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X. *On the Photo-Electric Discharge from Metallic Surfaces in Different Gases.*

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The experiments described in this paper were designed with a view to studying as systematically as possible the dependence of the magnitude of the photo-electric current from a metal surface illuminated by ultra-violet light—or Hallwachs effect, as it is called, after the name of its discoverer, by continental physicists—on the pressure and nature of the gas in which the illuminated surface is enclosed.

Very few experiments appear to have been made on the comparison of photo-electric currents in different gases, and the experiments hitherto carried out on the photo-electric effect in gases at pressures other than atmospheric have been made principally to test special points in theory; such as those made by Townsend ('Phil. Mag.,' 6th series, vol. 3, p. 557, 1902) in support of the theory of the genesis of ions by collision.

The researches of Stoletow and of von Schweidler are, however, exceptions, though their results do not enable comparisons of the photo-electric currents at different pressures to be made, except under certain very special conditions. The deductions drawn by Stoletow from his observations—which are summarized in the 'Comptes Rendus,' vol. 108, p. 1241, 1889—will be dealt with more fully later, but it will be advantageous to refer at the present stage to von Schweidler's experiments ('Sitz.-Ber. d. k. Akad. Wien,' Abth. IIa, vol. 107, p. 881, 1898, and vol. 108, p. 273, 1899).

E. von Schweidler examined more especially the effect of varying the potential difference between the electrodes on the photo-electric current, giving curves connecting these quantities at a few different pressures between 1 and 760 millims. mercury. The curves at the different pressures were independently obtained, and no data are given which enable a comparison of the curves with one another to be made. They show, however, that at each pressure examined the current increases rapidly with the potential difference up to a certain value, after which the increase is much more gradual until another critical value is reached, when a further increase in the

potential again causes a rapid increase in the current. The experiments were conducted solely in air and the results obtained are purely qualitative.

Owing to the complicated nature of the connection between the photo-electric current and the potential difference between the electrodes, it is not possible to compare the currents for different pressures or gases under any simple definite conditions, as would have been the case if a saturation current had existed for ionisation produced by the photo-electric effect as it does for that produced by Röntgen rays. Under the circumstances the only satisfactory method of comparing, for example, the currents in a gas at two different pressures appeared to be to draw the complete curve connecting the current and the potential difference for each pressure, keeping the intensity of the illumination constant throughout the whole series of observations at both pressures.

Source of Ultra-Violet Light.

The greatest difficulty encountered during the course of the research was that of obtaining a source of ultra-violet light which could be relied upon to remain approximately constant, at least, in intensity throughout the whole course of long ranges of observations, often extending over many hours. An arc light or the spark between zinc terminals in the secondary of an induction coil worked from accumulators, with some form of interrupter in the primary circuit, which are the sources of ultra-violet light ordinarily used, proved utterly unsuitable, as did also arrangements suggested by Kreusler ('Verh. der Phys. Gesel. Berlin,' Jahrg. 17, p. 898) and Wulf ('Ann. der Phys.,' vol. 9, p. 948, 1902).

The source ultimately adopted and used in the majority of the experiments described below was an arc between iron wire terminals. The wires were tapped into the ends of long brass screws working in corresponding threads in brass pieces attached to the sides of a wooden frame, this arrangement rendering it easy to adjust the sparking distance without displacing its position.

The terminals of the arc were connected to the secondary terminals of an induction coil, in parallel with which were also three large Leyden jars. An alternating current of about 4 ampères passed through the primary of the coil when a key in the primary circuit was closed.

In order to obtain an arc which will work constantly for a sufficiently long time it is necessary to use iron wires of such a diameter, and regulate the current through the primary, so that although the terminals become white hot, yet the heat developed is just not sufficient to cause particles of the iron to be melted off. Under favourable conditions, when the ends of the terminals had once become properly rounded, the intensity of the arc would remain quite constant, without any need for adjusting the spark length, when run for as many as fifty or a hundred 10-second periods with intervals of a few minutes between each.

An arc between aluminium terminals was also tried, but proved unsatisfactory

owing to the rapid volatilization of the aluminium and consequent lengthening of the arc, thus causing an alteration in the intensity of the light emitted.

The arrangement described above, although proving satisfactory as a rule, required much attention at times, and a modified form has recently been adopted which, though not so simple in construction, affords a much more reliable source of ultra-violet light. The improvement consists in having the iron terminals in an atmosphere of pure hydrogen, the spark apparatus being shown diagrammatically in fig. 1. A brass tube B, 12 centims. in length and 3 centims. in diameter, was closed at one end by a quartz window Q. The iron terminals TT were admitted through the side tubes SS, and were surrounded by glass tubes GG, as shown in the figure. This was necessary in order to prevent short-circuiting across the brass vessel, and long side tubes were necessary, as it was found that a metallic film was deposited on surfaces near the spark, which was also liable to cause short circuits unless some such precaution was taken. All joints were made airtight by sealing wax. A continuous slow stream of hydrogen was passed through the apparatus, entering at A and leaving at E. The hydrogen was prepared in a KIPP'S apparatus from pure zinc and hydrochloric acid, and was dried by bubbling slowly through concentrated sulphuric acid and passing through long tubes packed with calcium chloride. It was necessary to ensure that the hydrogen was perfectly free from oxygen, or water vapour was formed when the discharge passed, and this being opaque to ultra-violet rays would quickly rob the light passing out through the quartz window of these rays. The length of spark used was about 6 millims.

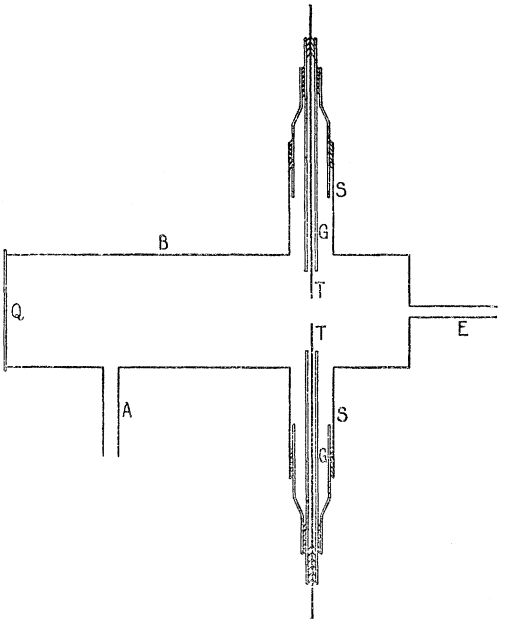

Fig. 1.

The ultra-violet light obtained by this method remained practically unaltered in intensity for hours or even days, the spark being usually run for 10-second periods every few minutes.

The later series of experiments were made using this source of light, though the simpler arc in air is quite satisfactory unless very long series of observations are needed or great accuracy is required.

Apparatus and Method Employed.

In order to be able to test the constancy of the ultra-violet light employed, two separate pieces of apparatus were used, in one of which the conditions under which

the photo-electric currents were measured remained invariable, whilst in the other the conditions were altered as required. The first apparatus served as a means of testing the regularity of the intensity of the light, and, on the assumption that the photo-electric effect is proportional to the intensity, of correcting for any small irregularities which might occur in the strength of the light, though this was rarely necessary, while in the second apparatus the experiments proper were carried out.

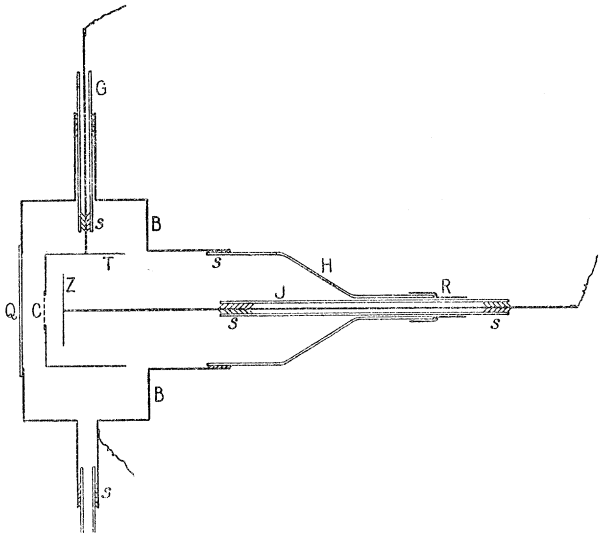

Fig. 2.

The apparatus with which most of the series of observations were made is shown diagrammatically in fig. 2.

The brass vessel, BB, consisted of two cylinders of different diameters arranged end-on as shown. An opening 4·5 centims. in diameter, cut in the front face of the larger cylinder, was closed by a quartz window Q, attached by sealing wax. Two brass side tubes were soldered on to this cylinder, through one of which passed a glass tube G. Through this was fixed a stout brass rod which supported a thin copper tube T, one end of which was covered by a very fine copper grating C, the wires of which were 0·25 millim. in diameter, placed 0·25 millim. apart, and which formed one electrode. The other side tube served to connect to a pump and gauge. Into the back of the smaller cylinder fitted a wide glass tube H, drawn down narrower at the other end, into which a second glass tube, J, would just slide easily. A brass rod supporting the other electrode, F, passed through this inner tube, and by this arrangement the electrode could be changed or removed to be polished by breaking the one joint between the wide glass tube H and the brass cylinder. All the joints SS were of sealing wax and perfectly air-tight. They were arranged as far as possible so as to ensure the insulation of the electrodes remaining permanently good.

The joint between the two glass tubes carrying the rod connecting to the electrode F (that at R) was made by slipping rubber compression tubing over the two tubes, after lubricating well with glycerine. This made a perfectly air-tight joint and enabled the distance between the two electrodes to be altered by any desired amount, when the apparatus was exhausted, without admitting any air and thereby altering the pressure.

The front of the tube T, covered by the gauze, or rather grating, formed of similar wires to those described above, only allowed the light to fall on the central portion of the electrode F, and the apparatus had the further advantage that

the light only traversed a small thickness of the gas in the vessel before reaching the electrode.

The second apparatus, used principally for testing the ultra-violet light, is shown diagrammatically in fig. 3. It was of much smaller volume than the other one, and in this apparatus the electrode, Z, was always of zinc. The apparatus was only used at low pressures and it was seldom necessary to repolish the zinc, it being found that at pressures below, say, a tenth of an atmosphere, zinc showed little or no signs of fatigue when illuminated by ultra-violet light. Further description of this apparatus is unnecessary, the lettering of fig. 2 applying also to this diagram.

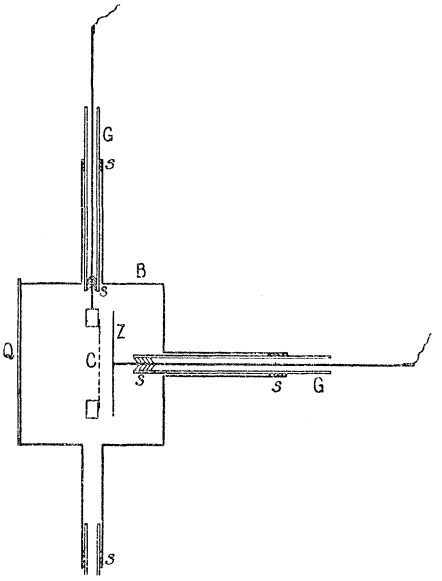

Fig. 3.

Each leak apparatus (as they may be termed for brevity) was connected to a Töpler pump and to a barometer column. The pressures were read by noting the differences in height between these and true barometer columns placed beside them. The main apparatus was also connected to a McLeod gauge which enabled pressures down to 0·001 millim. to be accurately read. Suitable drying bulbs containing phosphorous pentoxide were included between the pump, McLeod gauge, and leak apparatus. A side tube closed by a good stop-cock was attached to the tube connecting the pump and leak apparatus, by means of which any desired gas could be admitted into the apparatus or the whole exhausted down to any pressure above about 20 millims. by connecting to a water pump.

The apparatus was so arranged that the spark gap was in the focus of a quartz convex lens of about 30 centims. focal length, and by turning the lens slightly a parallel beam of rays could be thrown on to the sensitive electrode of either leak apparatus. Each of these electrodes was connected to the negative terminal of a battery of small secondary cells, the number of which could be varied up to 180. The other electrodes, the gauzes, were connected through a three-way key to one pair of quadrants of an electrometer and to earth, except when a key, which we will term the electrometer key, was raised. The other pair of quadrants of the electrometer, the positive terminal of the battery, and the metal case of each leak apparatus, were all permanently earthed. All wires leading to the electrometer were run through earthed brass tubes, and when additional capacity was introduced into the electrometer circuit, a parallel plate condenser enclosed in a metal-lined box was used, the casing of the box being also connected to earth.

The electrometer was of the ordinary type, and was used with electric lamp filament and scale. The needle was usually charged to a potential of 400 volts,

and, as tested with a standard cell, gave a deflection of about 70 divisions for a volt on a scale 3 metres away.

In taking an observation, the electrometer key was first raised so as to insulate the one pair of electrometer quadrants and the zero position of the filament image on the scale noted. The key in the primary circuit of the induction coil was now closed and the spark allowed to run for usually 10 seconds, when the primary circuit was again broken, and the deflection of the electrometer needle noted. The spark was run and the observations taken at regular intervals as far as possible.

Variation of the Photo-Electric Current with the Pressure of the Gas.

The following series of experiments on the variation of the photo-electric current from an illuminated zinc surface with the pressure of the surrounding gas, were carried out in hydrogen, so as to avoid errors arising from the tiring of the zinc surface which occurs in air at ordinary pressures when it is illuminated by ultra-violet light. In hydrogen, the zinc showed no signs of this fatigue effect under the influence of the light, and after taking a complete series of observations it was always possible to repeat any one of them and obtain the same values for the currents as before; the same holds true in air also at pressures below about one-tenth of an atmosphere.

The results obtained for a whole series of pressures, ranging from 760 millims. down to 0·008 millim., are given in Table I. The zinc electrode was situated 3·5 millims. behind the gauze electrode, and a difference of potential of 1 volt between the electrometer quadrant-pairs corresponded to a deflection of 60·6 divisions on the scale. The currents are measured in electrometer scale divisions per 10 seconds. The total capacity of the leak apparatus, electrometer, and connecting wires was about 90 centims., so that a deflection of 60 divisions per 10 seconds corresponds to a current of 10^{-10} ampère (very nearly).

The intensity of the ultra-violet light, as measured by the second leak apparatus, showed no appreciable change throughout the course of the observations, the deflections obtained for 10 seconds' illumination being, at the beginning, 212, 208 divisions; at intervals during the experiments, 204, 209, 212, 215 divisions; and at the end, 214 and 209 divisions. As a further precaution, the first set of observations taken (that at 760 millims.) was repeated at the close, and almost identical values for the currents obtained, as the numbers given show.

TABLE I.

Potential to which zinc is charged in cells. (1 cell = 2·1 volts.)	Current from zinc surface in hydrogen in electrometer scale divisions in 10 seconds, the pressure being—											
	760 millims.	351 millims.	101 millims.	49·5 millims.	20 millims.	8 millims.	3·3 millims.	0·70 millim.	0·27 millim.	0·13 millim.	0·008 millim.	760 millims.
4	—	—	21	29	48	71	108	118	92	89	67	—
20	16	26	40	51	80	111	158	213	149	131	—	16
40	—	—	—	—	—	—	280	412	240	—	—	—
60	—	—	64	77	116	204	—	—	—	140	—	—
80	—	—	—	—	—	338	—	—	—	—	—	—
100	34	44	76	100	167	—	—	—	—	142	—	33
140	—	—	—	—	303	—	—	—	—	144	—	—
180	43	61	98	145	—	—	—	—	—	158	67	45

These results can be seen more clearly from fig. 4, where the curves connecting the currents and potential difference at the different pressures are plotted. The curves corresponding to the three lowest pressures are shown by dotted lines to avoid confusion.

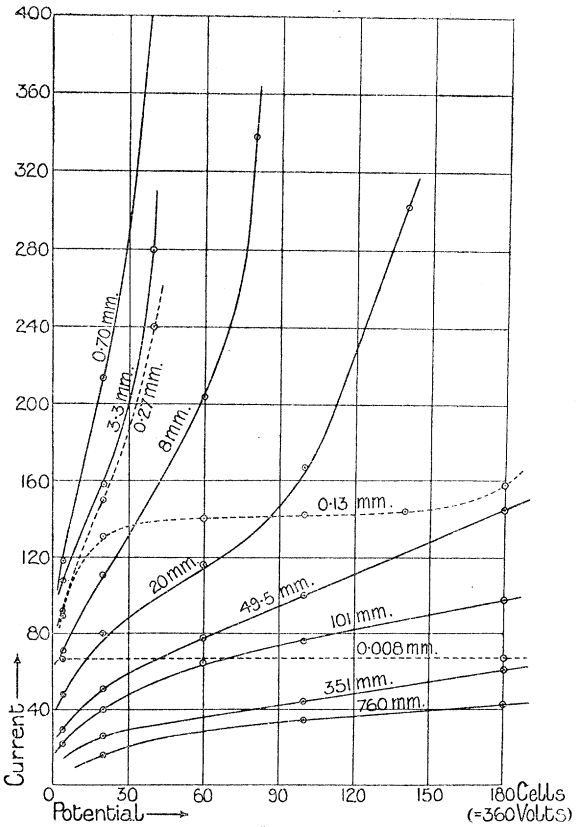

Fig. 4.

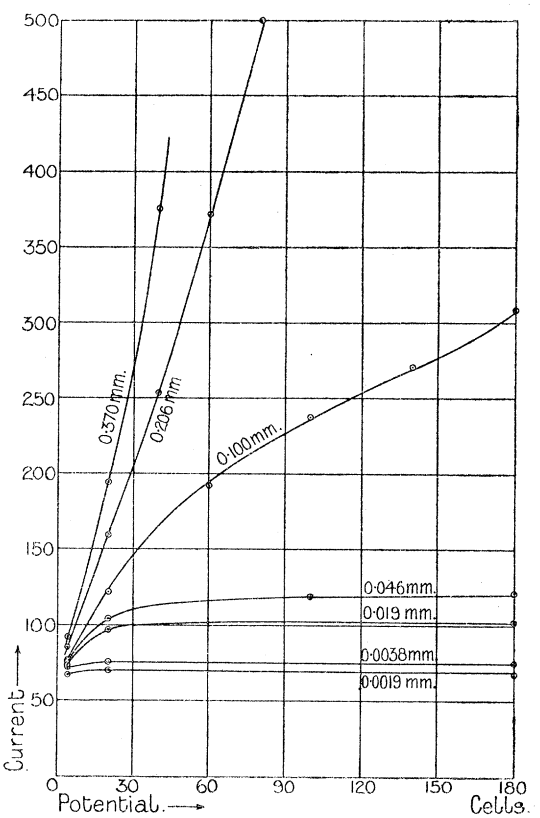

Fig. 5.

The results of a further set of observations, showing more fully than the above the variation of the photo-electric current at very low pressures, are given in Table II. The distance between the electrodes was again 3·5 millims., and 1 volt on the electrometer corresponded to a deflection of 76 divisions. The illuminated electrode was, as

before, of zinc, but the experiments were carried out in air. The intensity of the light remained perfectly constant throughout the series. These experiments were carried out in the smaller leak apparatus (the larger being used as the standard) to avoid loss of time in pumping between successive sets of observations. The current-P.D. curves derived from these results are plotted in fig. 5.

TABLE II.

Potential to which zinc is charged in cells. (1 cell = 2·1 volts.)	Current from zinc surface in air in electrometer scale divisions in 10 seconds, the pressure being—						
	0·370 millim.	0·206 millim.	0·100 millim.	0·046 millim.	0·019 millim.	0·0038 millim.	0·0014 millim.
4	92	85	76	75	73	71	66
20	194	159	122	104	96	75	70
40	375	254	—	—	—	—	—
60	630	371	193	—	—	—	—
80	—	501	—	—	—	—	—
100	—	—	237	119	—	—	—
140	—	—	270	—	—	—	—
180	—	—	309	122	102	75	68

A further set of observations was made on the relation between the currents and pressure, using a platinum electrode instead of zinc. The larger leak apparatus was used, and the platinum electrode situated 2 millims. behind the gauze. 1 volt P.D. on the electrometer gave a deflection of 65·6 scale divisions. The series of observations was taken in the order given in Table III., and it was found that between the first and last experiments the light increased nearly 10 per cent. in intensity. This increase was gradual, and has been disregarded.

TABLE III.

Potential to which platinum is charged in cells. (1 cell = 2·1 volts.)	Current from platinum surface in air in electrometer scale divisions in 15 seconds, the pressure being—					
	25 millims.	7 millims.	2 millims.	0·24 millim.	0·061 millim.	0·026 millim.
4	—	—	26	42	36	35
20	29	40	65	65	41	36
40	—	—	117	97	—	—
60	42	62	200	125	—	—
80	—	105	357	—	—	—
100	50	198	—	162	44	—
120	—	406	—	—	—	—
140	67	—	—	209	—	—
160	—	—	—	330	—	—
180	103	—	—	—	46	35

The photo-electric currents from the platinum electrode were found to be from 15 to 20 times less than those from a zinc electrode under the same conditions in air at a pressure of 25 millims.

The results given in Table III. are plotted in fig. 6, the ordinates, as before,

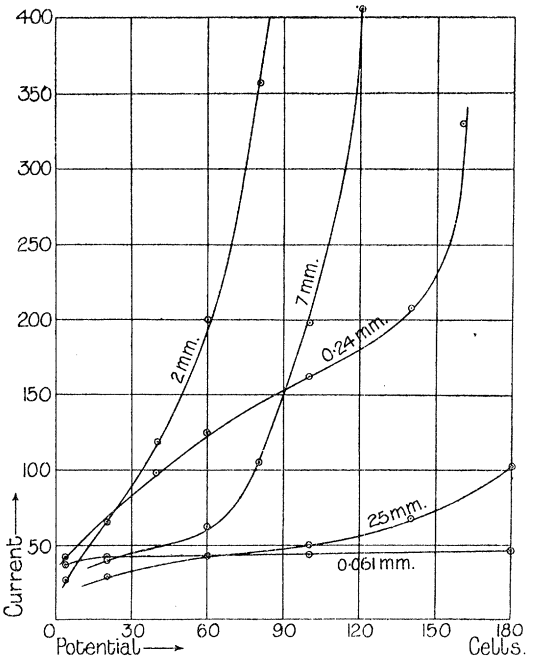

Fig. 6.

representing the currents, and the abscissæ the potentials to which the platinum is charged.

Comparison of Photo-Electric Currents in Different Gases.

The results of a number of series of observations on the photo-electric currents from an illuminated zinc surface in the three gases, air, hydrogen, and carbon dioxide are given in the following Tables IV. to VII. The hydrogen was prepared in a Kipp's apparatus from pure zinc and hydrochloric acid, and was dried by keeping it for some time in a long tube filled with lumps of calcium chloride before permitting it to enter the leak apparatus. The hydrochloric acid was removed by passing the gas through a tube containing solid caustic potash in most of the experiments at low pressures; but this was found to be an unnecessary precaution, the hydrogen gas being given off so very slowly that no appreciable amount of the acid was carried over with it. The carbon dioxide was prepared from marble and hydrochloric acid, and was similarly dried. Before allowing a fresh gas to enter the leak apparatus, the latter was exhausted until the pressure of the gas remaining in it was less than $\frac{1}{100}$ millim. mercury. The new gas was then admitted, the stop-cock closed, and the apparatus again exhausted and refilled, so that no trace of the original gas might remain. Other details are given as Notes at the foot of each table.

TABLE IV.

Potential to which zinc is charged in cells. (1 cell = 2·1 volts.)	Current from zinc surface in electrometer scale divisions in 10 seconds in—				
	H_2.		CO_2.		Air.
	760 millims.	76 millims.	760 millims.	76 millims.	760 millims.
4	—	36	—	81	—
20	32	96	45	192	39
100	73	176	128	323	89
180	92	261	176	455	112

Notes.—The experiments were carried out in the small leak apparatus, the zinc electrode being situated 3·5 millims. behind the gauze. A P.D. of 1 volt between the electrometer quadrants corresponded to a deflection of 72 divisions.

The standard apparatus indicated a sudden change in the intensity of the light of 22 per cent. during the course of the last set of readings (CO_2 at 76 millims. pressure), which has been corrected for in the table.

The curves plotted from these observations are given in fig. 7.

TABLE V.

Potential to which zinc is charged in cells. (1 cell = 2·1 volts.)	Current from zinc surface in electrometer scale divisions in 10 seconds in—		
	Air.	H_2.	CO_2.
	30 millims.	30 millims.	30 millims.
4	80	67	133
20	182	144	225
60	253	213	295
80	—	277	—
100	339	407	396
120	406	665	537
140	502	—	825

Notes.—The experiments were carried out in the large leak apparatus, the zinc electrode being situated 2 millims. behind the gauze. A P.D. of 1 volt between the electrometer quadrants corresponded to a deflection of 66·4 divisions. A capacity of 240 centims. was placed in parallel with the electrometer. A very intense spark was used which kept constant to within 3 or 4 per cent., the various sets of observations being repeated a second time after the whole had been once taken.

The results given in this table are plotted in fig. 8.

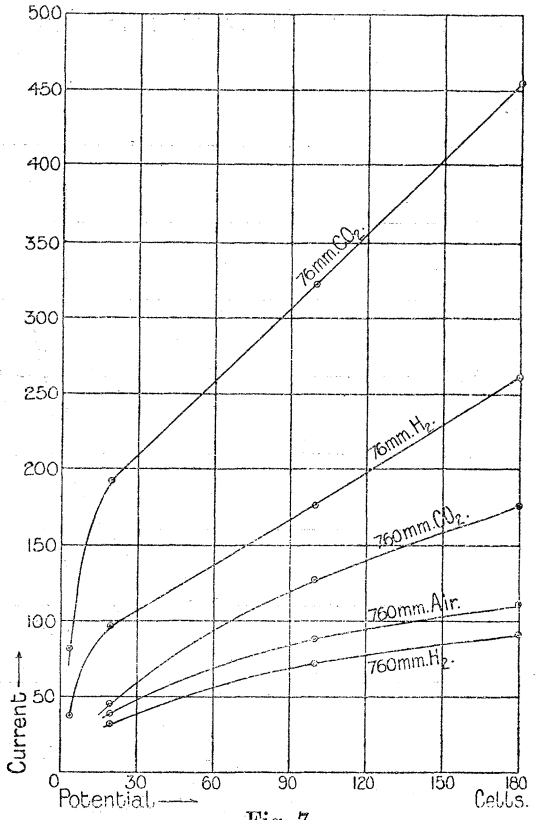

Fig. 7.

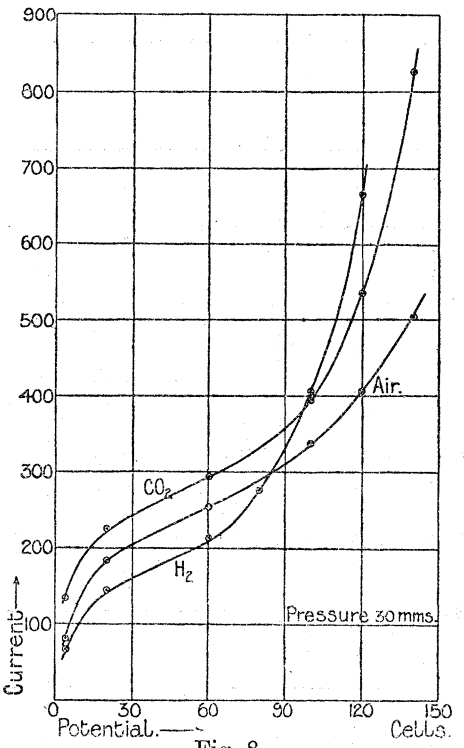

Fig. 8.

TABLE VI.

Potential to which zinc is charged in cells. (1 cell = 2·1 volts.)	Current from zinc surface in electrometer scale divisions in 10 seconds in—					
	Air.		H_2.		CO_2.	
	18 millims.	6 millims.	18 millims.	6 millims.	18 millims.	6 millims.
4	36	49	32	47	65	84
20	78	118	60	93	104	130
40	—	143	—	140	—	158
60	116	166	96	253	139	225
80	132	243	111	459	—	335
100	149	450	142	—	165	—
120	164	—	205	—	—	—
140	178	—	358	—	215	—
160	216	—	—	—	282	—
180	282	—	—	—	375	—

Notes.—The experiments were carried out in the small leak apparatus, the zinc electrode being situated 3·5 millims. behind the gauze. A P.D. of 1 volt between the electrometer quadrants corresponded to a deflection of 77 divisions.

This set of observations was one of the last taken and the spark used was so constant as to render the use of a second apparatus as a check quite unnecessary, the

first set of readings taken being repeated at the end and in every case identical values obtained.

The results given in this table are plotted in fig 9.

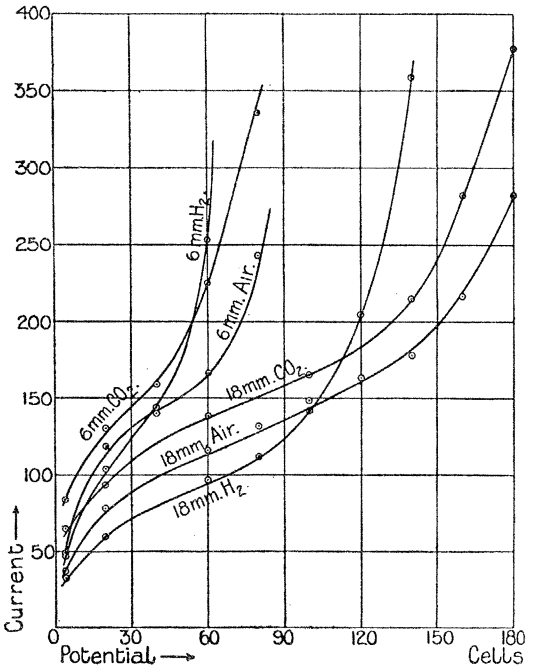

Fig. 9.

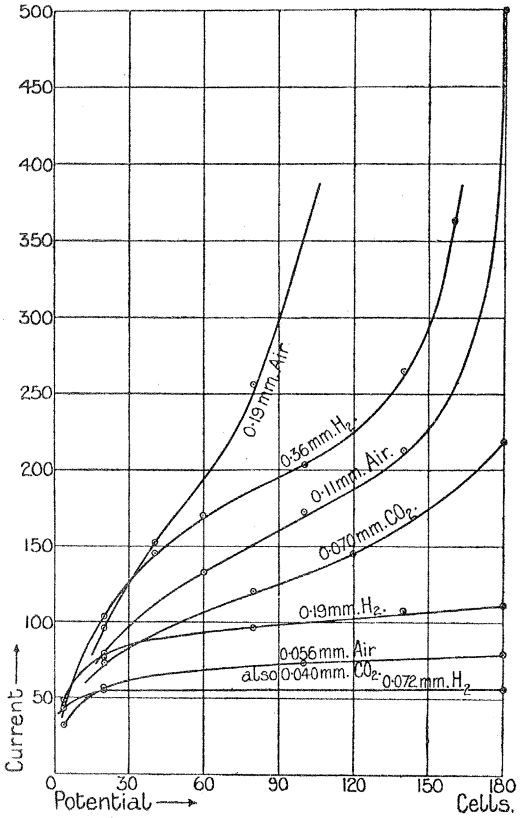

Fig 10.

TABLE VII.

Potential to which zinc is charged in cells. (1 cell = 2·1 volts.)	Current from zinc surface in electrometer scale divisions in 10 seconds in—											
	H_2.				Air.					CO_2.		
	0·36 millim.	0·25 millim.	0·19 millim.	0·072 millim.	0·44 millim.	0·19 millim.	0·11 millim.	0·056 millim.	0·016 millim.	0·21 millim.	0·070 millim.	0·050 millim.
4	43	49	48	42	58	50	45	32	29	47	—	—
20	104	90	80	55	116	96	78	56	34	93	74	61
40	145	—	—	—	200	153	—	—	—	155	—	—
60	170	—	—	—	387	—	133	—	—	234	—	—
80	—	—	96	—	—	256	—	—	—	330	120	—
100	203	124	—	—	—	354	172	74	—	—	—	73
120	—	—	—	—	—	—	—	—	—	—	140	—
140	265	147	107	—	—	—	213	—	—	—	—	—
160	362	—	—	—	—	—	—	—	—	—	—	—
180	700	191	111	57	—	—	508	80	34	—	217	78

Notes.—The experiments were carried out in the small leak apparatus, the zinc electrode being situated 3·5 millims. behind the gauze. A P.D. of 1 volt. between

the electrometer quadrants corresponded to a deflection of 68·4 divisions. A capacity of 240 centims. was placed in parallel with the electrometer. The standard showed that no appreciable alteration occurred in the intensity of the light during the course of the observations. The results given in this table are plotted in fig. 10.

The results of two sets of observations taken after substituting a platinum electrode for the zinc are given in Tables VIII. and IX., and the corresponding

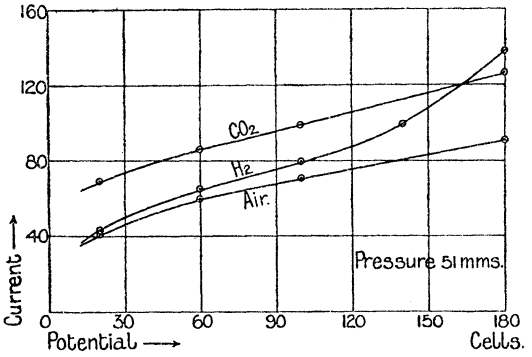

Fig. 11.

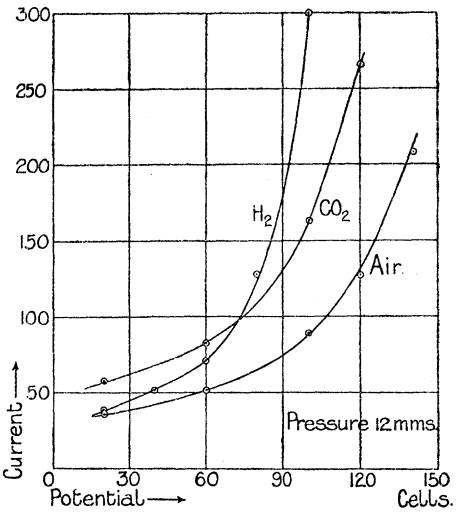

Fig 12.

curves in figs. 11 and 12. The large leak apparatus was used, and the distance separating the platinum and gauze was 2 millims. in each case.

TABLE VIII.

Potential to which platinum is charged in cells. (1 cell = 2·1 volts.)	Current from platinum surface in electrometer scale divisions in 15 seconds in—		
	Air.	H_2.	CO_2.
	51 millims.	51 millims.	51 millims.
20	41	43	69
60	60	65	86
100	71	80	99
140	—	100	—
180	91	138	127

Note.—1 volt P.D. between the electrometer quadrants corresponded to a deflection of 68 divisions.

TABLE IX.

Potential to which platinum is charged in cells. (1 cell = 2·1 volts.)	Current from platinum surface in electrometer scale divisions in 15 seconds in—		
	Air.	H_2.	CO_2.
	12 millims.	12 millims.	12 millims.
20	36	39	58
40	—	51	—
60	51	72	83
80	—	128	—
100	90	301	163
120	128	—	266
140	208	—	—

Note.—1 volt P.D. between the electrometer quadrants corresponded to a deflection of 67 divisions.

The photo-electric currents in carbon monoxide were also compared with those in air, the results at two typical pressures, viz., 20 millims. and 0·045 millim., being given in the following Table X. The zinc electrode was situated 3 millims. behind the gauze, and 1 volt P.D. between the electrometer quadrants corresponded to a deflection of 72 divisions. The carbon monoxide was prepared from sodium formate and strong sulphuric acid, and was washed and dried before allowing it to enter the leak apparatus.

TABLE X.

Potential to which the zinc is charged in cells. (1 cell = 2·1 volts.)	Current from zinc surface in electrometer scale divisions in 10 seconds in—			
	Air.	CO.	Air.	CO.
	20 millims.	20 millims.	0·045 millim.	0·045 millim.
4	92	73	144	111
20	144	124	182	154
60	212	170	218	173
100	263	203	216	169
140	351	258	—	—
160	475	—	—	—
180	—	394	214	170

These results are plotted in fig. 13.

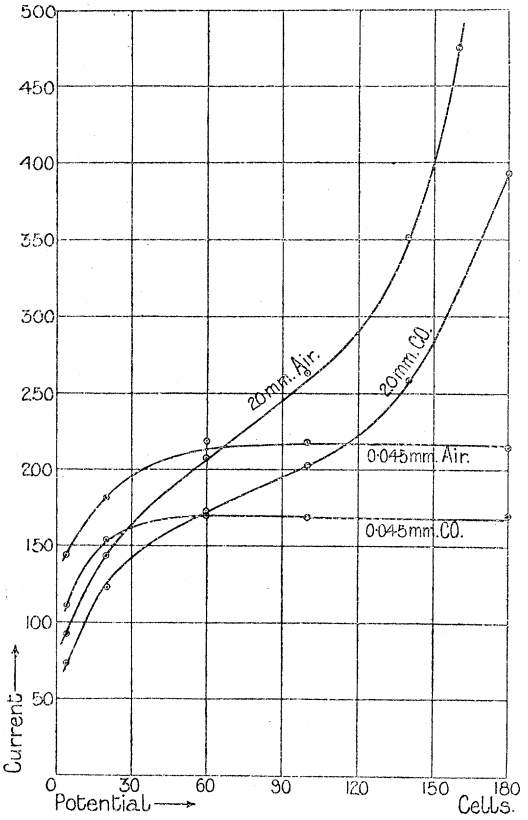

Fig. 13.

Discussion of Observations.

From the series of curves given in figs. 4 and 5 certain of STOLETOW's results can be verified at a glance. Thus the first result given by STOLETOW—that when the potential is kept constant and the pressure gradually decreased, the current first increases, reaches a maximum, and then decreases towards a finite limit which is independent of the potential within very wide limits—can be seen at once from fig. 4. The second result given by STOLETOW—that at ordinary pressures the current increases slowly with the potential difference, approaching a kind of saturation which is more marked at low pressures—needs modification. As the pressure is lowered the flatter part of the current-E.M.F. curve, corresponding to approximate saturation, becomes steeper and steeper until at a few millimetres pressure there does not appear to be any approach to saturation, a small change in the potential difference producing a big alteration in the current, whatever the potential difference may be. It is only when the pressure is much lower than this that a further decrease in pressure produces a closer approach to saturation, until at a pressure of about a tenth of a millimetre, depending on the distance between the electrodes, we actually get a true saturation current which decreases with the pressure, approaching a finite value as the pressure is indefinitely decreased.

Except for the fact that at the higher pressures no true saturation current exists, the sets of curves obtained can be simply explained by the ionic theory of conduction. We regard the metal surface illuminated by ultra-violet light in a similar manner to a hot surface, and suppose that negative corpuscles escape from the surface under the influence of light, and, in the absence of any force tending to drag them further, simply diffuse back into the metal. If now the illuminated surface is negatively charged, a field is set up and the corpuscles are enabled to escape, and a state of equilibrium will be established when the total number of corpuscles given out by the metal is equal to the sum of the number finding their way to the positive electrode and the number diffusing back into the metal; and, as the field is increased, the latter number will become small compared to the former and we shall get a saturation current—neglecting, of course, any complications introduced by the presence of the surrounding gas.

The curves of fig. 4 show that although we never get a saturation current at the higher pressures, yet at all pressures the current-E.M.F. curve is less steep as soon as a certain potential gradient has been reached. As the potential difference is further increased the current increases more slowly, but uniformly, with the potential difference until another critical potential gradient has been reached, beyond which the current increases much more rapidly than the potential difference, and this rapid increase goes on until an actual spark discharge takes place between the electrodes. From fig. 4 we see that in hydrogen at 20 millims. pressure this latter stage begins when the potential gradient is about 80 cells per 3·5 millims., or nearly 500 volts per centimetre. This second rise in the curve has been shown by Professor Townsend ('Phil. Mag.,' 6th series, vol. 1, p. 198, 1901) to be due to the ionisation of the molecules of the gas by the corpuscles themselves, and the potential gradient at which it begins is inversely proportional to the pressure.

The fact that the current-E.M.F. curves are not horizontal even when we should expect saturation, and that they become steeper and steeper at their flattest parts as the pressure is decreased, seems to indicate that there is ionisation by collision to some extent at gradients much below those at which the second rise in the curve leading up to the spark discharge commences. We have not as yet, however, succeeded in obtaining a thoroughly satisfactory explanation of this phenomenon.

According to Paschen's tables, quoted in Professor J. J. Thomson's 'Recent Researches,' the potential gradient necessary for a spark to pass between plates 0·35 centim. apart in air is 116 electrostatic units per centimetre, or 34,800 volts per centimetre at 750 millims. pressure, and in hydrogen 0·55 of this, or 19,200 volts per centimetre. On the supposition, therefore, that ionisation by collision begins at potential gradients slightly lower than those necessary for the discharge to occur—which appeared to be the case at these moderately low pressures, the current-potential difference curve becoming rapidly steeper and steeper until the actual discharge passed—and that the sparking potential is inversely proportional to the pressure,

ionisation by collision should commence in hydrogen at 20 millims. pressure at a potential gradient somewhat less than 520 volts per centimetre, which is in close agreement with the value taken from the corresponding curve in fig. 4, and given above, viz., 500 volts per centimetre.

When the pressure is decreased below a few tenths of a millimetre, the character of the curves alters completely, and we now begin to get perfect saturation currents. This critical pressure corresponds to that at which the mean free path of the ions becomes comparable with the distance separating the electrodes. As soon as this is the case, the number of molecules which can be struck by the corpuscles shot off from the illuminated electrode becomes very limited and a small potential gradient will be sufficient to cause saturation. Further decreasing the pressure will decrease this saturation current, until at very low pressures the whole current will be practically due to the corpuscles shot off from the cathode, as only a very small fraction of these will strike a molecule in the course of their journey from one electrode to the other. The curves in fig. 5 show most clearly the variation of the currents at these low pressures. We see that there is a sudden change in the curves between pressures of 0·2 and 0·05 millim., and we know from other considerations that the mean free path of the corpuscle in air is of the same order as the distance between the electrodes (0·35 centim.) at about these pressures.*

The curves at the very lowest pressures agree with LENARD'S result ('Ann. der Physik,' vol. 2, p. 359, 1900) for cathode rays produced by ultra-violet light, that in a vacuum a very large change in the potential difference produces no change in the current.

The curves of fig. 6, obtained with a platinum cathode in air, present no peculiar features, being similar to those obtained with the zinc cathode. The fact that the electrodes in this case were only 2 millims. apart introduces slight modifications, the sudden change in the curves which occurs when the mean free path of the ion and the distance apart of the electrode become comparable, appearing at a higher pressure than before when the electrodes were 3·5 centims. apart, as we should naturally expect.

The curves given in figs. 7 to 10, showing the relations between the photo-electric currents in the three gases air, hydrogen, and carbon dioxide, all show that at the higher pressures the current is greater in carbon dioxide than in air, and greater again in air than in hydrogen for all potential gradients up to those at which the genesis of ions by collision begins. They also show that this stage begins in hydrogen at a much lower potential gradient than in air or carbon dioxide, the potential gradient required to cause ionisation by collision in these two gases being approximately the same. This is what we should expect, on the supposition

* TOWNSEND, in 'Phil. Mag.,' February, 1901, p. 224, gives the mean free path of an ion in air as $4{\cdot}3 \times 10^{-5}$ centim. at 760 millims. pressure, corresponding to a mean free path of 0·34 centim. at 0·10 millim. pressure.

previously made as to the connection between the potential at which ionisation by collision commences and that necessary for a discharge to pass, from a consideration of the sparking potentials in these gases at atmospheric pressures, the potential gradient necessary for a discharge to pass in hydrogen being only 0·55 times that required in air.

A comparison of the curves for hydrogen in figs. 4 and 9 will show the consistent character of the results obtained.

For pressures down to a tenth of an atmosphere the currents in carbon dioxide are approximately 1·75 times as great as those in hydrogen for all potential gradients for which the current lies on the more horizontal part of the current-E.M.F. curve, that is for those currents nearest approaching to saturation. The currents in air are greater than those in hydrogen, though not nearly so great as those in carbon dioxide. At lower pressures (see figs. 7 and 8) the ratio becomes much less, at 18 millims. pressures the current in carbon dioxide being less than 1·5 times that in hydrogen, as before, for points lying on the less steep portion of the curve.

At still lower pressures the ionisation by collision introduces complications even with small potential differences, and soon becomes the dominant factor in determining the currents until the very lowest pressures are reached. At pressures below about 0·005 millim. the method employed ceases to be satisfactory, as the corpuscles given off by the cathode are shot right through the meshes of the gauze. Some observations which were made, using a gauze of rather wide mesh, are given in the following table as showing some apparently remarkable results which were traced to this cause :—

TABLE XI.

Potential difference between the electrodes in volts.	Current in arbitrary units.
2	52
8	109
40	124
120	148
200	138
280	126
360	112

The experiments were made in air at a pressure of 0·024 millim., the distance separating the electrodes being 2 millims. They show that beyond a certain potential an increase in the potential difference between the electrodes produced a decrease in the current. That this was due to the corpuscles being shot through the meshes of the gauze as soon as the potential gradient was big enough to give them a sufficiently great velocity was shown by substituting a much finer gauze,

when, under otherwise identical conditions, no such decrease in the current was obtained.

The curves given in fig. 10, showing the relation between current and potential at various low pressures in air, hydrogen, and carbon dioxide, are all readily understood if we remember that the mean free path of the corpuscles in hydrogen is, from the kinetic theory of the gases, about twice that in air or carbon dioxide, and that a lower potential difference is required to start ionisation by collision in hydrogen than in the other gases.

The curves of figs. 11 and 12 obtained after substitution for the zinc of a platinum electrode are similar to those obtained using the zinc electrode, except that at the lower potential differences the currents in hydrogen are slightly greater than those in air, whereas the opposite was the case with the zinc.

The currents in air, hydrogen and carbon dioxide were also compared using an aluminium electrode. The results obtained were identical in their general character with those obtained using zinc, though the sensitiveness of the aluminium was much smaller than that of the zinc.

From the curves of fig. 13 we see that the currents in carbon monoxide, using a zinc electrode, are some 20 per cent. less than in air, being in fact almost the same as those in hydrogen until the potentials used are great enough to cause ionisation by collision, which sets in in air and carbon monoxide at about the same potential gradient.

Experiments have been carried out on the photo-electric effect in certain less simple gases, such as marsh gas and benzene vapour. The results obtained are complicated by the very large absorption of the ultra-violet light in its passage through the gas, and are being further investigated.

My best thanks are due to Professor J. J. THOMSON, in whose laboratory the above investigation was carried out, for his advice and encouragement throughout the whole course of the research.

[*Note added October 18th*, 1903.—During the past Long Vacation Term experiments have been made on the photo-electric currents in gases at very low pressures with a new form of apparatus, in which the use of the gauze electrode was discontinued as not being suitable for work at pressures below about 0·02 millim. Two parallel plates, separated by a distance of 12 millims., were employed as electrodes, the ultra-violet light falling obliquely on to the sensitive electrode, and a guard ring arrangement being used to procure a perfectly uniform field between the electrodes. With this apparatus experiments have been made on the magnitude of the photo-electric currents in the various gases down to pressures of less than 0·002 millim. Below a pressure of 0·01 to 0·005 millim. the currents seem to be quite independent

of either the nature or pressure of the gas. No precautions were taken to free the gas from mercury vapour; but it is hoped at an early date to further investigate the currents at these low pressures, taking precautions to absorb all the mercury vapour in the leak apparatus.

The results indicate that the whole of the differences observed in the magnitude of the currents in the various gases depend only upon secondary ionisation occurring at the surface of the metal and on ionisation by collision in the gas itself.]

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