THE NATURE OF SPARK DISCHARGE AT VERY SMALL DISTANCES.

BY ELMER H. WILLIAMS.

HISTORICAL.

THE general subject of spark discharge in gases has commanded the attention of investigators for many years, dating back to the time of Volta.[1] However, the earlier experiments of Volta, Riess[2] and others of their time possess little more than historic interest, since the means at their disposal for measuring differences of potential was unreliable. It was not until 1860 that Lord Kelvin,[3] then Professor William Thomson, conducted the first trustworthy investigation on the spark discharge between two electrodes and the potential difference necessary to produce discharge with varying distances. In his researches, Kelvin measured the distances by which the plates were separated by means of a micrometer screw, and the potential differences necessary to produce a discharge across the intervening dielectric were measured with the absolute electrometer. The results obtained show that the difference of potential necessary to break down the intervening medium is not directly proportional to the distance between the electrodes. Later, important investigations were carried on by Baille,[4] Liebig,[5] Paschen[6] and Peace,[7] in which they showed that, for pressures considerably greater than the "critical pressure" and for comparatively large distances, the relation between the spark potential and the spark-length is a linear one, *i. e.*, if V is the spark potential measured in electrostatic units and x the spark-length at atmospheric pressure, measured in centimeters, then

$$V = ax + b,$$

[1]Volta, Identita, p. 53; Earhart, Phil. Mag. (6), 1, p. 147.

[2]Riess, Pogg. Ann., Vol. 40, p. 333.

[3]Lord Kelvin, Collected Papers on Electrostatics and Magnetism, p. 247.

[4]Baille, Annales de Chimie et de Physique (5), 25, p. 486, 1882.

[5]Liebig, Phil. Mag. (5), 24, p. 106, 1887.

[6]Paschen, Wied. Ann., 37, p. 79, 1889.

[7]Peace, Proc. Roy. Soc., 52, p. 99, 1892.

where a and b are constants depending on the gas. Paschen established the law that, for given potential differences, the product of the sparking distance and the gaseous pressure for producing a spark is a constant, *i. e.*, if d is the spark length and p the pressure of the gas, V is a function of pd. Peace, using parallel plate electrodes, found that there was a minimum spark potential, *i. e.*, if the pressure is kept constant and the length varied there is a point, depending on the pressure of the gas, at which the potential increases with the decrease of distance (see Fig. 1); also, that if the distance

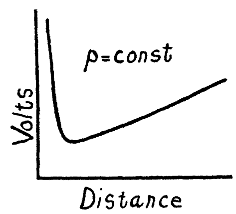

Fig. 1.

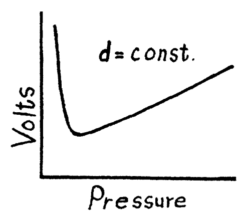

Fig. 2.

is kept constant, and the pressure varied the same phenomenon is observed (see Fig. 2). Peace found this point, called the minimum spark potential, to be independent of the spark-length. However, he did not investigate the phenomenon for very small distances. In air, the minimum spark potential is given as about 350 volts.

The developments of the electron theory have brought the subject of spark discharge into especial prominence within the last decade. Important investigations have been made by Earhart,[1] Carr,[2] Kinsley,[3] Hobbs[4] and Almy,[5] in which they have used refined methods for measuring the spark-lengths. By means of the interferometer they have been able to measure accurately distances to one twentieth of a wave-length of sodium light. Due to the fact that the above investigators used spherical electrodes, their curves do not show the increase of potential difference with diminishing distance between the electrodes that Peace obtained in his observations, since the least distance between the electrodes is not necessarily

[1]Earhart, Phil. Mag. (6), 1, p. 147, 1901.
[2]Carr, Proc. Roy. Soc., 71, p. 374, 1903.
[3]Kinsley, Phil. Mag. (6), 9, p. 692, 1905.
[4]Hobbs, Phil. Mag. (6), 10, p. 617, 1905.
[5]Almy, Phil. Mag. (6), 16, p. 456, 1908.

equal to the spark-length. Thus, when the distance is less than the critical spark-length, the spark will pass, not across the shortest distance, but across the place where the distance is equal to the critical spark-length. Earhart carried his measurements to very short distances and found that when the distance between the electrodes falls to less than about 3×10^{-4} cm., there is a very rapid diminution of the spark potential which, according to his results, seems to become directly proportional to the distance.

The results of Kinsley and Hobbs agree with those of Earhart in that they show a rapid diminution of the spark potential for very short distances. Kinsley, by a special arrangement of his interferometer, was able to measure exceedingly short distances; in some cases he records spark-lengths as small as 3×10^{-7} cm., and a sparking potential of only one volt. Hobbs obtained the exceedingly important and suggestive result that for spark-lengths below about 3×10^{-4} cm., the relation between the spark-length and the potential difference is independent of the pressure and nature of the gas, while it does depend upon the nature of the metal of which the electrodes are made.

If the results of Earhart, Kinsley and Hobbs are correct, Paschen's law does not hold for very short distances, and the phenomenon of discharge at very short spark-lengths must be different from that at greater distances. Now, J. J. Thomson has shown that the discharge for comparatively large distances is due to ionization by collision of the gas between the electrodes.[1] If, for very small distances, ionization does not take place to such an extent as to make the gas conducting, the discharge must take place by some other means. It might be carried by a current of electrons, by a current of positive ions, by currents of both electrons and positive ions, or by material particles torn from the electrodes themselves. In any of these cases we should expect that the material of which the electrodes are made would exert a large influence upon the discharge potential for any given distance.

J. J. Thomson[2] offers a "possible explanation" of the behavior of the discharge when the electrodes are very close together. He

[1] J. J. Thomson, Conduction of Electricity through Gases, p. 270.

[2] J. J. Thomson, Conduction of Electricity through Gases, p. 456.

makes use of the hypothesis that in a metal, even at ordinary temperatures, free corpuscles are moving about in every direction. Now, if these corpuscles could escape from the metal under ordinary conditions, the metal would be unable to retain a charge of negative electricity. J. J. Thomson states that one of the reasons the corpuscles do not escape is that as soon as they leave the metal there is an electrostatic attraction between the corpuscle and the metal which drags the corpuscle back. Assuming the external electric force which Earhart obtained in his experiment, he finds, by a simple calculation, that if the distance of the corpuscle from the surface of the metal exceeds a certain amount, 10^{-7} cm., the pull of the external field would be able to drag the corpuscle away, thus causing that electrode to act like a cathode. This discharge would, therefore, have the character of a small arc or of the hot lime cathode, and a discharge of negative electricity would pass to the opposite electrode. J. J. Thomson further states that if his explanation is correct "the discharge across these very small distances is entirely carried by the corpuscles and no part of it by the positive ions."

Referring to the observation of Hobbs, that the spark potential depends on the material of which the electrodes are made, the above author suggests that "it would be interesting to see whether these carriers are corpuscles or a mixture of negatively electrified corpuscles and positively electrified atoms." "This could be tested," he says, "by making the two electrodes of different metals; if all the carriers are corpuscles the potential difference would depend only upon the metal used for the negative electrode; if they were all positively electrified atoms, then only the positive electrode would be active, while if they were a mixture both electrodes would affect the potential."

Earhart,[1] in 1908, made a series of observations with the object of determining if possible, the nature of the carriers of the discharge. He used the three metals platinum, silver and aluminium, and from his observations came to the conclusion that both positive ions and negative corpuscles are the carriers for the discharge produced by potential differences less than the least ionizing potential. Earhart,

[1]Earhart, Phil. Mag. (6), 16, p. 48, 1908.

however, made only a small number of observations with each pair of electrodes and his readings varied widely for each spark distance, so that it does not appear that he is fully justified in his conclusions.

Later Almy,[1] investigating the subject of spark potential, came to a conclusion that is entirely different from that of Earhart, Kinsley and Hobbs. He states that his evidence seems conclusive that with spark-gaps down to at least 0.3 wave-length of sodium light a potential of 330 volts is not sufficient to produce discharge through air at atmospheric pressure. Almy used very small platinum spheres, 0.007 cm. in diameter, and also needle points, and he suggests that the electrostatic force which exists between two large electrodes brought within such short distances as were used by Earhart, Kinsley and Hobbs, is sufficient to bring the electrodes into contact at potentials less than the "minimum," so that the potentials that produced short circuits in the spark-gaps were simply those required to give the requisite displacement of the electrodes. If this be true, it is difficult to understand why Hobbs obtained the result that the spark discharge depends on the material of the electrodes and not on the nature of the gas in such a regular way.

Since this question has a very important bearing in the electron theory, the present investigation was undertaken not only to clear up the apparent discrepancies, but also to investigate the whole question of electric discharge at short distances.

Description of Apparatus.

The apparatus consisted of electrodes mounted on a standard Michelson interferometer made by Gaertner. The whole was inclosed in an air-tight iron box. The movable carriage of the interferometer C, Fig. 3, carried the plane electrode E, a disk about 2 cm. in diameter which was fitted carefully into the socket S and held in place by the nut N. A part of the socket S which was of greater diameter, was fitted to receive a worm screw W, by which the electrode could be turned about a longitudinal axis, thus presenting a new surface before each discharge. The shaft, on the end of which was the worm screw, was arranged so that it could be disconnected after the disk had been turned, in order that the movable

[1] Almy, Phil. Mag. (6), 16, p. 456, 1908.

carriage might be free from any vibrations or distortions of the sides of the iron box. The pressure with which the socket *S* fitted against

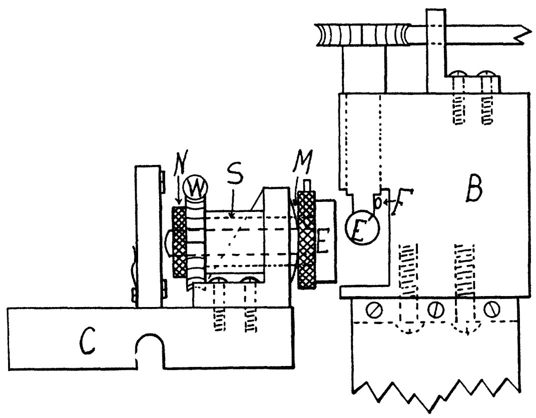

Fig. 3.

its bearings was regulated by the spring washer *M*. This was made as great as possible, the limit being that which could be overcome by the worm screw *W*.

The support of the spherical electrode was attached to the interferometer bed itself in order to avoid vibrations and to make the electrode more rigid. In the original form, this support consisted of a heavy, vertical brass plate through which passed, at an angle of about 45°, the rod carrying the ball. The bearings were carefully ground cones held in place by a heavy spring. However, it was found that this could not be made rigid enough to withstand the electrostatic forces without being pulled to the other electrode. After several changes, the arrangement shown in Fig. 3 was adopted. This consisted of a heavy brass block *B*, which could be rigidly clamped to the interferometer base. A vertical hole was drilled into this block and a section of the block removed. Into this hole was inserted a closely fitting rod carrying at its lower end the ball electrode *E'*. Although the cylinder and rod of this electrode fitted perfectly so far as could be detected, yet to guard against a possible movement of the magnitude of one wave-length of light or less, a spring *F* was placed behind the rod so that it was always held against the front surface of its receptacle. In order to take up lost motion of the movable carriage and to facilitate manipulation, heavy rubber bands were placed around the supports of the electrodes close to their bases. This device also gave greater stability.

In Fig. 4 is shown a diagram of the electrical connections. Circuit *a* consists of a galvanometer, an E.M.F. of about one volt, and the electrodes in series. The deflection of the galvanometer indicated when the electrodes were in contact, also the instant at which contact was broken. The breaking of the circuit between the electrodes could be detected to within one tenth of a fringe, or one twentieth of a wave-length of sodium light. Circuit *b* contained the source of E.M.F., the electrodes and a high resistance *R* in series. The E.M.F. was furnished by a bank of small storage cells *B*, which were connected across a water rheostat. The plunger *P* could be raised vertically, thus increasing the fall of potential between its lower end and the bottom of the tube *T*. A movement of 0.5 cm. corresponded to a change of one volt between the electrodes. A Kelvin electrostatic voltmeter, in shunt with the electrodes, was used to measure the difference of potential. This was calibrated frequently by means of a potentiometer and standard cell, and was found to be very constant. The results were also checked from time to time with a Weston standard "semi-portable" voltmeter.

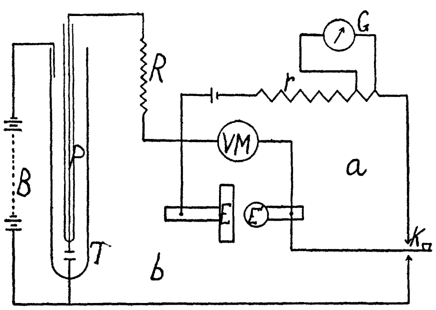

Fig. 4.

Method and Procedure.

The surfaces of the electrodes were carefully polished with fine emery powder and jewelers' rouge and placed in position. The box was then sealed, the air replaced by dry, dust-free air, and allowed to stand for some time. On beginning the observations, the electrodes were brought into contact and separated again by means of the micrometer screw, the point at which the surfaces ceased to be in contact being indicated by the galvanometer *G*. After the circuit had been broken between the electrodes, they were separated until a number of fringes n had passed the cross-hair of the telescope that was focused on them. Then $n/2$ equals the distance in wave-lengths between the plates, since the passage of a fringe corresponds to one half wave-length displacement of the carriage.[1] The main circuit b was then closed and the plunger p, of the water rheostat, raised very slowly until the discharge potential was reached. During the latter part of this increase in potential, stops of from one to two minutes were made after each increase of one volt, in order that the effect of lag might be eliminated.

Electrostatic Force Between the Electrodes.

The electrostatic force between the electrodes is a very important factor in the determination of spark potentials at very short distances. In order to gain an idea of the magnitude of this force, the following calculation was made. Experimental tests were also carried on for the same purpose.

The electrostatic force between two electrodes, one a plane and the other a sphere of 1 cm. diameter, where the electrodes are any given distance apart, say one wave-length of sodium light, may be calculated, approximately, in the following way.

Divide the plane A, Fig. 5, into areas whose boundaries are distant 1λ, 2λ, 3λ, etc., from the sphere B. Call these areas A_1, A_2, A_3, etc. We can consider any one of these areas, A_n, to be surrounded by a guard ring and compute the attraction between it and an equal area A_n', whose distance from A_n is equal to the shortest distance between A_n and the corresponding area of the sphere. This force between A_n and A_n' will be greater than the force between A_n and the above mentioned area of the sphere. Thus, by taking the sum of the forces on all the areas, we will obtain an upper limit of the attraction between the two electrodes.

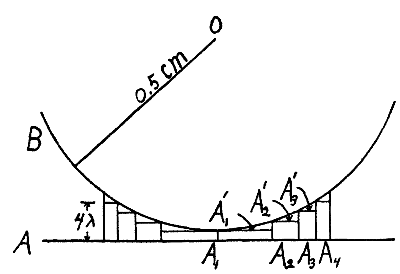

Fig. 5.

[1] Mann, Manual of Advanced Optics.

A simple geometric consideration leads to the following result:

$$A_n = \text{const.}$$
$$= 1.87 \times 10^{-4} \text{ sq. cm.}$$

The force acting on the plane A is

$$F = \sum_1^n F_{A_x}.$$

Now this force will be less than the force between the plane A and the planes A_1', A_2', etc., of Fig. 5.

Therefore,

$$F < 1.87 \times 10^{-4} \sum_1^n F'_{A_x},$$

where F'_{A_x} equals the force per unit area between any area A_x and the corresponding area A_x'. This force may be calculated from the general formula,

$$F_{\text{gr.}} = \frac{V^2 A}{8\pi d^2 g}.$$

If we assume $V = 300$ volts, *i. e.*, one electrostatic unit of potential, and $n = 20$, we get

$$F < 3.41 \text{ gr.}$$

When $n = 20$, the force per unit area is only one fourth of one per cent. of what it is when $n = 1$, and since the series is convergent, the terms after this may be neglected without introducing any appreciable error.

Maxwell[1] gives the following formula for the electrostatic force between two spheres whose radii are a and b, and the distance between whose centers is c.

$$F = \frac{1}{2}\left[V_a^2 \frac{dq_{aa}}{dc}\, 2V_a V_b \frac{dq_{ab}}{dc} + V_b^2 \frac{dq_{bb}}{dc} \right].$$

If the radius of one is taken equal to one centimeter and that of the other very great, and the distance between the electrodes is taken to be of the magnitude of one wave-length of light, the formula converges so badly that it cannot be easily applied.

[1]Maxwell, Electricity and Magnetism, Vol. I., p. 272.

Experimental Test of Stability.

The preliminary work of this investigation consisted of testing the stability of the electrodes. The electrode attached to the movable carriage was chosen upon which to experiment as it was the one to which the method of attack was most easily applied. It was tested in the following way. The mirror was removed from the carriage and a plane electrode, polished so that it would give good fringes, was mounted in its place. A spherical electrode 3 or 4 mm. in diameter was placed in front of this plane and rigidly clamped to the interferometer base. The carriage of the interferometer was loaded with extra weights placed centrally over the bearings. The electrodes were then brought into contact and separated again to distances of 1λ, 2λ, 3λ, etc., after which the voltage was applied. Repeated observations with voltages as high as 300 and spark-gaps of 1λ and 2λ showed no perceptible movement of the electrode. A movement of one fourth wave-length, or one half fringe, could easily have been detected. This showed that it was possible to construct electrodes that could withstand the electrostatic forces which exist between them without being drawn together. However, this electrode had no arrangement whereby a new surface could be presented from without an air-tight box. Later, when this arrangement was added, great difficulty was experienced in getting a construction by which the electrode was free to turn and yet retain the necessary stability. The form described on the previous pages was finally adopted. This form was not tested by the above sensitive method, since the nature of the data obtained indicated quite accurately the degree of stability.

Results.

1. *Effect of Kind of Material of Which the Electrodes Are Made upon the Discharge Potential.*—Since the primary object of this research was to investigate the effect of the material of the electrodes upon the spark potential with a view of determining therefrom the nature of the discharge, a series of observations was made with the materials platinum, silver, aluminium and brass in a number of combinations. Tables I. to IX. inclusive give the results of these observations. Distances in wave-lengths are given in the column

under λ and potential differences in volts in the column under *V*. Each table includes from two to three series taken on different days.

TABLE I.

Al+. *Al*−.

λ	V	λ	V	λ	V
1	323	2	343	3	370
1	298	2	370	3	369
1	284	2	369	3	370
1	310	2	371	5	370
1	263	2	370	5	371
1.5	357	2	370	5	371
1.5	371	3	372	5	370
1.5	368	3	359	5	372
1.5	347	3	371	5	368
1.5	370	3	371	5	371

TABLE II.

Brass+. *Al*−.

λ	V	λ	V	λ	V
1	302	1.5	300	3	369
1	372	1.5	341	3	371
1	277	1.5	372	3	368
1	258	1.5	371	3	370
1	269	1.5	369	3	370
1	347	2	346	3	366
1	370	2	370	3	371
1	371	2	371	5	369
1.5	371	2	369	5	371
1.5	369	2	339	5	371
1.5	326	2	370	5	368
1.5	370	2	350	5	369
1.5	372	2	369	5	371
1.5	348	2	370	5	370
1.5	370	3	369	5	371

Table III.

Brass –. Al +.

λ	V	λ	V	λ	V
1	371	1.5	340	3	346
1	337	1.5	371	3	370
1	324	2	325	3	369
1	346	2	370	3	370
1	369	2	369	3	371
1	369	2	357	5	363
1	289	2	371	5	369
1.5	371	2	333	5	371
1.5	310	2	371	5	371
1.5	368	2	316	5	370
1.5	370	3	368	5	369
1.5	369	3	371	5	370
1.5	354	3	370	5	372
		3	370	5	368

Table IV.

Pt +. Pt –.

λ	V	λ	V	λ	V
1	357	1.5	340	3	371
1	345	1.5	371	3	369
1	370	1.5	370	3	370
1	335	2	370	3	371
1	319	2	371	5	372
1	284	2	367	5	370
1	332	2	370	5	371
1.5	371	2	371	5	369
1.5	369	3	369	5	370

Table V.

Al +. Ag –.

λ	V	λ	V	λ	V
1	323	1.5	369	3	369
1	316	1.5	346	3	371
1	368	2	372	3	372
1	334	2	371	3	371
1.5	372	2	370	5	370
1.5	370	2	370	5	371
				5	371

Table VI.

Pt+. *Ag*−.

λ	V	λ	V	λ	V
1	241	1.5	372	3	371
1	306	1.5	370	3	372
1	331	1.5	371	3	370
1	368	2	371	5	369
1	346	2	372	5	371
1.5	372	2	372	5	372
1.5	317	2	371		

Table VII.

Brass+. *Pt*−.

λ	V	λ	V	λ	V
1	343	1.5	330	3	372
1	324	1.5	368	3	369
1	286	1.5	370	3	371
1	331	1.5	368	3	364
1	304	2	368	3	370
1	345	2	372	3	368
1	299	2	369	3	369
1	318	2	370	5	370
1.5	366	2	369	5	372
1.5	367	2	368	5	368
1.5	368	2	370	5	370
1.5	370	2	343	5	368
1.5	367	2	369	5	371
1.5	364	3	371	5	370

TABLE VIII.

Brass –. *Pt* +.

λ	V	λ	V	λ	V
1	340	1.5	306	3	371
1	262	1.5	371	3	372
1	356	2	371	3	372
1	320	2	370	3	370
1	344	2	368	3	371
1	365	2	370	5	372
1	337	2	372	5	372
1.5	372	2	367	5	372
1.5	371	2	371	5	371
1.5	372	2	370	5	372
1.5	370	2	372	5	371
1.5	372	3	372	5	371
1.5	367	3	372	5	372
1.5	370	3	369		

TABLE IX.

Al –. *Ag* +.

λ	V	λ	V	λ	V
1	255	1.5	370	3	371
1	290	1.5	338	3	372
1	321	2	372	3	372
1	273	2	372	3	372
1.5	371	2	371	5	372
1.5	304	2	370	5	372
1.5	327	2	372	5	371

The results given in these tables show beyond a doubt that the material of which the electrodes are made has no effect on the discharge potential. It is true that in those cases where aluminium is used the values for 1λ, and even for 1.5λ and 2λ, are not as consistent as in the case of other metals. This, however, is due to a mechanical difficulty. Aluminium is by far the softest metal of the above list and when attempts were made to polish it, instead of the projection being removed they were pushed into the depressions. The result was that a very good polish could be obtained yet when the aluminium electrode was subjected to strong electrostatic forces, with one of the original depressions opposite the other electrode, the material filling the depression was pulled out producing a metallic bridge and thus short circuit.

In these researches, I have not attempted to work with distances below one wave-length of sodium light. There are two reasons for this: (1) The inability to get perfectly stable electrodes, which make readings for shorter distances unreliable; (2) the limit to the degree of polish which could be obtained with the means at hand.

Not only do the above tables show that the discharge potential does not depend upon the material of which the electrodes are made, but also that there is no decrease in the discharge potential for distances below five wave-lengths of sodium light. In Fig. 6 is

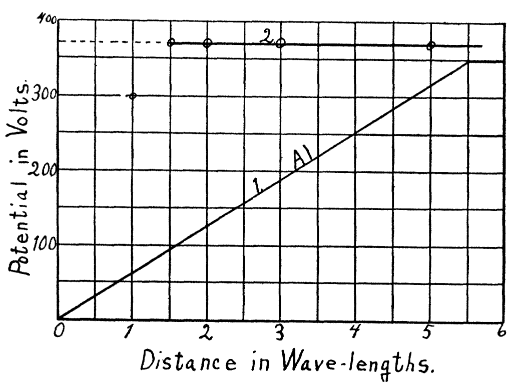

Fig. 6.

shown a representation of the results which I obtained as given in Table I. (curve no. 2), and also the curve for aluminium electrodes given by Hobbs in his paper (curve no. 1). Whereas the knee in the curve given by Hobbs occurs at 5.6λ, the same does not occur in my results until the distance between the electrodes is as short as 1.5λ or less. Since the conditions are the same with the exception of the mechanical construction, we must conclude that if we could construct perfectly stable electrodes and produce a perfect polish, the knee of the curve could be made to approach the y-axis to within at least a small fractional part of a wave-length of light. It has been calculated that an electric force of about 10^9 volts per cm. is sufficient to drag an electron out of an atom. Now, a difference of potential of 370 volts across a distance of .005 wave-length would give this force, so that within this distance the discharge might have the character of a small arc of of a hot lime cathode as suggested in the theory of J. J. Thomson.

2. *Path of the Discharge.*—Since, at atmospheric pressure, the discharge potential remains constant for distances below about 10λ, the path length of the discharge must be constant, *i. e.*, if one plane and one spherical electrode is used, as in my case, the discharge

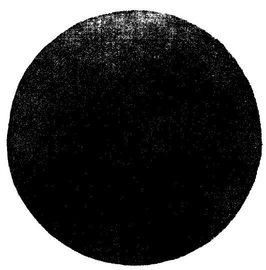

Fig. 7.

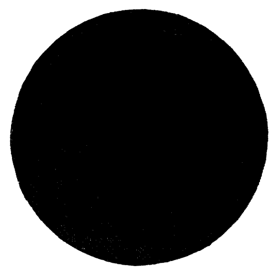

Fig. 8.

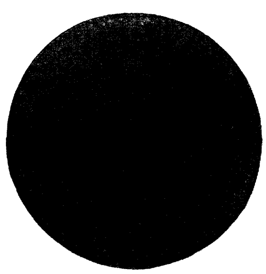

Fig. 9.

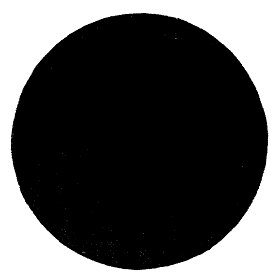

Fig. 10.

path will not be across the shortest distance. To verify this I have taken photo-micrographs of the plane electrode at the point where discharge occurs (see Figs. 7 to 10). The magnification of the photo-micrographs is 50. In Fig. 9, a capacity of .01 M.F. was shunted across the electrodes so that a thicker spark and larger pit was produced. In the other photographs no capacity was used. When the distance between the electrodes is 2λ (Figs. 7 and 8) and 3λ (Fig. 9), the discharge produces on the polished surface of the plane electrode a circle with the center entirely free from pits. Examination of the sphere showed also a circle of pits, but in the latter case it was impossible to photograph the circle because of the inability of getting large enough area of the spherical electrode within the focus of the photo-micrographic apparatus. In Fig. 10 the distance between the electrodes is 5λ and we see that the circle becomes much smaller—the space within which there are no pits having almost disappeared. Thus for distances between the electrodes equal to 2λ and 3λ it is evident that the discharge does not take place across the shortest distance, but across a place where the distance is equal to the critical distance for the pressure involved. According to the experiments of Hittorf[1] and others, we should expect that if the pressure were reduced the diameter of the circle would become greater. From the fact that each spark disturbs the metal of the electrodes, we should expect that the light of the spark should contain line spectra of the metals between which the sparks occur.

3. *Effect of Ionization by Means of Ultra-violet Light.*—I have shown that the nature of the material of which the electrodes are made has no effect upon the discharge potential, also, that the path of the discharge is not the shortest path between the electrodes when these are very close together; therefore the nature of the discharge must be the same for very short as for greater distances; *i. e.*, ionization is the important factor. If the number of ions per cubic centimeter is increased, the chances of ionization due to collision of the ions moving under the influence of the strong electric field is increased proportionally, and the spark will pass at a lower potential. In my investigations, the gas surrounding the electrodes was ionized by means of ultra-violet light for some time, in most cases from eight to ten minutes, and readings were taken the same as before. A comparison of these results, given in Tables X. to XV. with the results obtained with the same electrodes (see Tables VIII. and IX.) when no ionizing agent was present other than the electrostatic force which existed between the electrodes, substantiates the above conclusions.

[1]Hittorf, Wied. Ann., 21, p. 96, 1884.

TABLE X.

Br.—. *Pt*+.

λ	V
1.5	145
1.5	170
1.5	150
2	170
2	170
2	160
3	260
3	230
5	320
5	320

TABLE XI.

Br—. *Pt*+.

λ	V
1.5	160
2	170
2	150
2	150
2	150
3	240
3	220
5	315
5	315

TABLE XII.

Br—. *Pt*+.

λ	V
1.5	140
1.5	150
1.5	120
1.5	150
2	160
2	160
2	150
3	260
3	220
5	300
5	310

TABLE XIII.

Al—. *Ag*+.

λ	V
2	110
2	180
2	150
5	315
5	320
5	320

TABLE XIV.

Al—. *Ag*+.

λ	V
2	150
2	180
2	160
2	150
3	230
5	310
5	315
5	320

TABLE XV.

Al—. *Ag*+.

λ	V
2	190
2	160
2	160
2	150
3	210
3	260
3	240
5	310
5	310
5	330

It is interesting to note that while the electrostatic force which exists between the electrodes, which is about 5×10^6 volts per cm. when the distance is 1λ and the voltage 300, is unable to produce ionization, the force contained in a beam of light *is* able to do so. This is a strong point in favor of the electromagnetic emission theory of light as advocated by J. J. Thomson[1] and Jakob Kunz.[2]

Ionization consists in dragging an electron out of an atom or molecule. At ordinary temperatures this soon combines with another atom so that a negative ion is an atom that has acquired an electron, and a positive ion is an atom that has lost an electron.

[1]J. J. Thomson, Phil. Mag. (6), 19, p. 301, 1910.

[2]Jakob Ku nz, PHYS. REV. 29, p. 212, 1909.

If the ionizing agent is a Roentgen pulse, the distribution of energy in the electromagnetic field is continuous according to Maxwell's theory of electromagnetism. If this is true and one of the atoms struck by the pulse is ionized, why are not all ionized? It cannot be due to a special property of the atoms themselves for then ionization would be affected by temperature which is not the case.

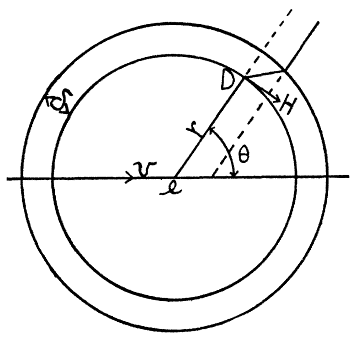

Fig. 11.

According to the theory that the distribution of energy is continuous, the tangential electric force E_t in the direction DH of Fig. 11 is

$$E_t = \frac{ev \sin\theta}{rc\delta}.$$

If

$$\begin{aligned} e &= 4.65 \times 10^{-10}, \\ \sin\theta &= 1, \\ r &= 10, \\ v &= 10^{10}, \\ \delta &= 10^{-8}, \\ c &= 3 \times 10^{10}; \end{aligned}$$

then

$$E_t = .46 \text{ volt per cm.}$$

The force with which an electron is attached to an atom may be obtained from optical phenomena. Neglecting damping by radiation, the equation of motion of an electron in an atom may be written in the form

$$m\frac{d^2x}{dt^2} = -X.$$

Let

$$X = a^2x = E_re,$$

or

$$a^2 = E_re/x,$$

where x is the displacement and E_r the restoring force.

The time of vibration of the electron is

$$T = 2\pi\sqrt{\frac{m}{a^2}}$$

$$= 2\pi\sqrt{\frac{mx}{E_r e}},$$

or

$$T^2 = \frac{4\pi^2 mx}{E_r e}.$$

therefore

$$E_r = \frac{4\pi^2 mx}{T^2 e}.$$

Take x = radius of atom = 10^{-8} cm. (approx.),

$$m = 8.8 \times 10^{-28} \text{ gr.},$$
$$e = 4.65 \times 10^{-10}.$$

If we assume that the electron vibrates with the frequency of sodium light

$$T = 2 \times 10^{-15}.$$

Then

$$E_r = 2 \times 10^5 \text{ absolute electrostatic units per cm.}$$
$$= 6 \times 10^7 \text{ volts per cm.}$$

We may also estimate the order of magnitude of E_r by considering the energy required to produce an ion, *i. e.*, $U = 4.4 \times 10^{-11}$ ergs, and writing this energy as

$$U = \int_0^x X dx = \int_0^x a^2 x dx$$

$$= \frac{a^2 x^2}{2}$$

$$= \frac{E_r e x}{2};$$

therefore

$$E_r = \frac{2U}{ex}.$$

The values of U and e are known; therefore we have only to assume the value of x, the radius of the atom, whereas in the previous consideration we had also to assume T, the period of vibration of the electron. Assuming x to be 10^{-8} cm. we have

$$E_r = 2 \times 10^7 \text{ absolute electrostatic units per cm.}$$
$$= 6 \times 10^9 \text{ volts per cm.}$$

This is 10^{10} times greater than the electrical force in a Roentgen pulse.

Since the electrical force of the Roentgen pulse is so small compared with the restoring force acting on the electron, it is surprising that any atoms are ionized at all.

A large number of pulses might, if they came regularly, ionize an atom, but in the case of Roentgen pulses there is no regularity, *i. e.*, resonance is impossible.

Let the ionizing agent be ultra-violet light. Assuming the wave theory, how long a time will be required to produce an ion? Let us assume that the maximum electric force E_0 of Fig. 12, acts all the time and that the force acts always in the same direction; also that there is no loss due to radiation, *i. e.*, no damping. Each of these assumptions will tend to make the time less than in the actual case. The velocity imparted to an electron during a half period is

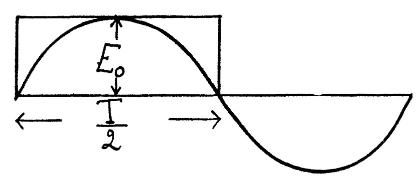

Fig. 12.

$$v = \frac{E_0 e}{m} \frac{T}{2}.$$

The kinetic energy acquired by the electron during this time will be

$$\text{K.E.} = \tfrac{1}{2} m v^2 = \tfrac{1}{8} \frac{E_0^2 e^2 T^2}{m},$$

and in one second it will acquire

$$\text{K.E.}_1 = \tfrac{1}{4} \frac{E_0^2 e^2 T}{m}.$$

Assuming the maximum electrical force E_0 of ultra-violet light to be 0.5 volt per cm., which is probably high, we have

$$E_0 = 1/600,$$
$$e = 4.65 \times 10^{-10},$$
$$T = 10^{-15},$$
$$m = 8.8 \times 10^{-28};$$

therefore

$$\text{K.E.}_1 = 1.7 \times 10^{-13} \text{ ergs.}$$

The probable value of the energy required to drag an electron out of an atom is 4.4×10^{-11} ergs. Therefore, on the above assumptions, the time required for ultra-violet light to produce one electron would be

$$\frac{4.4 \times 10^{-11}}{1.7 \times 10^{-13}} \text{ sec.} = 258 \text{ sec.}$$
$$= 4.3 \text{ min.}$$

In my investigations with ultra-violet light, given in Tables X. to XV., the effect, on applying the light to the dielectric when the potential difference was many volts below the discharge potential, was *instantaneous*. For example, while the discharge potential for a distance of two wave-lengths is 370 volts for dry air at atmospheric pressure, yet, if ultra-violet light was applied when the potential difference was as low as 250 or even 200 volts, a discharge took place instantly. In obtaining the data given in Tables X. to XV. the light was applied continuously. To begin with, a potential of 30 or 40 volts was applied; this was raised slowly until the potential was reached where discharge occurred which, in most cases, took from eight to ten minutes as stated above. Thus the wave theory cannot account for ionization by means of ultra-violet light, whereas the electromagnetic emission theory can.

It remains undetermined whether the light acts primarily on the metal, or on the molecules of the gas, or on both.

4. *Nature of the Gas: Effect of Moisture.*—Early in the course of my work some readings were taken with the electrodes surrounded by the air of the room; later the apparatus was placed in an iron box and surrounded by dry dust-free air. It was noticed that the discharge potential in the latter case was considerably higher than

in the former, although both conditions gave very consistent results. In order to determine more exactly the effect of moisture upon the

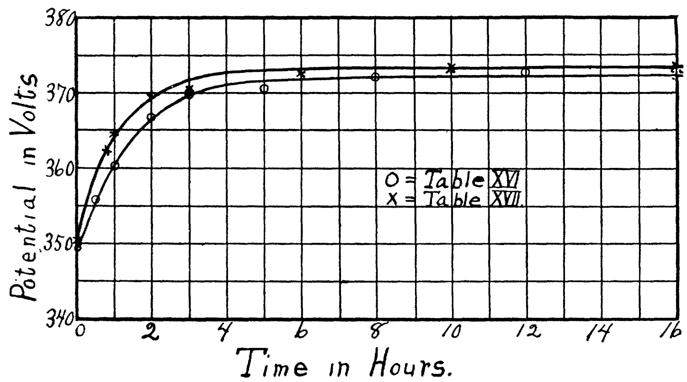

Fig. 13.

discharge potential, the apparatus was surrounded by air which had been passed through two tubes, one containing $CaCl_2$ and the other cotton-wool. The air was passed through at such a rate that

TABLE XVI. TABLE XVII.

Br −. *Pt* +. *Distance* = 5λ.

Time.	Voltage.	Time.	Voltage.
9:00 A. M.	349	11:00 A. M.	350
" "	350	" "	350
9:30 "	355	11:40 "	362
" "	357	" "	363
10:00 "	361	12:00 "	364
" "	360	1:00 P. M.	370
11:00 "	366	" "	369
" "	367	2:00 "	370
12:00 "	369	5:00 "	372
" "	370	" "	373
2:00 P. M.	371	9:00 "	373
" "	370	" "	373
5:00 "	372	8:00 A. M.	373
" "	372	" "	373
9:00 "	373		
9:00 A. M. (24 hrs.)	372		

only a part of the moisture was removed. Within the box containing the apparatus was placed a large vessel containing strong sulphuric acid. The change of the minimum potential with the degree of dryness of the air is shown in Tables XVI. and XVII., and graphically in Fig. 13. From these results it will be seen that the nature of the dielectric between the electrodes has an influence upon the discharge potential, *i. e.*, the presence of moisture lowers the discharge potential for very short as well as for greater distances. The results also indicate that for dry air at atmospheric pressure the minimum potential is 372 volts instead of 350 volts as usually given. It remains to be investigated how saturated air behaves.

Summary.

The following are the principal results which have been established by this investigation:

1. The material of which the electrodes are made has no effect upon the discharge potential.

2. The nature of the discharge for very short distances is the same as for greater distances.

3. The discharge potential for a distance between the electrodes of one wave-length of sodium light is the same as for five wave-lengths, being in both cases the minimum potential which is 372 volts.

4. When the distance between the electrodes is very short, 5λ or less, the path of the discharge is not along the shortest distance.

5. Ionization of the gas between the electrodes lowers the discharge potential.

6. The electric force in a beam of ultra-violet light is, according to the wave theory, 0.5 volt per cm.; yet the beam of light is able to produce an action which cannot be brought about by a constant electrostatic force of 5×10^6 volts per cm. This points to a modification of the wave theory as suggested by the electromagnetic emission theory of light.

7. The nature of the dielectric effects the discharge potential—the presence of moisture lowering this potential. For dry air the minimum potential is 372 volts whether the distance between the electrodes is 1λ or 5λ.

In conclusion, I desire to express my gratitude to Professor A. P. Carman for his kindly interest in my work, and to Professor Jakob Kunz for many valuable suggestions throughout the course of this investigation.

Laboratory of Physics,
University of Illinois,
April 15, 1910.

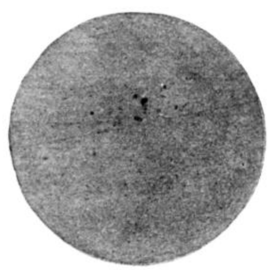

Fig. 10.

Fig. 7.

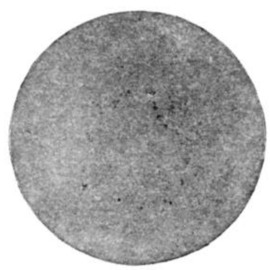

Fig. 8.

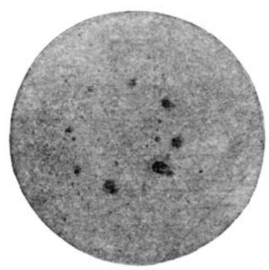

Fig. 9.