LXIII. *Conductivity produced in Hydrogen and Carbonic Acid Gas by the Motion of Negatively Charged Ions.* By JOHN S. TOWNSEND, *M.A., Wykeham Professor of Physics, Oxford, and* P. J. KIRKBY, *M.A., Fellow of New College, Oxford* *.

1. THE experiments described in this paper are a continuation of those which have been published in 'Nature,' 9th August, 1900, p. 340, and in the 'Philosophical Magazine,' February 1901, p. 198. These papers contain an account of experiments which were made at the Cavendish Laboratory, about a year ago, on the conductivity produced in air at low pressures. The current between two parallel plates was found to depend upon the distance between the plates, the pressure, and the electric force in a manner quite different from the current at high pressures. The conductivity was obtained by allowing Röntgen rays to pass through the gas; and it was found that the accompanying phenomena could be explained by supposing that the negative ions produced by the action of the rays generated others by collisions with neutral molecules, the new negative ions thus generated having the same properties as those produced by the rays.

The proof of this theory rested, in the first place, on the connexion between the current and electric force for various distances between the plates. The number of ions, α, generated by a single ion in going through a distance of one centimetre was found from the experiments. The values of α thus found experimentally depended on the pressure, p, of the air and the electric force, X, acting between the plates. The relation connecting the three variables α, p, and X was found to be of the form $\alpha = pf\left(\frac{X}{p}\right)$, which shows that α is proportional to p when $\frac{X}{p}$ is constant.

Further evidence in support of the theory was thus obtained, since from the kinetic theory of gases it is easy to show that α, p, and X should be connected in the above manner.

The application of this theory led to the conclusion that an ion makes 21 collisions with molecules in going through one centimetre of air at one millimetre pressure. When the force acting on the ion is sufficiently great, two new ions (one positive and one negative) are produced at each collision. For smaller forces new ions are not produced at each collision.

---

* Communicated by the Authors.

It was found that on some occasions new ions were produced when the velocity of the colliding ion is equal to the velocity acquired in moving freely between two points differing in potential by 5 volts. From this it was concluded that the energy required to ionize a molecule is not greater than $\frac{5\times e}{300}$, e being the charge on an ion in electrostatic units.

It was also shown that the collision theory explained the results obtained by Stoletow with ultra-violet light[*].

Experiments have recently been made by Prof. E. Rutherford and Mr. R. K. McClung[†] to determine the energy required to produce an ion. It was concluded that the amount of energy necessary to ionize a molecule was equal to the energy acquired by an ion in travelling freely between two points differing in potential by 175 volts. If the energy were as large as this there would be no appreciable number of new ions produced by collisions, unless the potential-difference between the electrodes in the gas considerably exceeded 175 volts. In the experiments with Röntgen rays, to which we have referred, and also in Stoletow's experiments with ultra-violet light, large increases in conductivity were obtained when the potential-difference was as low as 60 volts. It would therefore be impossible to explain these experiments by a collision theory if the value of the energy required to ionize a molecule were as great as $\frac{175\times e}{300}$.

In order to avoid this difficulty we might have attributed the increases in conductivity at low pressures to a surface-effect, and have adopted the theory of surface-layers, which was given by Prof. J. J. Thomson[‡] as an explanation of Stoletow's results.

We do not, however, consider that this theory gives a good explanation of the phenomena, since it does not explain the effects obtained by separating the plates. The method employed by Prof. E. Rutherford and Mr. R. K. McClung for finding the energy necessary to produce an ion consisted in determining the total energy of a beam of rays, the rate of absorption of the rays by a gas, and the conductivity of the gas. When the energy absorbed by the gas was thus found, and the corresponding number of ions, the amount of energy required to produce one ion was deduced. We are of opinion that an estimation of the energy required to produce an ion by this method is not wholly trustworthy. There

---

[*] Stoletow, *Journ. de Phys.* ser. 2, vol. ix.

[†] E. Rutherford and R. K. McClung, Phil. Trans. 1901.

[‡] Phil. Mag. Dec. 1899.

seems to be no means of determining how much of the energy of Röntgen rays absorbed by the gas goes to produce ions, and how much is spent in heating the gas. In the case of ordinary light traversing a gas, the energy which is absorbed is converted into heat without the genesis of ions. Prof. Rutherford and Mr. McClung's results cannot therefore be held to invalidate the collision theory.

2. We have found that the phenomena which characterize the conductivity of air at low pressures are also to be met with in hydrogen and carbonic acid gas. The experiments with these gases were made in the same manner as those which were previously made with air. Particular care was taken to make the apparatus air-tight. The pressure of the gas as shown by a McLeod gauge did not alter perceptibly during a week. Some of the experiments were repeated with fresh gas, and the same conductivities were obtained. The method of conducting the experiments has already been described in the previous papers.

When the electric force was reversed a small difference in the conductivity was obtained, which, as has already been explained, arises from the secondary rays emanating from one of the electrodes. The currents were obtained for various electric forces, while the pressure of the gas and the strength of the radiation were kept constant. Several sets of observations were thus made with different pressures. The following tables give the mean currents obtained by reversing the force. The pressure of the gas in millimetres of mercury is given at the head of each column. The difference of potential between the electrodes is given in the first column. The sets of observations given in the different columns are numbered for future reference.

Experiments were made with different strengths of radiation, and it was found that when the pressure was constant the ratios of the currents corresponding to the various forces did not depend upon the intensity of the Röntgen rays. No precautions were therefore taken to have the different sets of observations made with the same intensity of radiation.

In these experiments the current was practically constant for forces in the neighbourhood of 72 volts per centimetre. Experiments 3 and 4 at pressures of 14·5 and 9·5 mms. were not continued for the higher forces in order to avoid taking observations near the sparking potential. The rays used in the experiments at 9·5 mm. pressure were stronger than those used in the other three sets. If we had maintained the same strength of rays throughout, the first numbers in the fourth column would have been very small and difficult to determine accurately. On the other hand, the bulbs which give the strongest rays are as a rule less constant, so that in order to arrive at the same degree of accuracy at the lower pressures the observations had to be repeated several times.

TABLE I.—Currents in Hydrogen between plates 5·3 millimetres apart. The electric force X acting on the gas being given in volts per centimetre.

X.	Pressures.			
	34	23·5	14·5	9·5
72	19·1	11	6·25	12·5
215	...	...	...	13·5
287	...	...	...	16·1
358	...	...	...	21·2
430	...	...	...	31·5
502	...	...	...	53·5
574	...	14	15·7	103
665	...	...	...	...
717	...	...	39·7	234
789	24·7	23·5	80·5	...
843	...	...	191	...
897	31	41	...	...
951	36	58	...	...
	1.	2.	3.	4.

In the above experiments the current which is obtained with a force of 72 volts per centimetre represents the number of ions produced in the gas by the rays. This current remains constant until new ions are produced by collisions. The electric force required to produce an appreciable number of ions diminishes as the pressure is lowered. For pressures lower than 9·5 millimetres, the ions can be detected when the difference of potential between the plates is as low as 38 volts. This is shown by the results given in Table II. (p. 634).

It will be seen from the last set of experiments that the current reaches a constant value. When this stage is reached, the force is large enough to produce new ions at every collision.

Table II.—Currents in Hydrogen.
Plates 5·5 millims. apart.

X.	Pressures.			
	4·7	1·77	·84	·356
69	7	5·43	...	...
138	8·2	9·1	9·2	6·4
207	11	15·5	12·6	...
276	18	25·5	17·2	...
345	32·5	40·5	20·8	...
415	68	66·5	25·5	11·2
484	153	119	31·6	11·2
553	490	...	40	11·2
	5.	6.	7.	8.

The following experiments were made with the plates farther apart in order to obtain experimental results in support of equation (1) (section 3) :—

Table III.—Currents in Hydrogen.
Plates 10·3 millims. apart.

X.	Pressures.		
	14·5	9·5	4·7
37	13·1	24·7	12·5
185	...	27·5	...
221	...	...	32·5
295	15·1	42	109
332	...	...	280
369	...	78·5	
406	20·1	119	
435	...	194	
464	29·8	325	
493	...	670	

At pressures of about 30 millimetres the presence of new ions in hydrogen can easily be detected by a potential-difference of 500 volts between the electrodes 5 millimetres apart. With carbonic acid gas at 30 millimetres pressure, a much higher voltage would be necessary to obtain an appreciable number of new ions.

With plates 5 millimetres apart very large conductivities can be obtained at a pressure of about 4 millimetres. In some cases the conductivities were so great that they could not conveniently be measured by a sensitive electrometer.

When this point was reached, the determinations of current were first made for the smaller forces with a suitable strength of rays. The set of determinations at the fixed pressure was continued for higher forces with the rays reduced to a fraction of their original strength. The first observation in the second series was made with the same force as the last observation in the first series, in order to find the amount by which the rays were reduced. The numbers tabulated are the observed currents multiplied by a factor, and represent the currents which would have been obtained if the rays had been left at the same strength throughout. The last six numbers in experiment 3 in the following table were obtained in this way.

TABLE IV.—Currents in Carbonic Acid Gas.
Plates 5 millimetres apart.

X.	Pressures.						
	18·3	8·8	3·95	1·4	·68	·25	·097
76	140	35	19·6	7·6	5·25	5·3	...
152	141	35·5	...	10·8	8·1	7·8	...
228	...	...	...	...	13·6	...	...
304	...	...	33	30·8	20	...	...
380	...	...	48	54·4	29·3	...	...
456	...	...	75	95·7	40·2	14·1	19·5
532	153	64	126	162	52·9	...	...
608	...	88	216	250	72	16·2	...
684	...	129	420	411	99	...	...
760	198	195	778	660	161	19	...
836	232	302	1460	...	...	...	...
912	286	530	2830	...	...	21·3	23·5
972	337	850	4330	...	...	...	...
1032	395	1290	8300	...	...	...	...
	1.	2.	3.	4.	5.	6.	7.

3. We have found from these observations the number of ions, α, that a single ion generates in going one centimetre in a gas at pressure p under an electric force X. When the temperature is constant α is a function of X and p.

If n_0 negative ions are distributed uniformly between two plates, and a force X perpendicular to the plates acts on them, the total number which reach the positive plate is

$$n = n_0 \frac{\epsilon^{\alpha l} - 1}{\alpha l} \, {}^{*},$$

l being the distance between the plates.

---

* J. S. Townsend, 'Nature,' 9th Aug. 1900.

The equation takes into account the fact that each negative ion generated by collision produces α ions per centimetre as well as the original n_0 ions.

In our experiments the number n_0 is easily found for the larger pressures, being proportional to the smallest current given in the tables. In these cases the force acting on the gas is insufficient to cause new ions to be produced by collisions, and is large enough to collect all the ions generated by the rays on the plates. This is obvious from the fact that the current is practically constant for a large range of forces of the order of 80 volts per centimetre.

The ratio $\frac{n}{n_0}$ for any other force X is the ratio of the current produced by X to the current obtained with the smallest force given in the tables. These ratios can therefore be obtained by experiment, and by means of equation (1) the values of α corresponding to the different values of X and p can be calculated. The values of α obtained by equation (1) for a fixed pressure and force were the same for different values of l.

This point was examined very carefully with air ; and it will be seen from the experiments given in the two previous papers, that when α is constant the effects produced by changing the distance l are in accordance with the formula. At lower pressures, when new ions are generated with forces less than 80 volts per centimetre, the current corresponding to n_0 was found by an application of the theory to which we have already alluded, and of which we shall give a simple explanation.

In section 5 of the paper in the Phil. Mag. to which we have referred, it was shown that an ion travelling freely between two points differing in potential by 4 volts acquires a velocity ten times as great as its mean velocity of agitation. If we assume for the present that the mass of a negative ion is smaller than the mass of a molecule of a gas, then the velocities acquired by the negative ions under small electromotive forces will be so great in comparison with the velocities of agitation of the molecules, that the latter may be considered to be at rest.

In travelling under an electric force through the gas, an ion makes a number of collisions with the molecules, the velocities of impact depending upon the free paths. The circumstances attending the collisions will vary in many ways, and the impacts may be considered to be of various types. On some occasions, when the velocity of the colliding ion is sufficiently great, the effect of the collision will be to produce two new ions, one positive and one negative. Let us consider the effect of increasing the pressure and force in the same proportion on the value of α, which we shall consider to be an unknown function of p and X. When p is increased to $z \times p$, the total number of collisions per centimetre will be increased in the ratio z, and all the free paths will be diminished in the same ratio; a force $z \times \mathrm{X}$ acting along these shortened paths will have the same effect as the force X acting on the longer free paths. Hence the types of collision will not be altered, and the only effect of increasing p and X will be to increase the number of collisions per centimetre of any specified type by the factor z. In particular, those types of impact which produce new ions will be increased by the factor z.

The connexion between the three variables α, p, and X must therefore be such that when p and X are altered in the same proportion, a similar alteration takes place in α. In general, let $\alpha = \phi(\mathrm{X}, p)$; therefore

$$z\alpha = \phi(z\mathrm{X}, zp) \quad \text{and} \quad z\phi(\mathrm{X}, p) = \phi(z\mathrm{X}, zp).$$

Hence ϕ is of the form $pf\left(\frac{\mathrm{X}}{p}\right)$, and

$$\frac{\alpha}{p} = f\left(\frac{\mathrm{X}}{p}\right). \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

This equation does not involve any assumption as to the velocities of the ions before or after impact. If we take the values of α for a fixed pressure and plot a curve having as coordinates $\frac{\mathrm{X}}{p}$ and $\frac{\alpha}{p}$, its equation would be $y = f(x)$, the same for all pressures. In fig. 1 we have marked the positions of the points determining the curves for the various pressures for the smaller values of the variables. The curves in fig. 2 are on a different scale and correspond to the larger values of $\frac{\mathrm{X}}{p}$ and $\frac{\alpha}{p}$. Each point is numbered to indicate the experiment in the tables from which the value of α was determined; the points bearing the same number belong to observations at the same pressure. It is obvious that the curve through one set of points goes through some of the other sets. It was impossible to get points belonging to one set to cover the whole range of the curves, as a discharge takes place in some cases for rather small values of X. The curves overlap sufficiently to justify us in regarding this coincidence as a confirmation of the collision-theory.

The point of contact of the tangent from the origin determines the value of $\frac{X}{p}$, which gives the pressure for which α is a maximum when the force is constant. This result is easily obtained by differentiating α with respect to p in equation 1. The points corresponding to experiments 8 with hydrogen and 6 and 7 with carbonic acid gas are not represented in the diagrams, as the scale would have to be greatly reduced in order to take in points corresponding to such large values of $\frac{X}{p}$.

The determination of the constant n_0 for experiments 6 and 7 with hydrogen and experiments 5 and 6 with carbonic acid were determined from the curves. The value of $\frac{\alpha}{p}$ was found from the curve for the value of $\frac{X}{p}$ corresponding to the smallest current found experimentally. The value of n_0 was then deduced from the equation

$$n = n_0 \frac{\epsilon^{\alpha l} - 1}{\alpha l},$$

and the number so found was used to obtain the values of $\frac{n}{n_0}$ for the larger forces. Instead of having recourse to this method, we might have made a series of experiments with forces smaller than 80 volts per centimetre, and thus have determined n_0. This would have involved a good deal of experimental work, as the electrometer-deflexions were very small. We therefore considered it best to calculate n_0 from the determinations of current with 80 volts per centimetre.

The last experiments serve to determine the maximum values of $\frac{\alpha}{p}$. The value of $\frac{\alpha}{p}$ obtained from experiment 8 with hydrogen was 11·5. In carbonic acid gas, the largest value of $\frac{\alpha}{p}$ obtained from experiment 6 was 23, corresponding to $\frac{X}{p} = 3600$; from experiment 7 it was found that $\frac{\alpha}{p}$ reached the value 29 when $\frac{X}{p}$ was 9120.

4. The results at which we have thus arrived enable us to compare the mean free paths of ions with those of molecules. We have found that a negative ion makes 11·5 collisions per centimetre in hydrogen at 1 mm. pressure, and 29 collisions

per centimetre in carbonic acid gas at the same pressure. The mean free paths at that pressure are therefore the reciprocals of these numbers.

The mean free paths of molecules of gases at 760 mm. pressure and 0° centigrade, as deduced from experiments on viscosity, are* $1{\cdot}78 \times 10^{-5}$ centimetre for hydrogen and $\cdot 65 \times 10^{-5}$ for carbonic acid gas.

At one millimetre pressure and 12° centigrade the mean free paths would be ·0141 and ·0051 for the two gases respectively. (The temperature at which our experiments were made was about 12° centigrade.) The number of collisions per centimetre would consequently be 78 for hydrogen and 196 for carbonic acid gas.

The collisions of a single molecule A with other molecules of the gas arise partly from the motion of the molecule in question, and partly from the general motion of the gas. If the molecule were travelling so fast that the motion of translation of the rest of the gas was inappreciable in comparison with it, the number of collisions per centimetre would be less than the numbers given above in the ratio of 1 to 1·41. (See Maxwell, Phil. Mag. xix. 1860.) We therefore see that a molecule of hydrogen travelling very fast through the other hydrogen molecules would make 55 collisions per centimetre, and a molecule of carbonic acid would make 138 collisions per centimetre in an atmosphere of carbonic acid gas. The corresponding number for air is 91.

From these numbers we find that the mean free path of an ion is longer than the mean free path of a molecule in the following ratios :—

4·8 : 1 in hydrogen,
4·6 : 1 in carbonic acid gas,
4·3 : 1 in air.

If we suppose that the material of a molecule extends to a distance R from the centre, then according to our theory new ions are generated when the colliding ion, moving with a sufficient velocity, comes within a distance R of the centre of the molecule. If the linear dimensions of a negative ion are small compared with those of a molecule, we see from the above ratios that the centres of molecules are about 2R apart when collisions occur. If the above ratios were exactly 4 : 1, we should have concluded that molecules actually touch on collision.

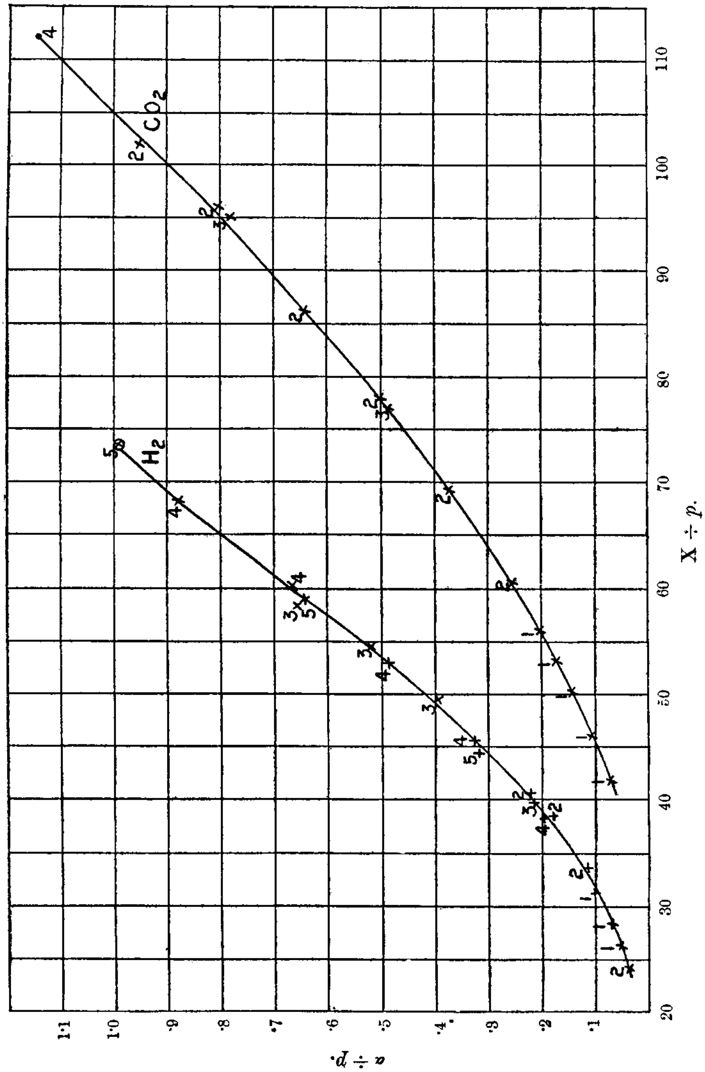
We hope to obtain more accurate determinations of the mean free path of ions by means of other experiments. In

---

* Meyer, 'Kinetic Theory of Gases.'

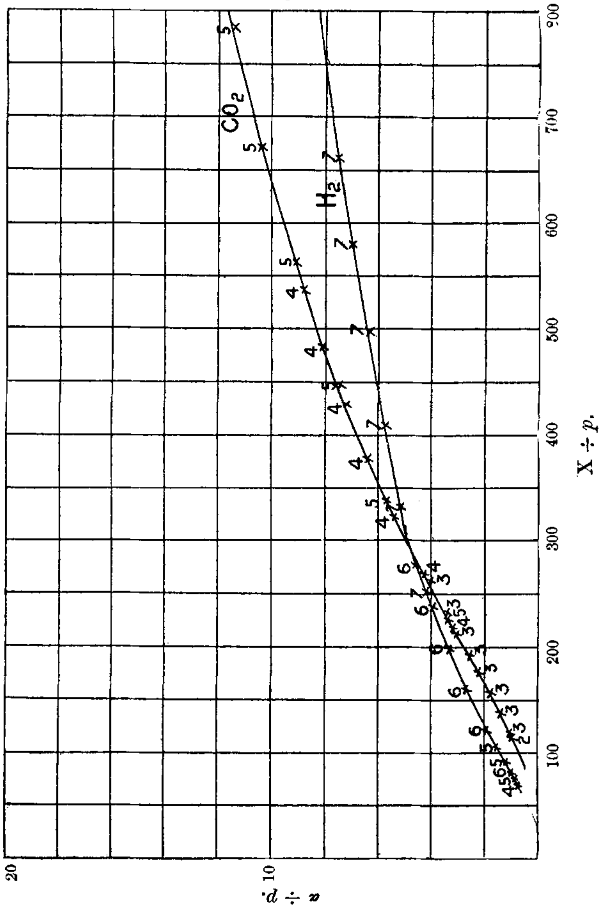
the experiments which we have given for low pressures the electrometer-deflexions were too small to allow of very accurate measurement, but we do not think that experimental errors would account for the differences between the above ratios and the ratio 4:1.

Fig. 1.



From the curves given in figs. 1 and 2 an estimation can be made of the number of new ions generated by a single ion moving with a fixed velocity through the gas. For this purpose it would be necessary to find the equations of the curves ; but we do not intend to investigate this point until

Fig. 2.



some other experiments are made at lower pressures, which may give the larger values of $\frac{\alpha}{p}$ more accurately.

For values of $\frac{X}{p}$ less than 800, the curve for carbonic acid almost coincides with the curve for air. We may conclude that for small velocities of the colliding ion the ratio of the number of new ions generated to the total number of collisions is nearly the same for carbonic acid as for air.

Consequently, the energy necessary to ionize a molecule of carbonic acid would be of the same order as the energy necessary to ionize a molecule of air. It would appear from the relative shapes of the curves for hydrogen and carbonic acid, that it requires less energy to ionize hydrogen than air or carbonic acid.

Experiments are at present being made on the conductivity between electrodes of various shapes. These investigations are important, as they enable us to find out whether the increased conductivity is due to the motion of the positive or negative ions. The results obtained with air led to the conclusion that the genesis of ions is to be attributed to the motion of the negative ions, and that apparently the positive ions take no part in producing new ions.

The experiments described in this paper were made at the University Observatory, Oxford; and we must express our thanks to Professor Turner for having placed some of his rooms at our disposal.

LXIV. *The Hysteresis of Nickel and Cobalt in a Rotating Magnetic Field.* *By* R. Beattie, *B.Sc.* *

SO far, the few who have worked at the subject of magnetic hysteresis in a rotating magnetic field have been content to experiment with iron and steel, without seeking to extend their investigations to other magnetic substances exhibiting hysteresis. To repair to some extent this omission, the experiments about to be described were made on the hysteresis in a rotating magnetic field of nickel and cobalt, the two metals which, next to iron, most deserve attention.

The method employed was similar to that previously used by the writer in conjunction with Mr. R. C. Clinker †. A cylindrical wooden box, B (fig. 1), with a tightly fitting lid, L, was suspended by a steel wire, W, between the poles, N, S, of an electromagnet which could be rotated round the vertical axis OW. A brass pin driven axially into the lid of the box passed loosely through a hole in a fixed support at O, and served to prevent lateral motion. The material to be examined, in the form of a thin circular disk seen edgeways at D, was placed in the box and held in position by the pressure against it of the lid.

When the magnet was rotated slowly so as to avoid the production of eddy-currents, the suspended system experienced

---

* Communicated by the Author.

† See 'The Electrician,' Oct. 2nd, 1896.