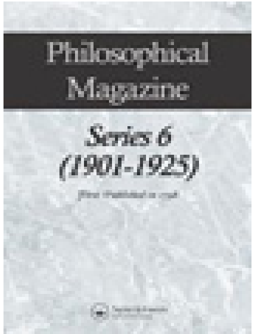

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[SIXTH SERIES.]

JUNE 1902.

LXVI. *The Conductivity produced in Gases by the aid of Ultra-Violet Light.* *By* JOHN S. TOWNSEND, *M.A.*, *Wykeham Professor of Physics, Oxford**.

1. IN some previous papers on the electrical conductivity of gases it has been proved that a number of complicated phenomena can be explained by the theory of the genesis of ions by collision. In those experiments which were designed to test the theory the conductivity was started in the gas by Röntgen rays. (J. S. Townsend, Phil. Mag. Feb. 1901; J. S. Townsend & P. J. Kirkby, Phil. Mag. June 1901; P. J. Kirkby, Feb. 1902.)

The electric forces which were used were such that the potential-differences between the electrodes were not sufficient of themselves to produce or maintain a continuous discharge.

A number of interesting results obtained by Stoletow† with ultra-violet light can also be explained by the same theory, but as his experiments are not arranged so as to give an accurate test of the theory, and were made with air alone, it was considered desirable to make some new experiments with air and other gases.

It is easy to devise experiments so as to obtain a simple test of the theory of the genesis of ions by collision, when the conductivity is started by means of ultra-violet light. In the experiments which are here described the conductivities

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* Communicated by the Author.

† Stoletow, *Journal de Physique*, ser. 2, vol. ix. 1890.

were measured between two parallel plates at different distances apart. The light fell on the negative electrode, which was a zinc plate. The light has the effect of setting free negative ions from the surface of the metal on which it falls. These ions, which I shall call the z ions, as they move through the gas under an electric force produce others by collisions with molecules. The increase of conductivity obtained by separating the plates is thus explained. The experiments also lead to the conclusion that the ions generated in the gas have exactly the same properties as the z ions. In order to show this, the conductivity was determined for different distances between the plates, the electric force, X, and the pressure, p, of the gas being kept constant. The number of ions, α, generated by one of the z ions in moving through a centimetre of gas is a function of X and p, so that α remains constant in the experiments with different distances between the plates. If the negative ions generated in the gas have the same properties as the z ions, the conductivity will increase by the factor $\epsilon^{\alpha x}$ when the distance between the plates is increased by the length x. The total number of ions n reaching the positive plate will be given by the formula

$$n = n_0 \, \epsilon^{\alpha d},$$

n_0 being the number of ions set free from the zinc plate, and d the distance between the plates. It was found that this formula gives the connexion between the values of n and d over a large range of forces and pressures.

2. The apparatus used in these experiments is shown in figures 1 and 2.

The conductivity took place between the two parallel plates A and B, figure 1. The plate A was of quartz silvered on the inside so as to obtain a conducting surface. The silvering was ruled with a series of fine parallel lines to allow some of the light to pass through the plate and fall on the surface of the lower plate B, which was of zinc. The plate A rested on a brass cap C, and the junction between the plate and the brass was made air-tight. The short ebonite tube E was screwed to the flat part of the cap on which the quartz plate rested, and a metal disk F was fixed to the lower end of the ebonite. This disk was thus in rigid connexion with the quartz plate A and parallel to it. The distance between the plates A and B could be adjusted by means of the screw S, which worked in a half-millimetre thread cut in the plate F. The wide glass tube D which contained the apparatus was ground flat at one end, and the brass cap was cemented to it. The other end was joined to a narrower tube about 33 inches long, which dipped into a vessel containing mercury.

Some of the ebonite tube E was cut away so as to allow the gas a free passage from the space between the plates to the other parts of the apparatus.

Fig. 1.

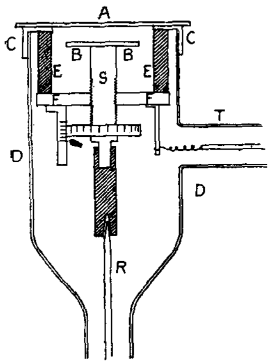
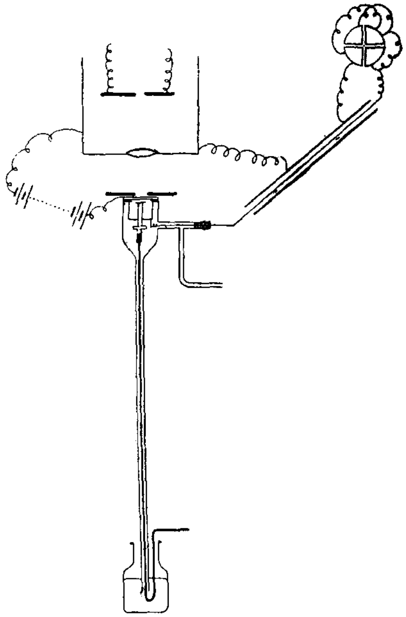


Fig. 2.



A short piece of ebonite was fixed to the screw S, and the rod R, coming through the mercury column below D, fitted into a notch cut in the ebonite. The distance between the plates A and B could be altered, without changing the pressure, by turning the end of the rod R, which was bent as shown in figure 2.

The apparatus was connected to a Toepler pump and a McLeod gauge. A small variation of pressure could be detected by means of the gauge, and it was found that the pressure only altered by about a five-hundredth of a millimetre during a set of observations.

When experimenting with hydrogen and carbonic acid, a fresh supply of gas was introduced into the apparatus before each set of experiments, so that the small leakage could not have produced any appreciable effect in the results.

Metallic connexion was made with the zinc plate by a rod passing through the side-tube T. The rod entered the apparatus through an ebonite plug in the end of the side-tube, and was thus insulated from the glass tube.

The zinc plate was in connexion with one pair of quadrants of an electrometer, the other pair of quadrants being to earth. The wire leading from the apparatus to the insulated quadrants passed along the centre of an earth-connected brass tube to prevent induction-effects. The silvered plate A was connected to the positive terminal of a battery of small Leclanché cells, and the other terminal was put to earth. When it was required to make experiments with a constant electric force, the number of cells employed was proportional to the distance between the plates. The cells were set up in sets of 24; each set had exactly the same potential, 35 volts.

The plate B connected to the electrometer never deviated much from zero potential, so that during an experiment the electric force between the plates was practically constant and equal to the potential of the battery divided by the distance between the plates.

Strips of tinfoil were wrapped round the ebonite tube E (about halfway between the brass cap and the disk E), and connected to earth through a second side-tube (not shown in the figure). This arrangement prevented any leakage of electricity over the surface of the ebonite from the plate A to the apparatus connected with the electrometer.

The ultra-violet light was produced by the spark of a leyden-jar discharge taking place between two aluminium points. An induction-coil was used for charging the leyden-jar. The whole apparatus for producing the light was surrounded by a metal screen connected to earth, so that the sparking should have no direct effect on the electrometer.

The spark-gap was at the focus of a quartz lens placed in an aperture of the screen vertically above the parallel plates A and B. A lead screen with a circular hole one centimetre in diameter was placed between the lens and the quartz plate, in order to confine the light to the central portion of the zinc plate. The latter was 2·4 centimetres in diameter, so that when the light fell upon it the conductivity took place only in the space where the field of force was uniform.

The apparatus was tested at various times, and it was found that no electrometer deflexion was produced by the sparking when the aperture in the lead screen was closed.

3. The observations were made in the usual manner. The coil which charged the leyden-jar was turned on for a fixed time, and the electrometer deflexion was observed. Several

observations were thus made with different distances between the plates, the electric force and the pressure being kept constant. These experiments were repeated alternately, and the mean of the observations was taken. As a rule the observations did not vary by more than 4 or 5 per cent., so that considerable accuracy could be obtained.

It is necessary to apply a small correction to the electrometer readings owing to the increase of capacity which occurs when the plate B is moved up towards A. The effect of moving B from a position 5 millimetres from A to 1 millimetre from A was to increase the capacity of the apparatus connected to the quadrants (including the quadrants) in the ratio of 82 : 80. The observations at the latter distance were increased by $2\frac{1}{2}$ per cent., and intermediate observations by a smaller factor, in order that the observations should be proportional to the current between the plates.

In most cases three conductivities, n_1, n_2, and n_3, were found for three distances, d_1, d_2, and d_3, between the plates, the electric force and pressure being constant. The distances were such that $d_2-d_1=d_3-d_2$.

According to the formula, $n=n_0\epsilon^{\alpha d}$, the corresponding conductivities satisfy the condition $\frac{n_2}{n_1}=\frac{n_3}{n_2}$ when the increase in conductivity arises from the action of the negative ions. By adopting this method of experimenting it is possible to guard against using forces which are too high, and which give rise to conductivities so large that they cannot be attributed to this process of ionization alone.

In the ordinary discharge arising from a high potential-difference between the electrodes, there must be at least two processes of ionization at work. The genesis of ions by the motion of negative ions alone cannot explain the phenomenon of a continuous discharge. It is evident, therefore, that some other cause is at work, and these experiments show that it begins to take effect at potentials much lower than the potential necessary to produce a discharge. With a suitable pressure, it was found that the ratios of the conductivities corresponding to equal increments of the distance d continually rose as the distance between the plates was increased, although the potential-difference between the plates was less than 300 volts. With hydrogen this effect is obtained with potentials less than 200 volts.

I have as yet made only a very incomplete examination of this second process of ionization, and in the following tables only a few examples of it are given.

The tables correspond to the different pressures. The force X is given in volts per centimetre. The conductivities n_1 n_2, n_3, &c. are the electrometer deflexions obtained in 10 seconds, and corrected for capacity as explained, the suffix denoting the distance between the plates in millimetres. The ratio of each conductivity to the preceding is given in the column R. It is not necessary to have the same intensity of light for the experiments at different pressures and forces, so that in the tables of results the numbers in the vertical columns do not accurately correspond to equal intensities of light.

TABLE I.—Air. Pressure 6 mms.

X.	n_1.	n_3.	n_5.	R.
350	16·9	19·2	22·2	1·14, 1·14
525	20·7	37·5	69	1·81, 1·84
700	28·2	97·5	345	3·47, 3·53

TABLE II.—Air. Pressure 2·5 mms.

X.	n_1.	n_3.	n_5.	R.
350	23	47·5	97·2	2·06, 2·05
525	29·7	126	547	4·24, 4·31
700	37·3	312	...	8·56 —

TABLE III.—Air. Pressure 1·04 mms.

X.	n_1.	n_3.	n_5.	R.
262	27·6	57	121	2·06, 2·12
350	31·5	86	241	2·73, 2·80
438	40	140	518	3·5, 3·7

Table IV.—Air. Pressure ·375 mm.

X.	n_1.	n_3.	n_5.	R.
262	34	63	126	1·83, 2·00
350	35·3	74	168	2·1, 2·26
438	42	99	231	2·35, 2·34
525	44·5	113	280	2·53, 2·48

Table V.—Air. Pressure ·148 mm.

X.	n_1.	n_5.	R.
262	35·8	73	2·04
350	38·4	83	2·16
525	41	92	2·25
700	42	99	2·35

Table VI.—Hydrogen. Pressure 67 mms.

X.	n_1.	n_2.	R.
1750	60·2	84	1·39

Table VII.—Hydrogen. Pressure 30 mms.

X.	n_1.	n_2.	n_3.	R.
1050	70·2	101·5	144	1·44, 1·43
1400	111	275	...	2·48
1750	208	990	...	4·75

TABLE VIII.—Hydrogen. Pressure 12 mms.

X.	n_1.	n_3.	n_5.	R.
350	46	...	64	1·39
525	61	112	200	1·83, 1·79
612	72·3	179	450	2·47, 2·51

TABLE IX.—Hydrogen. Pressure 5·06 mms.

X.	n_1.	n_3.	n_5.	R.
262	57·5	86	134	1·49, 1·55
350	67·5	145	312	2·15, 2·15
525	97	424	1800	4·37, 4·22
700	134	1120	...	8·35 —
	n_1.	n_2.		
875	187	721		3·82

TABLE X.—Hydrogen. Pressure 1·82 mms.

X.	n_1.	n_3.	n_5.		R.
262	62·5	128	276		2·05, 2·16
350	74	194	546		2·62, 2·80
	n_1.	n_2.	n_3.	n_4.	
525	97	187	359	875	1·93, 1·93, 2·44

TABLE XI.—Hydrogen. Pressure ·82 mm.

X.	n_1.	n_3.	n_5.	R.
262	62·5	112	204	1·79, 1·82
350	66·5	131	272	1·97, 2·07
525	67·5	144	405	2·14, 2·81

TABLE XII.—Hydrogen. Pressure ·385 mm.

X.	n_1.	n_5.	R.
262	55·4	112·5	2·03
350	57·5	123·5	2·15
525	66·6	147	2·21
700	71·8	158	2·21

TABLE XIII.—Carbonic Acid. Pressure 44 mms.

X.	n_1.	n_2.	R.
1750	70·3	89	1·26

TABLE XIV.—Carbonic Acid. Pressure 20·5 mms.

X.	n_1.	n_2.	n_3.	R.
1050	69·5	92	122	1·32, 1·33
1750	161	540	...	3·35

TABLE XV.—Carbonic Acid. Pressure 8·75 mms.

X.	n_1.	n_3.	n_5.	R.
350	49	...	65	1·33
700	82·5	199	480	2·41, 2·41
	n_1.	n_2.		
1050	144	407		2·82

TABLE XVI.—Carbonic Acid. Pressure 3·9 mms.

X.	n_1.	n_3.	n_5.	R.
262	64	...	107	1·67
350	74·5	124	210	1·67, 1·70
525	97	305	993	3·15, 3·24
	n_1.	n_2.	n_3.	
700	139	356	882	2·55, 2·49
1050	278	1400	...	5·04 —

TABLE XVII.—Carbonic Acid. Pressure 1·375 mms.

X.	n_1.	n_3.	n_5.	R.
262	65·5	132	266	2·01, 2·02
350	81	230	646	2·84, 2·81
	n_1.	n_2.	n_3.	
525	110	264	598	2·40, 2·26
700	152	450	1380	2·96, 3·07
1050	242	1080	...	4·46 —

TABLE XVIII.—Carbonic Acid. Pressure ·606 mm.

X.	n_1.	n_3.	n_5.	R.	
262	88	199	462	2·26,	2·32
350	97·5	282	853	2·90,	3·03
525	122	518	2270	4·24,	4·38
700	157	840	—	5·35	—

TABLE XIX.—Carbonic Acid. Pressure ·321 mm.

X.	n_1.	n_3.	n_5.	R.	
262	85	171	355	2·02,	2·07
350	95	217	508	2·28,	2·33
522	114	300	860	2·63,	2·86
	n_1.	n_2.	n_3.		
700	126	221	378	1·76,	1·71
1050	152	268	...	1·77	—

4. In these experiments the greatest potential-difference between the plates was 350 volts. An appreciable increase of conductivity can be obtained with this voltage with gases at several centimetres' pressure by having short distances between the plates. This can be seen from Tables VI., VII., and XIII., the conductivities having been determined with the plates at 1 and 2 millimetres apart.

The equality of the two ratios $\frac{n_3}{n_1}$ and $\frac{n_5}{n_3}$ (given in the last column of each table) shows that the conductivity is proportional to $\epsilon^{\alpha \times d}$, d being the distance between the plates, and α a constant depending on the force and pressure. When the force is constant and the pressure lowered the value of α at first increases as the pressure diminishes, then reaches a maximum, and afterwards diminishes. It will be shown that the pressure for which α is a maximum is proportional to X.

In certain cases the ratios $\frac{n_3}{n_1}$ and $\frac{n_5}{n_3}$ are not equal, the latter being much the larger of the two. This effect can be obtained with air at a millimetre pressure when the maximum potential-difference between the plates is less than 300 volts. The phenomenon occurs at lower voltages in hydrogen, as is shown by the experiments given in Tables X. and XI., in which a force of 52·5 volts per millimetre was used. With this force the conductivity of hydrogen at 1·82 mms. pressure increases by the factor 1·93 when the plates are separated from 1 to 2 or from 2 to 3 millimetres apart; a further separation of the plates from 3 to 4 millimetres increases the conductivity by the factor 2·44. This process continues until eventually a continuous discharge is obtained without the aid of the ultra-violet light. With the same force (52·5 volts per millimetre) a similar effect is produced at ·82 millimetre, the ratios $\frac{n_3}{n_1}$ and $\frac{n_5}{n_3}$ being 2·14 and 2·81 respectively. When the pressure is reduced to ·385 millimetre or increased to 5·06 millimetres, the effect disappears for distances up to 5 millimetres between the plates. I hope to make a more complete examination of this effect, as it may give an explanation of some of the complicated phenomena which occur in the vacuum-tube discharge.

For the present I shall confine the discussion to the effects produced by the motion of the negative ions through the gas.

5. The results of the experiments can be easily represented in a simple form. The ratios R were used to determine the values of α corresponding to the different forces and pressures, the quantity α is the number of ions which a negative ion produces in one centimetre of the gas at pressure p under an electric force X. In the calculations I have not included those values of $\frac{n_5}{n_3}$ which are greater than $\frac{n_3}{n_1}$ by an amount which cannot be attributed to experimental errors. In other cases the mean of the two ratios was equated to $\epsilon^{\alpha \times \cdot 2}$ in order to determine α, ·2 centimetre being the increase in the distance between the plates.

As I have already pointed out (Phil. Mag. February 1901), the connexion between α, X, and p should be of the form $\frac{\alpha}{p}=f\left(\frac{X}{p}\right)$. The simplest method of testing this property of the three variables is to take a number of values of $\frac{\alpha}{p}$ and $\frac{X}{p}$ determined over large ranges, and see whether the points whose coordinates are $\frac{\alpha}{p}$ and $\frac{X}{p}$ lie on a curve. All the values of $\frac{\alpha}{p}$ (derived from the experimental determinations) are marked on the accompanying diagrams, p being measured in millimetres of mercury, and X in volts per centimetre. It is evident that a curve runs through the set of points belonging to each gas. Each point is numbered in order to show from which table of observations the value of a was calculated. The range of values of $\frac{X}{p}$ and $\frac{\alpha}{p}$ are so large that it was found necessary to have two diagrams on different scales. From these curves it is possible to obtain the value of α for any force and any pressure.

6. The properties of the curves are interesting in many ways, and are in accordance with what we should expect from simple considerations.

When an ion travels through a gas under an electric force, it makes a number of collisions with the molecules which is proportional to the pressure. If the velocity of the ion is sufficiently great, the effect of a collision will be to produce two new ions. The free paths of the ion between the collisions are of various lengths which are inversely proportional to the pressure. The velocity acquired in a path of length x is proportional to $\sqrt{X \cdot x}$, so that the velocities of the ions must depend on the quantity $\frac{X}{p}$. The value of $\frac{X}{p}$ must be large in order that the ion may acquire a velocity along the shorter paths which will be sufficiently great to produce new ions on collision. When this effect is obtained further increases in X cannot give rise to larger values of α, as new ions will be produced at every collision. The maximum value of $\frac{\alpha}{p}$ represents the total number of collisions that an ion can make in going through one centimetre of a gas at a millimetre pressure.

The curves show that $\frac{\alpha}{p}$ approaches a maximum as $\frac{X}{p}$ increases, and, as we should expect, this value is larger for carbonic acid than for air, and larger for air than for hydrogen.

The pressure at which α is a maximum for a given force X is obtained by differentiating the equation $\alpha = pf\left(\frac{X}{p}\right)$ with respect to p; we thus obtain

$$f\left(\frac{X}{p}\right) - \frac{X}{p} \cdot f'\left(\frac{X}{p}\right) = 0,$$

so that p is proportional to X.

Fig. 3.

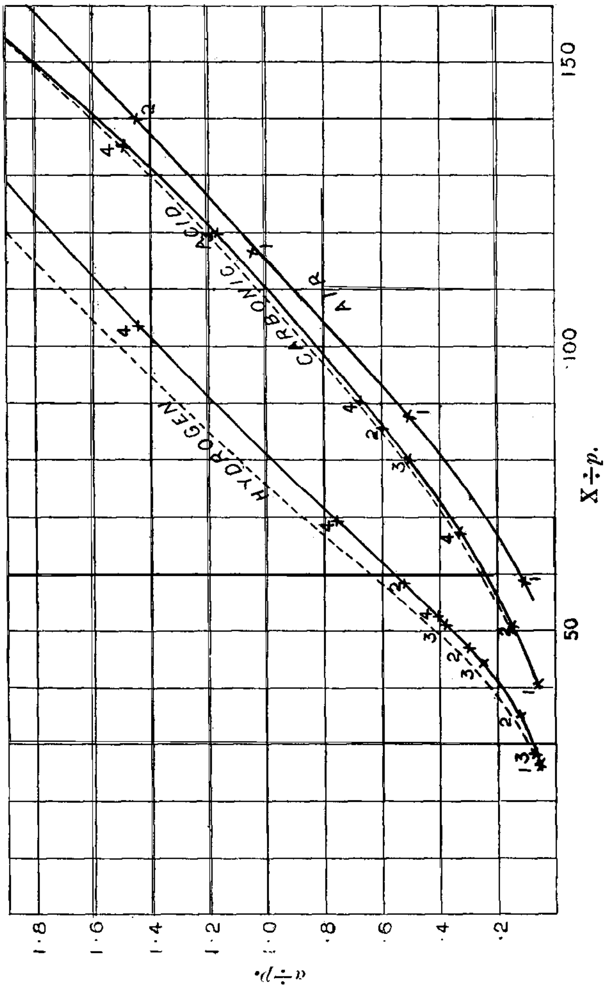
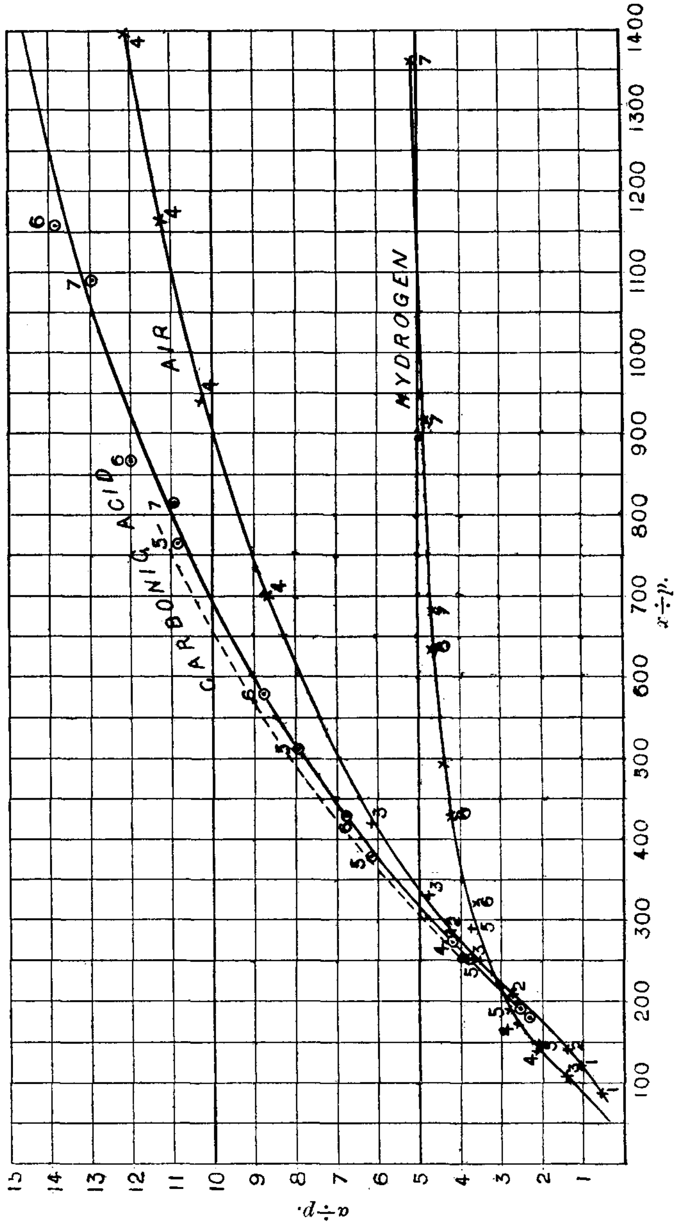


Fig. 4.


CARBONIC ACID
AIR
HYDROGEN
$x \div p$.
$\alpha \div p$.
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

The required value of $\frac{X}{p}$ is found by drawing a tangent from the origin to the curve. The values of $\frac{X}{p}$ for which α is a maximum are thus found to be approximately:—350, 160, 380 for air, hydrogen, and carbonic acid respectively.

Stoletow (*loc. cit.*) obtained this result for air experimentally. He found that when the force was constant and the pressure variable, the conductivity reached a maximum for a certain critical pressure. He also found that this pressure was proportional to the force and independent of the distance between the plates. When the force is expressed in volts per centimetre, the critical pressure, according to Stoletów's experiments, is given by the equation :

$$p=\frac{X}{380},$$

which is practically the same result that I obtained by drawing a tangent to the curve. The exact value of $\frac{X}{p}$ which gives the critical pressure cannot be found very accurately by either of these methods, so that we cannot expect the two numbers to agree very accurately.

We can, however, fix the maximum value of α with greater precision. It can be easily seen from the theory that the maximum value of α for a given force X is got from the slope of the tangent which passes through the origin.

The coordinates of the points of contact of the tangents to the curves for air, hydrogen, and carbonic acid are respectively:

$$\frac{\alpha}{p}=5{\cdot}2,\quad 2{\cdot}35,\quad 6{\cdot}1$$

$$\frac{X}{p}=350,\quad 160,\quad 380.$$

Hence when X is given and the pressure altered so as to obtain the maximum conductivity, the value of α will be

$$\frac{5{\cdot}2\,X}{350},\quad \frac{2{\cdot}35\,X}{160},\quad \text{and}\quad \frac{6{\cdot}1\,X}{380}$$

for the three gases respectively.

It is remarkable that these three numbers are nearly equal.

7. If the negative ions with which we have been dealing

are the same as those produced in a gas by Röntgen rays, the values of α should be the same under similar conditions of force and pressure. A comparison of the results shows that this is the case. There are, however, differences between the curves which are given in this paper and those which have been already published in the papers to which I have referred. The values of α as determined by the experiments with Röntgen rays are in some cases much too large. The greatest differences between the results arise with the larger values of $\frac{X}{p}$, and are principally due to the fact that when experimenting with Röntgen rays the forces at the lower pressures were so large that other sources of ionization came into play. As I have pointed out, it is easy to guard against this error when experimenting with ultra-violet light; but at the time the earlier experiments were being made I did not realize that the potential must be kept more than 100 volts below the sparking-point. Thus, in the experiments with hydrogen (Phil. Mag. June 1901) at 1·77 mm. pressure, the plates being 5·5 millimetres apart, potential-differences up to 220 volts were used; and at ·84 mm. the potential was taken up to 250 volts. Referring to Tables X. and XI. of this paper it will be seen that, with these pressures, potential-differences greater than 175 volts give rise to increases in conductivity which cannot be attributed to the action of negative ions. The values of α deduced from those experiments are therefore too high, and we cannot expect to find a good agreement between the present results and the determinations of α made with Röntgen rays for the larger values of $\frac{X}{p}$.

The curve corresponding to the smaller values of $\frac{X}{p}$ determined by Röntgen rays for hydrogen lies above the curve determined by ultra-violet light, in the position of the dotted line in the diagram.

The corresponding curve for air would lie between the air and carbonic-acid curves given in the diagram. In order not to complicate the figure this line has not been inserted. The potentials used with air were also too high in some of the experiments, so that the values of α are from 10 to 20 per cent. larger than those found with ultra-violet light for values of $\frac{X}{p}$ greater than 300.

With carbonic acid larger forces may be used than with air or hydrogen without producing conductivities which do not arise from the collisions of the negative ions. The curve for this gas obtained with Röntgen rays practically coincides with that obtained with ultra-violet light over a large range of forces. It lies slightly above the latter curve.

We cannot expect a closer resemblance between the two sets of curves as there are other effects, besides the one I have mentioned, which make it difficult to obtain very accurate determinations of the quantity α with Röntgen rays. The initial distribution of ions is not uniform between the plates, and the secondary radiation carries a charge which introduces complications. The larger values of $\frac{X}{p}$ can only be obtained from experiments at low pressures, and in these cases the initial ionization is small and of the same order as the charge carried by the secondary radiation. This method is therefore not suited for the determination of the larger values of $\frac{\alpha}{p}$. It ought to be easy to determine these numbers with ultra-violet light, and I hope to continue the experiments with air and carbonic acid, so as to obtain the maximum values of α for these gases.

The curve which I have given for hydrogen practically reaches the maximum value of $\frac{\alpha}{p}$, which is about 5·2.

8. The results obtained with the smaller values of $\frac{X}{p}$ are sufficient to lead to the conclusion that the negative ions generated in a gas by the motion of the zinc ions set free by ultra-violet light are identical with the ions produced by Röntgen rays in the same gas. The experiments with ultra-violet light show that the negative ions produced in any gas by the motion of the ions from the zinc plate are identical with the zinc ions themselves. Consequently the negative ions produced by Röntgen rays in any of these gases are exactly the same as the ions set free by ultra-violet light from a zinc plate.

We are also led to conclude from the experiments, that these negative ions are small compared with the molecules of any of the gases. A molecule of a gas makes more than four times the number of collisions that a negative ion makes in going through the same distance of the gas at a given pressure. Also, the property which they possess of generating new ions does not belong to the positive ions under similar conditions of force and pressure. These properties of the negative ion show that it must be small both as regards mass and linear dimensions compared with a molecule of hydrogen.

9. The size of the negative ion, when acted on by small forces, may be estimated from the determination of the rate of diffusion or the velocity under an electromotive force. In determining the latter quality in air, Rutherford* made experiments over a range of pressures extending from atmospheric pressure to 34 mms. At the lowest pressure a force of about 50 volts a centimetre was used, so that the value of $\frac{X}{p}$ was less than 2. The results of Rutherford's investigations showed that the negative ions are the same size over this range of pressures, and are large compared with the molecules.

On the other hand, it can be seen from the experiments described in this paper, that the ions in hydrogen at 67 millimetres pressure are of small mass while under a force of 1750 volts per centimetre, since they produce others by collisions. From the theory and the experiments which showed that $\alpha = pf\left(\frac{X}{p}\right)$, it is to be supposed that the negative ions would remain of small mass and produce others by collision in a gas at any pressure provided that the electric force is sufficiently strong. This immediately follows from the fact that the velocity at collision depends on the value of $\frac{X}{p}$ (see section 6).

It would appear from these investigations, that when ions are generated in a gas the negative ions are of a definite size independent of the gas and small compared with the molecules of hydrogen. When the ratio $\frac{X}{p}$ is small the positive and negative ions quickly acquire the properties of masses which are large compared with molecules, an effect which has usually been attributed to the formation of groups of molecules round the ions. If the force acting on the gas is increased, and the ratio $\frac{X}{p}$ exceeds a certain limit, some of the collisions between the ions and the molecules will be sufficiently violent to prevent the formation of a group of molecules round the ions. A further increase in the force causes the negative ions to collide with sufficient velocity to

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* E. Rutherford, Cambridge Phil. Soc. vol. ix. pt. viii. (1898).

disintegrate the molecule into positive and negative ions. The apparent masses of the ions therefore depend on the ratio of the electric force to the pressure.

10. The results of these experiments throw some light on the constitution of molecules of gases. We are led to conclude that:—It is possible to detach a particle from the molecule of a gas which is small, as regards mass and linear dimensions, compared with the molecule of hydrogen, also the particles produced from molecules of different gases are identically the same.

The mass of the negative ion coming from a zinc plate was previously shown by Professor Thomson* to be small compared with the molecule of hydrogen. The method which he adopted did not involve any of the principles underlying the present investigations.

A considerable number of phenomena connected with the electric discharge in gases may be explained in a general way by taking into consideration the physical properties of these negative ions. Thus some of the effects of variation of pressure, electric force, and distance between the plates can be accounted for. Also the high conductivity of gases under rapidly alternating forces may be due to the fact that the negative ions traverse a long distance before they are discharged by the electrodes. There are, however, many phenomena for which these physical properties supply no explanations: such as the appearance, at the electrodes, of the constituents of compound gases.

The experiments with ultra-violet light show that in carbonic acid the conductivity may arise from the genesis of small negative ions. I am at present continuing the researches with other gases and vapours, so as to obtain some additional evidence on this point, as it is to be expected that similar phenomena may occur with other compound gases.

LXVII. *On Vector Differentials.*

By FRANK LAUREN HITCHCOCK †.

1. IN studying physical quantities we are led to make a distinction between those which have by their very nature a direction in space, and those which, on the other hand, may be thought of as mere numbers. Directed quantities are conveniently called *vectors*, and non-directed ones *scalars*.

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* J. J. Thomson, Phil. Mag. December 1900.

† Communicated by the Author.