in preventing leakage.

Results and Discussion

Oxygen. The whole of the region investigated is shown in Fig. 3, curves (1) and (2). It will be noted that in all cases the ion current is small, and seems to attain a certain average value above which the maxima stand out. In some cases scattered points will be noticed. The maxima have been drawn conservatively, none being indicated unless it occurred very pronouncedly on at least one other curve. In some cases a maximum has been indicated even if it occurred faintly, but in these cases it has been considered because of the fact that it occurred on nearly all curves taken in that region. It must be borne in mind that these curves were not taken on the same day or on consecutive days or with the same ion chamber; curve (1) was taken with the small ion chamber and curve (2) with the large ion chamber, (1) representing the region from 0 to about 2 volts on curve (2). This, coupled with the fact that the corona discharge is not an invariant discharge, may explain the shift of the average value of ion current.

A large quantity of ozone is found in the corona in oxygen, hence a considerable quantity of the energy passing through the corona tube was used in its formation. Since the corona current was kept constant

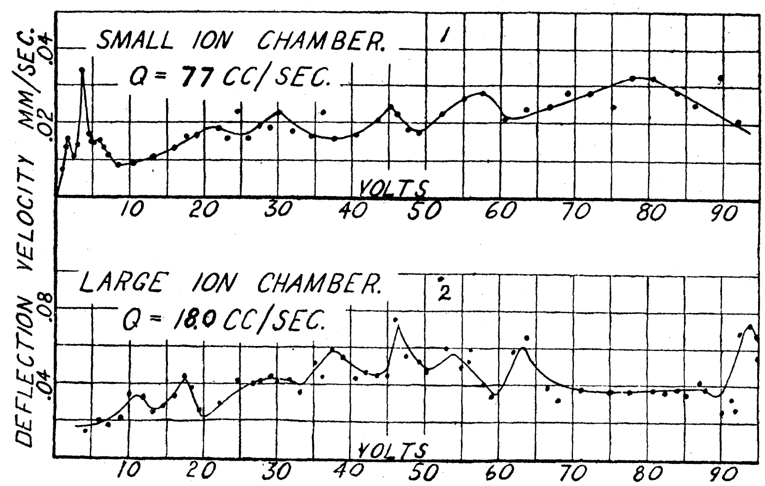

Fig. 3. Ion current in oxygen. Curve 1 represents the portion of curve 2 between 0 and 2 volts.

for all curves, this may be one reason for the small average value of the ion current.

The values of ion chamber potential, electrode length, and quantity of gas flowing per second are given below for the first seven points or mobilities secured for oxygen.

TABLE I

Sample set of data for the mobility of oxygen.

Cylinder potential E	Electrode length L	Gas per sec Q	Mobility K	Cylinder potential E	Electrode length L	Gas per sec Q	Mobility K
.75	25	76	.91	30	25	77	.023
.75	25	77	.92	29	25	76	.023
.75	25	78	.94	2.8	107	52.5	.025
			Ave. .92				Ave. .024
1.2	25	76	.57	45	25	77	.015
1.3	25	78	.54	45	25	76	.015
				67.5	25	120	.016
			Ave. .55				
2.85	25	76	.23				Ave. .015
3.00	25	78	.23	57.1	25	76	.012
3.5	25	79	.20	54.7	25	74	.012
				54.7	25	77.5	.012
			Ave. .23	54.7	25	76	.012
22.5	25	77	.031				
20.5	25	76	.033				Ave. .012
			Ave. .032				

Table II gives all the mobilities found, the number of times found, the number of curves taken over that region, and the strength of the peak in the curve.

TABLE II

Mobilities in Oxygen

Mobility cm/sec/volt/cm	Times repeated	Curves covering region		Mobility cm/sec/volt/cm	Times repeated	Curves covering region	
1.2×10^{-1}	3	3	W	3.8×10^{-3}	3	3	W
5.5 "	2	3	S	1.9 "	4	5	F
2.3 "	3	3	S	1.2 "	4	4	W
3.2×10^{-2}	2	3	W	9.4×10^{-4}	4	5	F
2.4 "	3	3	W	6.6 "	4	5	F
1.5 "	3	3	F	5.3 "	4	5	F
1.2 "	4	4	F	4.5 "	4	5	F
8.6×10^{-3}	3	4	S	3.9 "	4	5	W
6.6 "	3	4	W	2.8 "	3	5	S
5.4 "	2	3	F	2.1 "	1	1	S
4.6 "	2	3	S	1.8 "	1	1	S

In the case of oxygen as in the case of the other gases, the ion current was never brought to zero, in fact it showed no signs of going to zero even when the potential on the ion chamber cylinder was increased

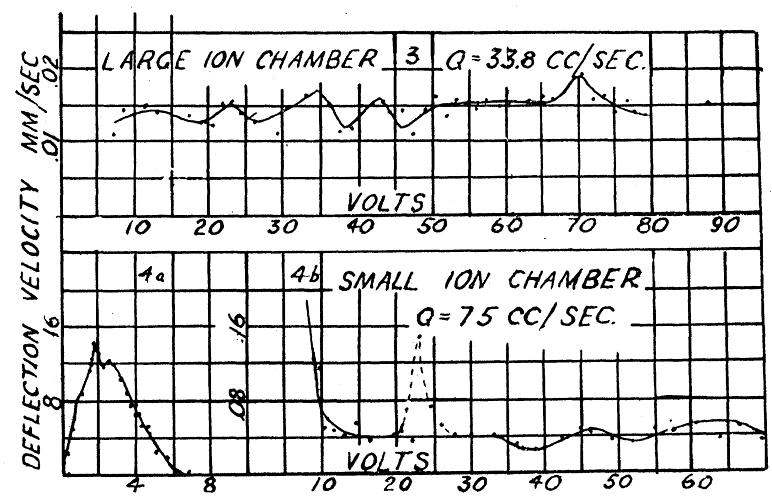

Fig. 4. Ion current in nitrogen. Curve 4*a* represents the region from 0 to 7 volts of 4*b*, and 4*b* in turn represents the region from 0 to 8 volts of 3. Apparently there is a maximum at *A* in 4*b* but it was not considered as it was not found on any other curves.

nearly 100 volts beyond that required to produce the minimum mobility listed. Hence, it may very well be that many more groups of ions are formed of exceedingly low mobility.

Nitrogen. This gas is unique among those used in that it gave a very high ion current in one small region, becoming 350 times as large as the oxygen average. Mobilities calculated in this region were from .72 to .25 cm/sec per volt/cm. In all other regions the ion current was of the same order of magnitude as was found in the case of oxygen and the same characteristics may be here observed as were pointed out above, namely, a rather marked average ion current with now and then a maximum rising up. These curves were taken on different dates, but still have the same characteristics. The results are presented in Table III.

TABLE III

Mobilities in Nitrogen

Mobility cm/sec/volt/cm	Times repeated	Curves covering region		Mobility cm/sec/volt/cm	Times repeated	Curves covering region	
7.1×10^{-1}	2	2	S	2.1×10^{-3}	2	3	F
3.7 "	2	2	S	1.4 "	2	3	S
2.5 "	4	4	S	1.0 "	4	4	S
1.0×10^{-2}	2	2	W	6.6×10^{-4}	4	4	S
5.5×10^{-3}	3	3	F	3.8 "	3	3	S
3.8 "	4	4	W	2.9 "	1	1	F

Carbon Dioxide. In the case of carbon dioxide, one curve is shown for each part of the region investigated. It will be noticed that the curves rise continually for a considerable period and then seem to take on a slow decline. There are always these points of maximum ion current superimposed on a seemingly steadily and slowly changing ion current. The average of this slowly changing current is two or three times as great as in the case of oxygen and nitrogen. Because of the difference in Q, the quantity of gas per second, and the difference in size of the ion chambers, curve 5 represents the region from 0 to 3 volts of curve 6.

TABLE IV

Mobilities in carbon dioxide

Mobility cm/sec/volt/cm	Times repeated	Curves covering region		Mobility cm/sec/volt/cm	Times repeated	Curves covering region	
4.1×10^{-1}	4	4	S	7.9×10^{-4}	3	5	W
1.8 "	3	4	S	4.7 "	5	5	S
2.6×10^{-2}	4	4	S	2.8 "	4	5	S
1.0 "	5	5	S	2.3 "	4	5	S
5.8×10^{-3}	2	3	F	2.1 "	4	4	W
5.1 "	2	4	S	1.9×10^{-4}	4	4	F
3.7 "	2	3	S	1.7 "	4	4	S
2.6 "	5	5	S	1.4 "	3	3	S
1.0 "	4	4	S	1.0 "	2	2	S

Curves 6, 7a, and 7b, show the same region so that the maxima of the same number give the same mobility, and they illustrate well the variation in the shape of the curves for consecutive curves. The maximum

(a) of curve 5, is, of course, not determined by the points plotted but other curves covering the same region showed very clearly that the maximum existed. Therefore it is reproduced in order that the data may be complete.

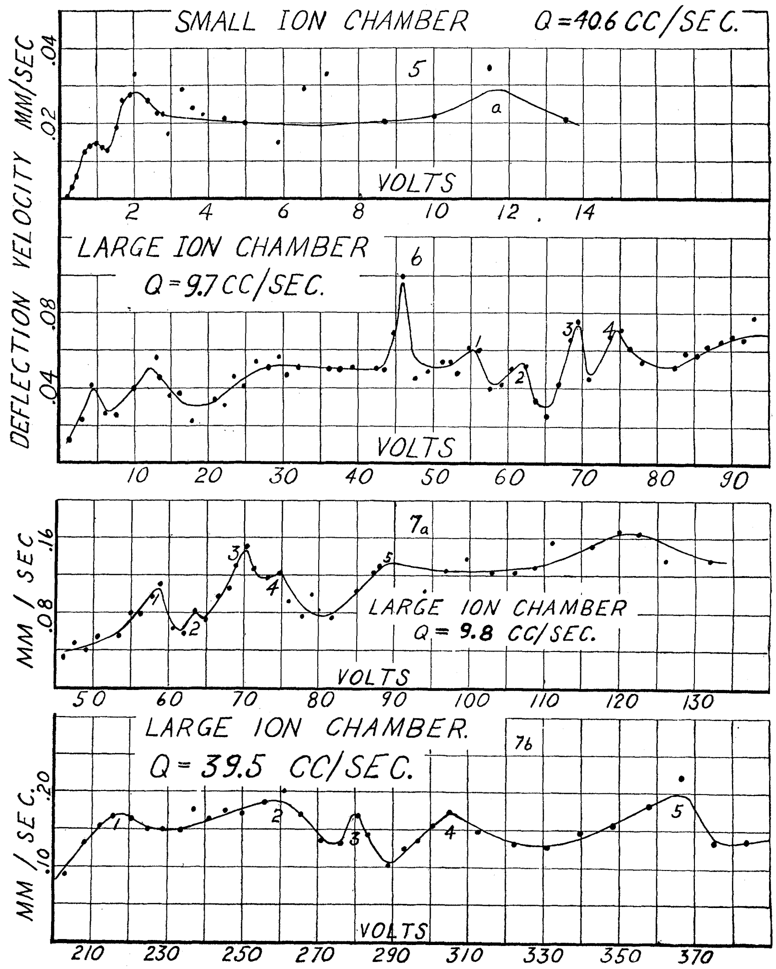

Fig. 5. Ion curve in carbon dioxide. Curves 6, 7*a* and 7*b* represent in part the same region and the numbered maxima on the three curves correspond, giving the same value of mobility.

The maxima were chosen very carefully and regions of severe scattering of points were not considered except as a maximum, well defined, was noted in another curve. The table of mobilities of the ions of carbon dioxide, is presented in Table IV.

Hydrogen was not used because of the instability of the discharge, it readily going over into the arc.

Discussion. Much progress has recently been made in enlarging the theoretical and experimental knowledge of the ions formed in the various gases by different methods, especially by L. B. Loeb, H. A. Erikson, and H. B. Wahlin. The problem is however hardly solved as there still remain contradictory statements in recent papers by Erikson,[5] who worked at atmospheric pressure, and Wahlin,[6] who used low pressures, regarding the influence of the mass and charge of the ion on its mobility. If it be tentatively assumed with Wahlin that the mass is the governing factor in the mobility, then it is possible to pick out mobilities in the above tables where the ratio of the mobilities is approximately equal to the inverse ratio of the square root of the molecular weight of the gases used. In the case of carbon dioxide, mobilities of carbon monoxide ions, corresponding to the mobilities of the nitrogen ions, and mobilities corresponding to those of oxygen ions would be expected. Several such cases were found. However if ions may acquire different charges then one might pick out mobilities in the different gases which are due to ions having two or three charges.

None of these figures is here given because the existence of such ions is not yet proved. It is indeed possible that all these mobilities may be attributed to metallic particles, atoms, or clusters of metallic molecules that are charged and that are formed by the disintegration of the corona wire by the discharge.

Attention is called to the fact that, of the mobilities given under the respective gases, some are above, some below the average value calculated by Kunz from the pressure increase. This is to be expected. The values of Kunz can only be checked by knowing the number of ions of each mobility which are formed, and by finding what pressure this totality of ions would create in the corona tube under the influence of the potential difference there present. The mobilities were not all found in the investigation as the curves were never brought back to zero, however all mobilities found are of the small value Kunz assumed.

A glance at the curves would seem to suggest that some of the peaks are drawn with greater sharpness than the method can give. It must be remembered, however, that the Zeleny method is one of high resolving power and further that the ordinates of the curves are arbitrary units and are exaggerated to show the form of the curves. Further

[5] H. A. Erikson, Phys. Rev. **24,** 502 (1924).
[6] H. B. Wahlin, Phys. Rev. **25,** 630 (1925).

work is now in progress with another form of apparatus and when results are secured the resolving power of both methods will be discussed.

FURTHER EXPERIMENTS

Long corona tube. As previously stated, a short corona tube was used so that all ions would have about the same age on entering the ion chamber. In order that the effect of a long corona tube might be noted one was constructed having a length of 30 cm, and a curve was taken on CO_2. As the distance between the corona tube and the ion chamber was the same as previously used, namely 25 cm, the curve should repeat itself in shape, only for greater corona current the ion current should increase. The youngest ions in the case of the long corona tube would be no older than the youngest ions of the short tube, but the

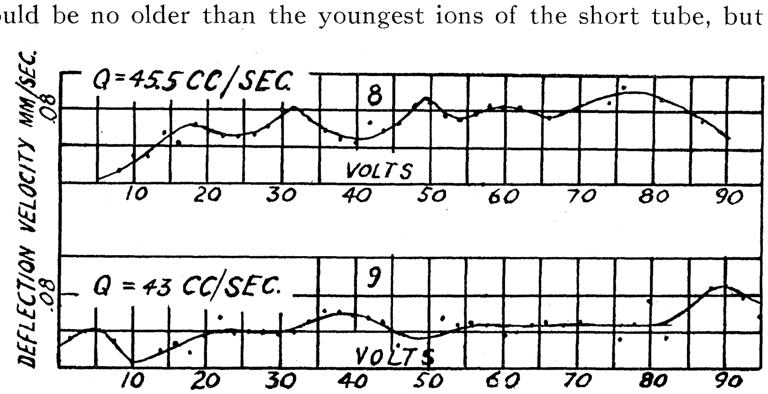

Fig. 6. Ion current in carbon dioxide. Curve 8, 115 cm between corona tube and ion chamber. Curve 9, 76 cm between corona tube and ion chamber.

oldest ions would have the greater age for the long tube. These expectations were realized and maxima were obtained which gave, quite exactly, mobilities previously obtained. The corona current for the long tube was 2.08 times that used in the short tube. The ion current increased about four times.

Variable distance from corona tube to ion chamber. As a final test the distance between corona tube and ion chamber was varied to note the effect on the mobilities present. Two curves were taken at each of the distances 115 cm and 76 cm and curves are reproduced, Fig. 6, showing the maxima obtained. The long corona tube and short ion chamber were used in order that the more rapidly moving ions might be observed and that the ion current might be large. The table shows the variation of the mobilities for carbon dioxide

115 cm:	2.2×10^{-2}	1.2×10^{-2}	8.2×10^{-3}	6.7×10^{-3}	5.2×10^{-3}
76 cm:	7.7×10^{-2}	1.7×10^{-2}	1.0×10^{-2}	4.3×10^{-3}	

It is thought that one grouping of ions, when the corona tube and ion chamber are separated by a short distance (25 cm) at which most of the tests were made, is unstable and goes over into another when the distance is increased. In other words the grouping of the atoms and molecules in the ions changes with time and tends toward the formation of larger clusters of ions having smaller mobility. This is in accord with the recent results of Erikson,[4] Wahlin,[7] and others.

Point discharge. After measurements had been made on the mobilities of the ions in the corona discharge, the same apparatus was used and a few rough curves were taken on the point discharge merely to confirm the values found by Chattock. In this case it was interesting to note that the ion current for each gas had about two maxima, a weak one yielding the value of mobility determined by Chattock and a strong one giving a value considerably less.

Chattock gave a value of 1.3 cm/sec per volt/cm as the mobility for positive O_2 ions. This method yielded, for rough measurements, the two mobilities 1.27 and .284 cm/sec per volt/cm. The mobility corresponding to that given by Chattock is defined by a rather weak maximum on the curve, whereas, the second mobility is very strongly defined.

CONCLUSIONS

It should be first noted that no mobilities of ions were obtained greater than .716 cm/sec per volt/cm for nitrogen. Others have found that the initial ion changes over into one of smaller mobility as time is increased. In all the measurements recorded in this paper the ions had an age of 2.5 sec or more. Most of the tests were made on ions of age about 5 sec and this is greater than the life of the initial ion of Erikson.

The measurements show that ions generated in the corona discharge have small mobilities and that nearly all mobilities can be found of a value less than 10^{-2}. These ions seem to be in about equal numbers because of the small average value of the ion current, except now and then a greater number of a certain mobility are formed. This fact is manifest on the maxima of the curves.

Nearly all ions are of very low mobility at atmospheric pressure at which measurements were made.

Assuming the mobility of the ion to depend on the charge, evidence can be found of ions which contain different charges. Also if it can be assumed that the mass influences the mobility, then ions may be picked out having the same charge but whose mobility varies inversely as

[7] H. B. Wahlin, Phil. Mag. **49**, 566 (1925).

the square root of the molecular weight. If these ions are gaseous then a comparison of the mobilities found shows evidence of the formation of oxygen and carbon monoxide in carbon dioxide. These may be identified by comparing mobilities of nitrogen and oxygen with those of carbon dioxide. Identical mobilities should appear for ions of the same charge and mass since nitrogen has the same molecular weight as carbon monoxide.

It was noted before that no single mobilities of ions have been found which alone account for the corona pressure from which J. Kunz calculated his mobilities. The pressure could be obtained probably by taking the sum of the impact energies of all ions generated by the corona but as apparently only a few of the ions were found in these measurements, no attempt was made at such a calculation. This matter will be taken up again in the near future.

The writer desires to express his appreciation to Dr. J. Kunz for his many helpful suggestions and keen interest in the work, and to Professor A. P. Carman for his interest and for the use of the laboratory and facilities.

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