



XLII. On the thermic and optical behaviour of gases under the influence of the electric discharge

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for the stream-line $\int ds$,

$$p = \rho \left\{ r \frac{ds}{dr} - s - V - \frac{1}{2} q^2 \right\} + C.$$

It does not seem to me to be possible in this general case to determine the forms of the stream-lines, or the resistance which the friction of the fluid opposes to the motion of the sphere. In the case where the motion is symmetrical to the axis of x , the resistance has been determined by Lamb ('Treatise on the Motion of Fluids,' page 126) by means of the dissipation-function; that process would scarcely be applicable to such a complicated case as the one in hand. I do not see that any other results of importance can be obtained from further study of this problem, unless, indeed, the velocities u, v, w can be given in some other form than that of an infinite series.

Washington, June 12, 1880.

XLII. On the Thermic and Optical Behaviour of Gases under the Influence of the Electric Discharge. By E. WIEDEMANN*.

[Plate IX.]

1. Introduction.

IN two previous experimental investigations (Wied. *Ann.* v. p. 500, 1878, vi. p. 298, 1879) I have examined the luminosity of gases under the influence of the electric discharge. The result of the first investigation was, that when a mixture of two gases is exposed to the electric discharge, of which the one is a metallic vapour and the other nitrogen or hydrogen, the lines of the metallic vapour are seen in the spectrum, while those of the other gas remain invisible; so that the propagation of the electricity is due entirely to the metallic vapour. The discharge in it is entirely discontinuous. The same result has been recently obtained by H. W. Vogel†, by photographic methods.

The second investigation showed that the temperature of the gas illuminating a Geissler's tube may be below 100°.

This last result has been recently confirmed by Hasselberg‡. Hittorf also has shown, but without accurate measurements, that the same conclusion is throughout in agreement with the phenomena.

* Translated from Wiedemann's *Annalen*, No. 6, 1880, with additions and corrections by the Author.

† H. W. Vogel, *Beibl.* iv. p. 125, 1880.

‡ Hasselberg, *Beibl.* iv. p. 132, 1880.

It has been shown by these investigations that the usual theory, which refers the emission of light by a gas under the influence of the electric discharge to an increase of temperature up to the point of incandescence, is no longer tenable, and that this point requires fresh experimental examination.

Spectrum analysis, so far as it employs the electric discharge for the production of spectra, has to examine the question of the dependence of the spectra produced on the quantity of electricity transmitted. For this purpose we must pass discharges of given quantities of electricity through a given gas of definite pressure, observe the spectral phenomena, and at the same time determine the magnitude of the quantities of energy or of heat given off by the discharges; for these alone can furnish a measure of the resultant phenomena of motion in the gas. As we cannot deal with a single discharge, we must determine the number of discharges which correspond to a given quantity of electricity. It is absolutely necessary that the gas should return to its original condition before the entrance of each new discharge, so that any previous heating may have ceased to be sensible, and especially that the gas should have become dark again.

The present research is intended to be a first contribution to the solution of this unusually complicated question.

In the first place I have thoroughly examined the thermic relationships of the discharge of the induction-machine under different conditions, and in doing so have observed a peculiar behaviour of positive and negative electricity. Then follow experiments to determine numerically the conditions under which the transformation of the band spectrum into the line spectrum occurs in the case of hydrogen, as well as some contributions to our knowledge of the discharge taking place from the negative electrode in highly rarefied gases; then follows a discussion of the employment in spectrum analysis of the other sources of electricity—induction coils, large galvanic batteries, and Leyden jars, and of the continuous and discontinuous discharge in gases.

Theoretical considerations on the discharge in gases and on the nature of spectra form the conclusion. There are particular subjects more briefly treated in this first paper, which shall be more fully investigated later.

2. *Apparatus.*

In correspondence with the problems for investigation, the apparatus employed consisted of three parts:—(1) the source of the electricity, and the arrangements to measure the intensity of the current; (2) the discharge-tube and its electrodes,

the calorimeters, and arrangements for exhausting ; (3) the arrangements for measuring the number of discharges.

1. The source of electricity employed was usually a Töpler's* electrical machine with 20 revolving disks, which was driven by a small Schmidt's water motor. In order to have a constant stream of water, most of the experiments were performed at night. In this way a constant velocity of revolution, and a constant deflection of the galvanometer included in the circuit, could be maintained for hours together.

The machine has a few drawbacks, in consequence of the powerful evolution of electricity. First, it attracts the dust very largely, the disks become dirty, and the production of electricity diminishes or even ceases altogether ; moreover large quantities of ozone are produced. Both of these defects are remedied pretty well by covering the machine over with a wooden cover with glass sides, and placing vessels of linseed-oil under it† After use for several weeks the disks become dirty in spite of all precautions, and must then be washed, either with water or with alcohol, by means of a sponge. Simple brushing is of no use.

In damp weather, and when the disks have become dirty, the direction of the current frequently becomes reversed. This may be prevented tolerably completely by warming the machine. A further peculiarity of this machine is that almost always when it has been allowed to run for a time, then stopped, and again put into action, the direction of the current is the opposite to that obtained at first. This was often very convenient in my experiments, since the electrode connected with the machine was generally wanted to serve first as a positive, and then as a negative electrode.

In order to introduce sparks of known length into the circuit, a spark-micrometer with spheres of 33 millims. diameter was employed. If no spark was to be introduced, the horizontal adjustable brass bars which carry the spheres were connected by a brass stirrup.

The reversal of connexions was always made on the machine itself, copper wires covered with gutta-percha being used for the connexions. One pole of the machine was always connected direct to earth, the other connected to the one insulated electrode of the discharge-tube, the other electrode of which was connected with the earth through the galvanometer.

* Töpler, *Berl. Ber.* 1879, p. 950 *et seqq.*; *Beibl.* iv. p. 398, 1880.

† The use of turpentine is not to be recommended, as it gradually forms a sticky substance on the disks, which destroys the varnish. This sticky substance probably consists of oxidation-products of turpentine, as the disks themselves may be washed with turpentine without damage.

The galvanometer was a Wiedemann's reflecting galvanometer of moderate strength, with coils of gutta-percha covered copper wire. The distance between the telescope and scales was 189 centims.

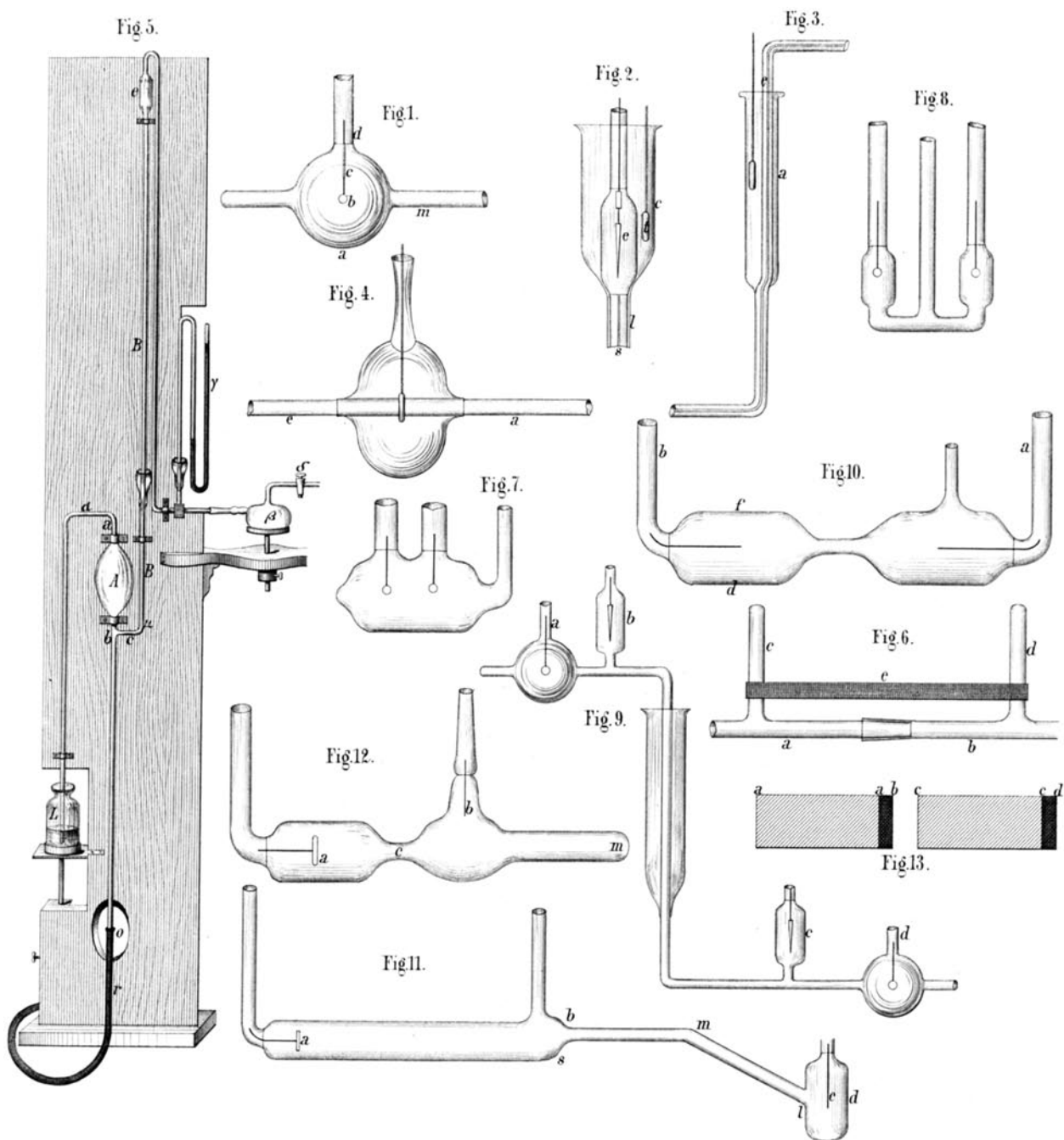
2. The discharge-tube includes the space containing the two electrodes and the part of the tube uniting them. This either was altogether absent so that the electrodes were immediately opposed to each other, or consisted of tubes of various shapes. But care was taken to avoid any shape in which two portions of the tube would be parallel to each other, as, for example, in a U-tube. In this case induction-phenomena of a very disturbing character occur.

The electrodes were made of aluminium in all definitive experiments, since this metal alone is not subject to dissipation by the discharge. They were either balls of 5 millims. diameter, or points 3 millims. thick at the base and 12 millims. long.

In conducting the electricity to the electrodes, in order to avoid as much as possible the scattering by points, and to ensure good contact, the following arrangement was adopted (Plate IX. fig. 1):—*a* is a glass-bulb, *b* the electrode, *c* a platinum wire screwed into it and covered with glass, *d* a glass tube joined to *a* by fusion, into which the wire *c* projects. The tube *d* can be filled with mercury, into which the wire conveying the electricity plunges. The discharge-tube is melted on at *m*. A similar arrangement is to be recommended for Geissler's tubes, which are much used, as they are easily broken by the pulling of the connecting wires at the projecting platinum wires.

If the heating was to be determined in the whole space between the two electrodes, the whole apparatus was plunged in a trough-shaped glass calorimeter of about 50 cubic centims. capacity. The arrangement shown in Plate IX. fig. 2 was employed to determine the heating at one electrode. *e* is the electrode with the portion of the tube surrounding it, *t* the thermometer, *c* the calorimeter with a tube-shaped portion *l* in which a glass tube *s* melted on to the discharge-tube was cemented. The part of the tube *s* next the electrode was constructed out of a capillary tube, in order as much as possible to prevent convection of heat by currents.

In order to determine the heating in the tube, the arrangements figs. 3 & 4 were employed. In the first, as in the experiment with the electrode, a portion *e* of the discharge-tube is carried vertically through the tube-shaped calorimeter *a*, and is bent horizontally above and below the calorimeter; in the second the discharge-tube *e* is horizontal, and the calorimeter *a* is pushed over it. The last arrangement must be



employed if the heating is to be measured at points lying near each other of tubes of varying width, or if the thermic action is to be observed at one part of a tube and close to the spectroscopic phenomena.

The calorimetric fluid employed was turpentine. It has a small specific heat when equal volumes are compared, and is a good insulator, a point of special importance when wide tubes are employed. The calorimeters themselves were made of glass, after preliminary experiments with brass calorimeters had shown that the fraction of the energy of the gas lost by radiation was excessively small.

The calorimeters with the discharge-tubes in them were placed in a cylindrical metallic vessel with double walls, being introduced either simply from above, or through an opening in the bottom. In this way irregular currents of air &c. were excluded, and, besides, a trustworthy correction for loss and gain by radiation during the experiment was rendered possible.

With the horizontal tubes similar wooden boxes with openings at the sides were employed. The gas to be experimented upon was carefully dried and admitted into the completely exhausted tube. Only air and hydrogen were employed for the most part.

As air-pump, a Töpler's * pump was employed.

As its arrangement is not widely known, it may be briefly described, with a few small changes which I have made in it. A wide oval vessel A (Plate IX. fig. 5), about 15 centims. high and 10 centims. wide, has glass tubes melted on to it above and below. The upper one, *a*, is bent round immediately above the globe. Its diameter is about 2 millims.; and its length, reckoned from the highest point *a*, is somewhat more than the greatest usual barometric height. Its lower end plunges into a vessel L containing mercury: it is highly advisable to cut the end of the capillary tube in L obliquely. The lower tube *b* is about 1 centim. in diameter and 88 centims. long. About 6 centims. below its junction with the bulb, a side-tube B is attached, which is bent at right angles, and ascends to a height of about 760 millims. above *a*, where (at *e*) it is expanded into a wider cylinder for a length of about 8 centims., and is then bent down again; at the level of the bulb it is again bent at right angles, forming a horizontal portion at *f*, to which a vessel *β*, containing phosphoric anhydride, and a manometer *γ* are attached by grinding. A tap *δ* enables the whole pump to be shut off from the atmosphere. To facilitate the cleaning of the pump, the long tube B is made

* Töpler, *Dingl. Journ.* clxiii. pp. 426-432, 1862.

in two portions connected by a ground joint, the form of which is that recommended by Gimmingham*. The lower portion of the tube is provided with a funnel-shaped portion which is filled with mercury; so that if the joint becomes a little loose it is not necessary to stop working.

The lower end of the tube *b* is connected at *o* with one end of an india-rubber tube, the other end of which communicates with a vessel of mercury *O*, which can be raised or lowered by a pulley not shown in the drawing.

The action of the pump is extremely simple. The vessel *O* is first raised and mercury allowed to enter the bulb *A*, by which the communication between *A* and *B* is interrupted. The air is driven out of *A*, and escapes through the mercury in *L*. When a certain quantity has escaped, the vessel *O* is lowered. The air is now drawn out of *B* and the parts of the apparatus communicating with it, into the bulb *A*. This takes place in a somewhat violent manner, since large bubbles of air enter the exhausted space above *A* and throw the mercury about; so that too much air must not be driven out of *A* at first†. When the exhaustion has advanced somewhat, another precaution is necessary, since if the flask were raised too high the mercury might be driven violently into *A*, and might possibly cause fracture, a result less to be apprehended if the tube *B* is of sufficient width. The pump has the great advantage that it is constructed entirely without taps, it works very easily and surely, and gives a very good exhaustion. Tubes may easily be prepared by its means which show the phenomena discovered by Hittorf‡ and recently further described by Crookes§.

The tubes to be exhausted were connected with the pump by means of a joint on the further side of the tap δ . In order to make connexion of the different pieces of apparatus with the pump, glass tubes of greater or less length must be employed connected with each other by joints. In order to make a secure joint, not liable to be affected by the shaking which occurred in pumping, the two parts *a* and *b* of the joint (Plate IX. fig. 6) were connected by an india-rubber band *e* passed round side-tubes *c* and *d*. Any accidental loosening was thus immediately remedied, and it was unnecessary to cover the joint with wax||.

* Gimmingham, *Beibl.* i. p. 175, 1877.

† For this reason, the pump employed in the physical laboratory at Berlin has been modified so that the points *Q* and δ are connected by another tube. The shocks are therefore much less powerful.

‡ Hittorf, *Pogg. Ann.* cxxxvi. p. 8, 1869.

§ Crookes, *Beibl.* iii. p. 527, 1879.

|| The whole of the glass apparatus employed was manufactured in an admirable manner by Mr. Götze, glass-blower in Leipsic.

3. For the determination of the number of discharges the very accurate heliometric method employed by Wiedemann and Rühlmann* could not be used, on account of the great number of discharges. It was difficult to attach a mirror to the axis of the machine itself, in consequence of the mode of its construction; and it made too few revolutions. In particular cases satisfactory results were obtained by a self-registering method. The end of the wire coming from the galvanometer usually connected to earth, was placed opposite to a cylinder covered with tin-foil and blackened; a tuning-fork was also made to record its vibrations on the blackened surface. The lamp-black is removed at each discharge. But this method is only applicable when the interpolation of a spark in the circuit is of no consequence.

The following method has been found satisfactory:—An ordinary Geissler's tube was placed in front of and parallel to the discharge-tube A, which was to be investigated thermically or spectroscopically. Both were then covered with paper so that the covered portion of the one corresponded to the uncovered portion of the other; and both were then observed in a revolving mirror. The discharge of a small induction-coil was passed through the Geissler's tube, the primary current of which was made and broken 100 times a second by means of a self-acting electromagnetic tuning-fork. The reflection in the revolving mirror showed a series of bright lines of light, at distances corresponding to hundredths of a second. By observing how many discharges of the tube A lay between two of the Geissler tubes, the number of discharges in $\frac{1}{100}$ of a second, and consequently the number per second, was ascertained. It was possible to make a tolerably accurate estimate when there were not more than 4 or 6 discharges in the $\frac{1}{100}$ of a second. But when the machine was in more vigorous action, as was always necessary when thermic measurements were to be made, the number was much greater (up to 60 times).

The number of discharges could, however, be obtained in this case by allowing the machine to run more slowly, and observing the deflection of the galvanometer which corresponded to a given number of discharges. In order to find the number of discharges during the measurements, it was only necessary to multiply the number observed in the first case by the ratio of the galvanometer-reading in the two cases. It is true that in doing so we make the assumption that the number of discharges is proportional to the current-strength; but this assumption is justified if between two

* Wiedemann and Rühlmann, *Pogg. Ann.* cxlv. p. 242, 1872

discharges the gas returns to its original condition—which is the case in our experiments, as no phosphorescence of the gas was observed.

This method, since it is one of estimation only, cannot of course give so accurate a result as the heliometric method; but it is sufficient for such qualitative-quantitative experiments as the present.

The measurements were made and calculated in the following way. The electrical machine was first set in action by turning on the water, the temperature of the thermometer in the calorimeter read off, and the galvanometer observed. The electrodes of the machine were then connected by a brass rod. After three to five minutes the temperature was read again, the brass rod removed by means of a cord passing over pulleys, and the current allowed to pass through the discharge-tube; at the same time the galvanometer was observed. After an interval of from one to eight minutes, the machine was again closed, and the thermometer observed from minute to minute, and read off at the end of three minutes, when the movement of the temperature in the calorimeter had become uniform. The experiment was allowed to last so long that a change of temperature of two or more degrees resulted; only in special cases, in which the heating in the whole tube, or that at the positive pole at very low pressures, was to be determined, was the change of temperature less.

After the experiment, the machine was stopped, and the calorimeter allowed to cool by radiation, so that its temperature might not alter too much. The measurements before and after the passage of the electricity enabled corrections to be applied to the observed rise of temperature, according to well-known methods. The correction could not be applied for the conduction of heat from the parts of the tube not surrounded by the calorimeter. Each experiment occupied at least half an hour.

The galvanometer-deflections were not reduced to angles, since for the degree of accuracy reached at present the error so caused may be neglected.

The heating is proportional, during varied action of the machine, to the deflection of the galvanometer, as my father's experiments and control-experiments of my own have shown. In fact, since the discharges are entirely discontinuous, and the intensity of each single discharge is the same, when n times as much electricity passes through there will be n times as many discharges, and consequently n times as much heat produced.

I desire to express my best thanks to Mr. Roth for the assistance he has rendered me in the measurements.

3. *General Measurements.*

Three groups of observations were made, in order to obtain a general idea of the way in which the thermic phenomena of the tube depended on the pressure.

1. The heating in the whole of a discharge-tube was determined.

2. The heating in a capillary tube was investigated, and experiments made on the influence of the width of the tube and of the shape of the electrodes.

3. The heating at an electrode was determined when the electrode was positive and when it was negative, and also both when it was connected with the source of electricity and when it was put to earth.

In particular cases the number of discharges was determined, and the measurements made with hydrogen-vacua, and then repeated with air-vacua. Further, air-sparks were introduced into the circuit, always between the machine and the discharge-tube.

Further experiments were made on the influence of the condensation of electricity on the walls of the discharge-tube, using mercury instead of turpentine as calorimetric fluid.

The arrangement of the tables is always the same. The first column, headed p , gives the pressure. At very low pressures which could not be read on the manometer the degree of the exhaustion is denoted by x or xx .

The following columns give the corrected amounts of heating of the calorimeter in one minute, calculated for an intensity of current corresponding to a galvanometer-deflection of 100 millims.

+ or - in the heading of a column indicates that the positive or negative electrode was connected with the machine, the other pole being put to earth.

The number of discharges given corresponds to a current giving a deflection of 10 millims.

I. *The heating in the whole tube* was determined by means of three different forms of apparatus.

The first consisted of a glass vessel, I, of the form shown in Plate IX. fig. 7. The distance of the electrodes was 16 millims., the water-equivalent of the whole apparatus 27.5 grammes.

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Air.			Hydrogen.		
p	+	-	p	+	-
680	1.15	1.02	680	1.03	0.90
360	0.80	0.55	350	0.56	0.58
14.9	0.40	—	126	0.27	0.25
32.4	0.16	0.18	34.6	0.11	0.10
11	0.06	0.066	11.7	0.055	0.06
3.7	0.056	0.065	3.9	0.060	0.06
0.4	0.065	0.081	1.5	0.063	0.062
x	1.25	1.01	0.1	0.26	0.33
			x	0.85	0.50

The numbers show that, as the pressure diminishes, the quantities of heat evolved diminish to a minimum and then rise again. With hydrogen the heating is generally less than with air.

Hydrogen and air show with alteration of pressure the same change in the number of discharges. In general this was less in air than in hydrogen, and larger when the positive electrode was put to earth than when the negative electrode was so connected.

For example, hydrogen gave for the number of discharges:—

$p=660, 45$; $p=365, 75$; $p=126, 180$; $p=x, 50$.

At pressures from 90 millims. to $\frac{1}{2}$ millim. the discharges were not to be separated, since a sufficient velocity of rotation could not be given to the mirror. Below the pressure of $\frac{1}{2}$ millim. the apparently continuous band of light resolved itself into separate luminous strips, the beginning and end of which were especially bright; but these strips also were resolved into single discharges as the exhaustion was continued.

The number of discharges increases therefore as the pressure diminishes, and then decreases again.

The measurement of the number of discharges is rendered very difficult at medium pressures by the extremely feeble intensity of the light, especially when the negative electrode is insulated. The colour of the conical discharge radiating from the positive electrode is greenish-white in hydrogen at a pressure of 365 millims.; a red spot appears at the positive electrode, at the point of the cone. When the exhaustion was carried far, the dark space round the negative electrode expanded as far as the positive pole, which it intersected in a circle. No positive discharge issued from within this space, which remained perfectly dark.

An increase in the number of discharges corresponds to a decrease in the quantity of electricity in each discharge, and consequently to a decrease in the potential before each discharge, if the electrodes remain of the same shape; but inas-

much as a decrease of the quantity of heat produced must result, the results found for the number of discharges and the quantity of heat produced are in agreement.

If the quantity of electricity e of potential V sinks to potential 0, the quantity of heat produced is proportional to eV . If, instead of one discharge of quantity e , n such discharges occur each of quantity $\frac{e}{n}$, then these sink from potential $\frac{V}{n}$ to potential 0. The quantities of heat produced are proportional to, $n \cdot \frac{V}{n} \cdot \frac{e}{n} = \frac{1}{n} Ve$, and therefore only $\frac{1}{n}$ as great as in the first case.

Warren De La Rue and Hugo Müller* have also found a minimum value for the potential necessary to discharge with decreasing pressure, but only with air. The same conclusion may be drawn from the experiments of Morren and De La Rive† and others. Thus, for example, De La Rive found a maximum for the intensity of the induced current when the discharges from an inductorium were passed through a gas at continually decreasing pressure, and hence concluded that the resistance was a minimum. In the same way we may conclude there is a minimum of potential necessary to discharge—since the less electricity discharges itself backwards through the coil, and consequently the more passes through the gas, the smaller does the potential at the ends of the secondary coil become.

An exactly similar series of experiments was made with electrodes at a distance of only $1\frac{1}{2}$ millim. from each other in air. The water-equivalent was 28 gr. The following values were obtained:—

p	+	—
673	0.17	0.28
63	0.090	0.083
1.7	0.107	0.071
0.6	0.13	0.13
∞	0.94	0.80

These numbers show the same result as the first series: *the heating at first decreases slowly, and then increases very rapidly as the pressure diminishes.*

The number of discharges was, for $p=0$, 90; for $p=63$ they were not to be counted; for $p=700$, about 250; so that here again we have a maximum.

* Warren De La Rue and Hugo Müller, Proc. Roy. Soc. xxix. p. 281 (1879).

† Morren and De La Rive, Wied. Galv. [2] ii. p. 316 &c.

That the amounts of heat here, especially at high pressures, are so much smaller than in the first case, is to be explained by the fact that the potential necessary for each discharge is here so much smaller than before, as the electrodes stood so much nearer to each other. The minimum appears here at a higher pressure than in the first case, since the decrease of heating which occurs in the spark and at the positive electrode is earlier compensated by the increase which takes place at the negative pole.

A third series of experiments is occupied with the determination of the total heating in hydrogen when between two ball-shaped electrodes is interposed a capillary tube about 1 millim. wide and 30 millims. long (Plate IX. fig. 8). In the first series the apparatus broke, in consequence of the high potential necessary when the pressure was very small, since the electrodes were somewhat too close together. The two series of observations are therefore not directly comparable. The first series gave:—

p	+	—
184	3.10	2.76
15	0.61	0.62
0.4	0.43	0.45

The second series, in which the water-equivalent was perceptibly higher, gave:—

p	+	—
1.3	0.134	0.15
x	0.73	0.48

Here also we see that the total heating at first diminishes with decreasing pressure (first series) and then increases again (second series).

It must remain for further experiments to decide in this case how positive and negative electricity behave, and what part is taken by the heating at the positive pole, and at the negative pole, and in the tube, and how these conditions alter when the length of the interposed capillary tube varies.

It seemed to be of interest to vary the quantity of electricity in each discharge, not only by change of pressure, but also by interpolation of sparks—and the more so since in the later experiments and in the study of the spectral phenomena, when the evolution of heat within the capillary tube was determined, this method became of manifold application.

With the apparatus I, in which only the quantity of turpen-

tine was somewhat different, the following amounts of heat were obtained for the positive discharge at the pressures p , when the spark-lengths 0 and 10 millims. were interposed:—

p	x	0.6	4.3	12.8	25.6	35	90	166.4	567	759
0	0.253	0.082	0.072	0.088	0.10	0.16	0.30	0.52	1.17	1.30
10	1.34	0.84	0.52	0.56	0.69	0.80	0.81	1.10	1.77	2.2

The number of discharges when no spark was interposed was

p ...	730	400	160	90	30
z ...	20	40	120	220	about 700

increasing now up to very low pressures and then decreasing.

With a spark-length of 10 millims. interposed the number z was about 13 for all pressures.

A comparison of these numbers shows that the amounts of heat corresponding to the same quantity of electricity transmitted are by no means inversely proportional to the number of discharges. Thus the number of discharges z_0 and z_{10} , and the quantities of heat w_0 and w_{10} , with the spark-distances 0 and 10 millims., and at the pressures p , are somewhat as follows:—

p	$z_0 : z_{10}$	$w_0 : w_{10}$
180	10 : 1	1 : 2
90	17 : 1	1 : 3
30	50 : 1	1 : 6

This may also be seen in another way. Whilst the amounts of heat between 759 and 4.3 millims. pressure without spark sink from 1.3 to 0.072, or to $\frac{1}{15}$, with spark interposed they sink only from 2.2 to 0.5—that is, only to $\frac{1}{4}$.

We may conclude from these facts that, when a spark is included in the circuit, the discharge of the whole electricity takes place at a lower potential than that which would result if the whole quantity of electricity passing in each single discharge were accumulated upon the electrodes. For then, if the number of discharges were increased ten times, the heat produced would become one tenth as great. The flow of electricity cannot, however, take place completely at the potential which is necessary for the commencement of the discharge, since then the heating would be independent of the number of discharges. We must rather assume that the discharge takes place at an intermediate potential, inasmuch as the electricity cannot flow off through the gas as fast as it flows in through the spark-length, and consequently becomes stored up.

A series of researches on the laws of the total heating of gases at high pressures when traversed by the discharge of a Leyden battery or of an induction-coil has recently been made by Villari*. They are in complete agreement with the consequences which follow from mechanical principles, as is the case with the problems treated by me. When, for example, Villari finds that the heating in sparks between two spheres is nearly proportional to the spark-length, that follows immediately from the law established by Macfarlane and others†, that the difference of potential necessary to the commencement of discharge between two spheres increases nearly proportionally to their distance apart, at any rate for short sparks. The same results were to be expected from the laws previously established connecting striking-distance with quantity of electricity discharged. Villari, however, is not able in his experiments to distinguish between the heating at the electrodes and in the spark itself, which corresponds to the capillary portion of a Geissler's tube.

II. Further, the amounts of heating produced in the tubes connecting the electrodes were determined when a spark of 10 millims. was included in the circuit, and when no spark was included. The width of the capillary tube (arrangement of fig. 3) was 0.4 millim.

The tables give the results obtained in a series of measurements.

Air.					Hydrogen.				
p	$F=0$	$F=10$	$F=0$	$F=10$	p	$F=0$	$F=10$	$F=0$	$F=10$
11.5	2.04	1.7	2.4	1.90	22	3.76	3.16a	3.45	3.2a
4.2	—	1.48	1.40	1.46	12.2	2.06	1.5	2.00	1.75
0.4	0.81	1.42	0.82	1.21	4.4	1.02	1.3	1.08	1.21
					0.6	0.49	1.16	0.50	0.92

a The spark measured only 5 millims.

To these observations belong determinations of the number of discharges. When the spark-length was 10 millims., the number reduced to a galvanometer-deflection 10 was always about 12 to 15 a second, whatever the pressure in the tube. The number decreased a little, it is true, with increase of pressure, within the limits of observation. It is otherwise when no spark is included in the circuit.

The results are given in the tables.

* Villari, *Beibl.* iii. p. 713, and iv. p. 404.

† Macfarlane, *Beibl.* iii. p. 429 (1879).

Air.			Hydrogen.		
p	+	—	p	+	—
17.5	40	80	24.4	35	55
6.2	75	90	8.2	100	86
2.4	100	90	3.1	80	101
1.1	75	110	0.8	90	350
0.3	40	180	x	55	170
x	60	140	xx	29	130

A second series with a somewhat wider capillary tube gave the following amounts of heat :—

Air.					Hydrogen.				
p	+		=		p	+		—	
	$F=0$	$F=10$	$F=0$	$F=10$		$F=0$	$F=10$	$F=0$	$F=10$
11	2.01	1.87	2.16	2.00	12.6	2.33	2.12	2.50	2.4
4.0	1.06	1.47	1.36	1.40	4.7	1.22	1.50	1.20	1.42
0.5	0.51	1.01	0.42	0.97	0.7	0.40	0.83	0.43	0.64
x	0.25	0.83	0.37	0.73	x	0.31	0.80	0.27	0.60

The corresponding number of discharges are :—

Air.			Hydrogen.		
p	+	—	p	+	—
14.0	66	33	13	80	90
5.9	83	60	5.1	90	90
2.2	150	110	1.1	90	120
0.8	110	190	0.3	60	280
0.3	50	330	x	60	90
x	50	200			
xx	30	90			

Here also the number of discharges was from 12 to 13 when a spark 10 millims. long was interposed.

With reference to the great differences of the number of discharges with and without interposed spark, the following general conclusion may be drawn from the observations :—

(1) *The heating in capillary tubes at pressures above 1 milim. is almost independent of the quantity of electricity passing in each discharge, and nearly proportional to the whole quantity of electricity which passes, always provided that no Leyden jar or condenser is included in the circuit.*

The deviations from this law at pressures under 1 milim., when the heating increases considerably when a spark is included, require further examination.

(2) *The heating produced by the positive discharge and by*

the negative discharge is nearly the same, in spite of the difference in the number of the discharges.

At a pressure of 0.7 millim., for example, the proportion of the number of positive discharges to that of the negative discharges is about as 1 : 4, the quantities of heat produced are about 0.40 and 0.43.

With decreasing pressure the heating diminishes rapidly, without passing through a minimum corresponding to the maximum number of discharges. A slight increase, however, was observed in some of the other tubes.

A special series of experiments had for their object to decide whether the heating in a capillary tube is dependent on the form of the electrodes or not. The arrangement of fig. 9 was employed. The measurements were made at several pressures, and with either positive or negative electrode put to earth, but without any spark included. The conducting-wires from the machine were plunged in *c* or *d*, the wires leading to the galvanometer in *a* or *b*.

The following table gives the amounts of heat produced :—

<i>p</i>	Spheres.		Points.	
	+	—	+	—
9.7	2.2	2.4	2.2	2.2
3.5	1.18	—	1.17	—
0.4	0.42	0.45	0.44	0.44
<i>x</i>	0.50	0.24	0.33	0.24

The amounts of heat, then, are in general nearly independent of the form of the electrodes.

This result agrees with that found when sparks are included.

Moreover the number of discharges alters very little with the form of the electrodes. Since somewhat long and wide portions of tube intervened between the electrodes and the capillary tube, the discharges were somewhat irregular, as they usually are in similar cases.

G. Wiedemann* has shown by experiments with Holtz's machine that the quantities of heat produced in a wide tube and in a narrow tube per unit length are always equal—a result which has since been confirmed by Naccari and Bellati† by use of the induction-coil.

I have, in the next place, made a further series of experiments with different thick-walled capillary tubes.

* Wiedemann, Pogg. Ann. clviii. p. 35, 1876.

† Naccari and Bellati, Atti dell' Ist. Ven. (5), vi. 1878; Beibl. ii. p. 720.

They were joined to each other by fusion, placed horizontally, and calorimeters pushed over them as shown in fig. 4. The narrower tube had a diameter of 0.6 millim., and the portion surrounded by the calorimeter a length of 42 millims.; for the wider tube the corresponding numbers were 2 millims. and 45 millims. The ratio of the sectional areas of the tubes was therefore 1 : 10; the water-equivalent was nearly the same for the two calorimeters.

The following table gives, in the usual way, the amounts of heat observed in the two calorimeters, which were always simultaneously observed :—

Hydrogen.					Air.				
p	$F=0$		$F=10$		p	$F=0$		$F=10$	
	wide	narrow	wide	narrow					
32.8	0.85	0.96	—	—	21.5	0.74	0.65	0.82	0.60
21	0.66	0.88	0.66	0.77	8.1	0.34	0.44	—	0.47
8.4	0.30	0.48	0.38	0.44	3.4	0.18	0.24	0.36	0.33
3.2	0.15	0.20	0.28	0.32					
0.6	0.06	0.17	0.12	0.24					
x	0.07	0.24	0.19	0.32					

The tables show (1) that, in agreement with the earlier results, *the difference of heating with and without spark is not very great*, both in wide and in narrow tubes; that, further, *the amounts of heat produced in the tubes of different width, with the same length of spark, do not differ very greatly*. In both cases, however, at low pressures there appear considerable deviations from these laws. In these, as in the former observations, the amount of heat increases perceptibly when the spark is included; and, moreover, the heating in the narrow tube is decidedly greater than in the wide one. Further insight into these relationships can only be obtained by additional experiments.

A further series of experiments was occupied with the behaviour of still wider tubes.

Two tubes, a capillary tube and a wider tube, of diameters 0.5 millim. and 4 millims., and thickness of glass 2 millims. and 1 millim., were united and included in the circuit, the calorimeters filled with turpentine, and the amounts of heat determined. The values obtained are given in the following tables. Those under A relate to the case in which the electrode next the capillary tube was put to earth, those under B to that in which the electrode next the wide tube was in connexion with the earth. The signs + and — mark the

nature of the electricity passing through, F the length of spark included; d , md , b , and mb denote that the wide tube was dark, moderately dark, bright, or moderately bright.

A.					B.				
p	F		Heating.		p	F		Heating.	
			Narrow.	Wide.				Narrow.	Wide.
x	+	0	0.20	0.07	x	+	0	0.19	0.09
—	—	0	0.17	0.09	—	—	0	0.18	0.09
—	+	5	0.23	0.18	—	+	5	0.30	0.13
—	—	5	0.18	0.09	—	—	5	0.20	0.10
—	+	10	0.39	0.26	—	+	10	0.49	0.16
—	—	10	0.27	0.13	—	—	10	0.21	0.11
3.8	+	0	1.15	0.38 md	4	+	0	1.12	0.25 d
—	—	0	1.35	0.85 b	—	—	0	1.36	1.08 b
—	+	1	0.95	0.29 d	—	+	5	1.22	0.57 b
—	—	1	1.23	0.91 b	—	—	5	1.50	0.80 b
—	+	8	1.11	0.66 d	5.3	+	0	1.35	0.20 d
—	—	8	1.03	0.83 b	—	—	0	1.62	1.20 b
7.3	+	0	1.72	0.73 d	—	+	4	1.53	0.41 mb
—	—	0	2.25	1.33 b	—	—	4	1.76	1.14 b
—	+	5	1.85	0.63 d					
—	—	5	1.90	1.25 b					

These tables afford, in the first place, a confirmation of the former results, inasmuch as in narrow tubes the heating is very nearly independent of the quantity of electricity transmitted, especially at high pressures. Further, *deviations from this law occur, especially with the positive discharge*. In the wide tube they are perceptible optically as well as thermally. By including sparks, a wide tube may be made dark which was luminous before, whilst a still further increase of the spark-length calls forth again an increase in brightness. With this there goes hand in hand a diminution and subsequent increase in the heating of the calorimeters, as the observations at the pressure 3.8, for example, show. It is nearly indifferent whether the electrode nearest to the wide tube is connected with the source of electricity or with the earth.

This peculiar behaviour of positive electricity becomes much more marked when we use calorimeters with mercury instead of turpentine.

The following table gives a series of such comparative measurements, which were made at very low pressures, whilst the electrode nearest the wide tube was connected with the machine;—

F	+		-	
	Narrow.	Wide.	Narrow.	Wide.
0	0.23	0.19	0.164	0.13
0	0.37	0.89	0.18	0.12
4	0.39	1.44	0.27	0.16
8	0.40	2.72	0.40	0.12

Whilst during the passage of the negative discharge through the wide tube only relatively small changes in the heat produced occur with changes in the spark-length, these become very considerable (from 0.19 to 2.72) when the positive discharge takes place through the wide tube. At the same time there were always strong charges on the tube-wall, which led to a fracture of its upper edge at a somewhat high pressure in the tube. Further investigations on the influence of condensation of the electricity on the wall of the tube would probably lead to important conclusions as to the nature of the discharge. I shall return to this further on.

III. The heating at the electrodes was determined by means of the arrangement of fig. 9, and first when no spark was included.

In a first series the electrode for which the heating was to be determined was a point connected with the source of electricity. The gas employed was air.

The amounts of heat were as follows :—

p	+	—	p	+	—
14.4	0.50	0.74	12	0.08	0.48
6.2	0.48	0.39	0.45	0.07	0.74
2.4	0.17	0.34	x	0.06	1.26

In a second series the amount of heat was also determined with point electrodes, both when the electrode in question was connected with the machine and also when it was put to earth. The following table contains under a the values obtained in the first case, and under b those obtained in the second case. The water-equivalent of the calorimeter &c. was 6.4. The gas employed was hydrogen :—

$a.$			$b.$		
p	+	—	p	+	—
26.5	0.63	0.60	26	0.62	0.50
8.1	0.26	0.39	8	0.24	0.30
2.6	0.15	0.37	2.4	0.14	0.41
0.6	0.06	0.64	0.8	0.10	0.81
0.2	0.07	0.63	x	0.10	1.05
x	0.09	0.77	—	—	—

In a third series the electrodes were spheres, the gas was hydrogen; the water-equivalent was 7·4. The following numbers were obtained :—

p	$a.$		$b.$	
	+	—	+	—
31	0·94	0·93	0·96	0·83
2·7	0·227	0·42	0·20	0·40
0·2	0·11	1·31	0·064	1·33
x	0·21	1·66	0·36	2·40

The conclusions to be drawn from the tables are as follows :—

(1) *The heating at the positive electrode diminishes continually and rapidly as the pressure decreases. At very low pressures there is occasionally a small increase. At the same time the glass round it shines with green light, as if the electrode became temporarily negative.*

(2) *The heating at the negative electrode at first decreases as the pressure becomes less, and then increases rapidly.*

The heating results partly from the heating of the electrode itself, partly from that of the enclosed gas, and partly from that of the glass envelope. At quite low pressures, at the negative pole, where the glass becomes luminous, no doubt the last of these is the most important. I have calculated how great the heating of each square cubic centimetre of the wall would be under the conditions of the experiments, on the assumption that the whole of the heat at the end of the discharge issuing from the negative electrode is produced upon the glass wall. I chose for this purpose the observations with point electrodes given under a , at very low pressures. The luminous surface of the glass had a magnitude of 5 square centimetres; upon this surface there was produced in each minute a quantity of heat of $0·77 \times 6·4 = 4·9$ calories, or 0·98 per square centimetre. By way of comparison, it may be mentioned that the radiation of the sun causes each minute a production of heat on each square centimetre of the earth's surface amounting to about 2 calories. It is to be observed, however, that the discharge from the negative pole lasts only a very short time (not even the thousandth part of the whole time), whilst the radiation of the sun acts continuously for the whole time.

A large number of measurements with electrodes of different forms were made, to determine the influence upon the heating at the electrode of introducing air-sparks of varying

length; but the results were not very constant. A few of these observations are given in the following table.

-						+					
p	$F=0$	2.	5.	10.	14.	p	$F=0$	2.	5.	10.	14.
14.4	0.74	...	0.66	...	...	14.4	0.50	...	0.41	...	...
6.2	0.39	0.33	0.43	0.42	...	6.2	0.48	...	...	0.26	...
2.4	0.34	0.58	0.68	0.46	...	2.4	0.17	0.15	0.25	0.37	...
1.2	0.43	...	0.59	0.77	0.90	1.2	0.08	...	0.30	...	0.50
x	1.26	1.15	1.4	1.35	...	x	0.06	0.32	0.46	0.91	...

The constantly observed fact is to be particularly mentioned, that at low pressures the heating at the positive electrode is unusually small when no spark is employed, but that it increases very rapidly as soon as a spark is introduced.

We may bring together the results of the observations of the heat produced when no spark is included in the circuit as follows:—

(1) *The total heating first decreases, and then rapidly increases, as the pressure decreases.*

(2) *The heating of the tube decreases rapidly, and then increases very slightly.*

(3) *The heating at the positive electrode first decreases rapidly, and then increases slightly.*

(4) *The heating at the negative electrode first decreases slowly, and then increases rapidly.*

Hence it follows that, for the thermal phenomena in the whole discharge-tube, in the experiments which I have made, and under normal conditions without the use of any air-spark, the phenomena at the negative electrode are the most important.

But from experiments on the positive discharge it follows, further, that deviations from the laws stated above depend upon a peculiar behaviour (p. 374) of positive electricity, which becomes specially important, not when the passage of electricity through the tube takes place at the normal potential corresponding to the construction of the tube, but when by the use of sparks or external resistances the quantity of electricity passing in each discharge is increased.

4. Absolute Determinations.

In order to obtain a measure of the quantity of heat produced in the capillary tube per unit length by the unit quantity of electricity, special measurements were made.

The calorimeter was of glass, the fluid in it water. The length of the portion of the capillary tube surrounded by

the water was 9·4 centims., its diameter 0·58 millim. The water-equivalent of the calorimeter and water was 16·2. The elevations of temperature (reduced, as usual, to a galvanometer-deflection of 100 millims. and one minute) were:—

	<i>p</i>	+	—
...	15·5	1·09	1·01
...	5·5	0·50	0·37
...			

The mean number of discharges was 60,000 per minute when $p=15·5$ millims., and 144,000 when $p=5·5$ millims.

Next, the deflection of the galvanometer must be reduced to definite units. With a thermo-current produced by a copper-silver element whose points of junction were maintained at 13° and 29°·2, and resistances introduced of the values in Siemens's units 0, 1, 2, and 3 respectively, the galvanometer gave deflections of 122, 37, 21, and 15 millims. From these numbers, and from the distance of scale and mirror, viz. 189 centims., the resistance of the element and of the galvanometer is found to be 0·43 Siemens.

[The intensity of the current corresponding to a deflection of 100 millims. is 1·000336 Siemens-Daniell unit. The numbers given in the original paper are erroneous through a mistake in the determination of the galvanometer-constant. Accordingly the numbers in the foregoing part have been corrected. —E. W.]

If now we denote by t the rise in temperature of the calorimeter, W its water-equivalent, l the length of the portion of the capillary tube included, then the quantity of heat evolved per unit length $B = \frac{Wt}{l}$; and if we assume that this is proportional to the quantity of electricity transmitted e , we obtain for the quantity of heat X produced by unit quantity of electricity in unit time per unit length,

$$X = \frac{Wt}{le}.$$

The values of X in our experiments are as follows:—

<i>p</i>	+	—
15·5	3200	2966
5·1	2636	1962

in which the centimetre is the unit of length, the gramme the unit of weight, the minute the unit of time, and the unit quan-

tity of electricity that involved in the Siemens-Daniell unit of electromotive force.

The quantities of heat evolved are very large; consequently the electricity must suffer great loss of potential. This is also seen from the following consideration.

If in a Daniell's cell one equivalent of zinc (32.6 grammes) is dissolved, a quantity of heat amounting to 23,900 calories becomes free. A current of unit strength (Siemens-Daniell) would set free in one second 0.0116 milligramme of hydrogen or $0.0116 \times 60 \times 32.6 = 22.7$ milligrammes zinc in one minute.

The whole quantity of heat produced in one minute by such a current is therefore $\frac{0.0227}{32.6} \times 23900 = 160$ calories, or about one twentieth of that found above.

The capillary tube had altogether a length of about 1 decimetre; so that in it alone, without taking account of the heating at the electrodes, about 45,000 calories would be produced by the unit quantity of electricity.

The temperature of the gas in the discharge-tube at each discharge may also be found from the experimental data, on the assumption that the whole heat goes to raise the temperature of the gas, and not to perform any internal work (see further on), and, further, that the discharge takes place so rapidly that there is no loss of heat externally.

If we denote by T the maximum temperature of the gas, c the specific heat* of unit weight, s the specific gravity at 760 millims, p the pressure at which the experiment was made, V the volume per unit length of the capillary tube, Z the number of discharges per minute, W the water-equivalence of the calorimeter, and t the elevation of temperature, we have

$$\frac{T \cdot c \cdot s \cdot p \cdot V \cdot Z}{760} = Wt.$$

According to the data of the experiment, the value of T was:—

p	+	—
15.5	1977	1830
5.1	1141	849.2

* The specific heat at constant pressure has been taken; for the heating of the gas in the vacuum-tube does not take place without expansion, as is shown by the following experiment. If a capillary tube be interposed between two wider tubes, then the whole be filled with hydrogen, and by interposing sparks the quantity of electricity be so far increased that the capillary tube assumes a bright-red colour, the red light continues a short distance (2–3 millims.) into the wider portion of the tube, as if the red luminous gas were driven into it.

Hence the temperature in these narrow tubes is already very low; in one ten times as wide it might sink to 100° C.

This is a further confirmation of the previously stated law that *a gas may be rendered luminous by electric discharges without any corresponding elevation of temperature.*

[To be continued.]

XLIII. *Air-Thermometers.* By D. WINSTANLEY*.

[Plate VII.]

A THERMOMETER which makes its indications in consequence of the dilatation and contraction of a gas offers several advantages over one which depends therefore on the volumetric variations of a liquid. Gases under constant pressure expand considerably more than liquids do for the same elevation in their temperature. Hence an air- or gas-thermometer, having the same size of bulb and tube as one in which a liquid only is employed, will have a more legible and open scale. Again, a given volume of a gas at the ordinary barometric tension of the air upon the level of the sea, when compared with an equal volume of a liquid body, requires so utterly insignificant an amount of heat to elevate its temperature through a given range, that a gas-thermometer is enormously more sensitive than one which depends upon a liquid for its expansional effects. And, finally, the very equal manner in which gases are dilated under the influence of equal increments of heat is a very strong point in favour of an air-thermometer.

As constructed by Galileo, the air-thermometer unfortunately gave readings which were influenced by the barometric variations of the outer air, a circumstance which has limited considerably its use and application. Happily it is not difficult to construct an instrument which shall be free from this defect. If we take an ordinary mercurial barometer made after a certain well-known pattern, *i. e.* with a bulb-shaped cistern surmounted by a neck into which we may insert a cork, and if as a matter of fact we *do* insert a cork, obviously that barometer ceases to show the tension of the outer air, and is a barometer only to the air enclosed within its bulbous cistern. But as the tension of this air will vary with its temperature, the height of the mercurial column will vary therewith as well; and that which *was* a barometer will, by the mere insertion of a cork, have become an air-thermometer, the readings of which are uninfluenced by the

* Communicated by the Physical Society, having been read at the Meeting on June 26.