THE UNIVERSITY OF MINNESOTA

GRADUATE SCHOOL

Report
of
Committee on Examination

This is to certify that we the undersigned, as a committee of the Graduate School, have given James William Broxon final oral examination for the degree of Master of Arts . We recommend that the degree of Master of Arts be conferred upon the candidate.

Minneapolis, Minnesota

June 2, 1920

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THE UNIVERSITY OF MINNESOTA

GRADUATE SCHOOL

Report
of
Committee on Thesis

The undersigned, acting as a Committee
of the Graduate School, have read the accompanying
thesis submitted by James William Broxon.
for the degree of Master of Arts.

They approve it as a thesis meeting the require-
ments of the Graduate School of the University of
Minnesota, and recommend that it be accepted in
partial fulfillment of the requirements for the
degree of Master of Arts.

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June 2, 1918

ELECTRICAL CONDUCTION
ACROSS
MINUTE AIR-GAPS

A Thesis Submitted to the
Faculty of the Graduate School of the
University of Minnesota
by
James William Broxon
in partial fulfillment of the requirements
for the degree of
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INTRODUCTION.

(1)
A few years ago R. W. Wood, while working with thin metallic films, found that their resistance was not materially changed when they were cut completely across by several diamond rulings. Preparing special films, he found their resistance in some cases to be increased only from 10 ohms to 13 ohms, although they were separated into distinct sections by as many as twenty rulings, and the cuts, when examined with a high power microscope, appeared entirely free from metal bridges. The potentials used were from 1 to .001 volt.

He carried the investigation further and found the same effect, both when he used the semi-transparent films of interferometer plates as electrodes, and when his electrodes were optical flats, plane to $1/20$ wave-length of light, separated by quartz fibres whose diameters were of the order of 5 wave-lengths, or when they were separated by sulphur dust or by lycopodium powder. The following method was the one in which he seemed to place the most confidence, however. Using a plano-convex lens of 6-ft. focus, he protected a circular area of 5 mm. diameter on the convex surface with a metal disc, and gilded the remainder of the convex surface with a deposit of gold thrown down in a vacuum. Placing the lens carefully upon a plate of speculum metal, he was able, by allowing the lens to rest upon its ungilded portion, to find the distance between

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the points on the two metal surfaces nearest contact, by means of the system of Newton's rings formed between the lens and the plate. By placing a small weight upon the lens and shifting its position slightly, he was able to adjust the length of the shortest gap from a maximum when the center of the system of rings was at the center of the ungilded portion, to zero.

As a result of his various experiments, Wood came to the conclusion that conduction would occur between two metal surfaces when they were separated by a distance of from 20 to 30 wave-lengths of sodium light, when an electromotive force of only one volt was applied across them.

This conclusion was a contradiction to those of previous experimenters who had investigated electrical conduction across small gaps. Carr, Shaw, Almy, and Williams had carried out quantitative experiments which seemed to prove that as two conductors were brought together the voltage necessary to produce a passage of electricity between them decreased directly with the distance of their separation, the pressure remaining constant, but that when a certain minimum potential had been reached, a higher voltage was needed for conduction as the gap was still further decreased. This minimum potential was of the order of 350 volts.

- (2 W.R.Carr, Proc. Roy. Soc. lxxi, p. 374 (1903).
(3 P.E.Shaw, Proc. Roy. Soc. lxxiii, p.337 (1904).
(4 J.E.Almy, Phil. Mag.(6) 16, p.456, 1908.
(5 E.H.Williams, Phys.Rev., 31, P.216, 1910.

On the other hand, Earhart and Kinsley had found that although this same law held over a great range, when the distance became very small, say less than 3 wave-lengths of sodium light, the voltage required for conduction did decrease as the gap was decreased. Hobbs investigated this effect using different metals as electrodes, and finding that the law of the minimum potential held constant over a considerable distance until the electrodes were very near together (6 to 3 wave-lengths), that the point at which the minimum potential ceased to hold varied with the metals composing the electrodes, and that for gaps less than these the conductance did not vary with the pressure, he concluded that for these very small distances the current was carried by the metal ions, themselves. It should be noted that Williams concluded after using various metals as electrodes, that the metal had absolutely no effect on the discharge potential.

What is significant, however, is that in no case, before the experiments by Wood, had anyone observed conduction across gaps at all near the magnitude of those examined by the latter, with such low voltages as he used. Since then, Rother has done work which to a degree substantiates Wood's conclusions.

(6 R.F.Earhart, Phil.Mag.(6) 1, p.147, 1901.

(7 Carl Kinsley, Phil.Mag.(6) 9, p.692, 1905.

(8 G.M.Hobbs, Phil.Mag.(6) 10, p.617, 1905.

(9 Franz Rother, Ann. d.Physik (4) 44, p.1238, 1914.

Using interferometer methods for measuring the gap, he found conduction with very low potentials for gaps less than one wave-length, and he also found that the conductivity of the gaps varied with the conductivity of the metals forming the electrodes.

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 However, Brown, England, and Householder have performed experiments each of which seems very good evidence that Wood's suggested atmosphere of free electrons outside the surface of a metal does not exist. England used electrodes composed of a plane and a sphere, measuring the extent of the gap by interferometer methods, and found that a gap of only $1/2$ wave-length was a complete insulator for 80 to 100 volts. Brown used parallel planes as electrodes, and although he could not get perfect insulation when the plates were separated by less than nine wave-lengths, he found that he could get perfect insulation when the plates were separated by quartz fibres with diameters of the order of 10 wave-lengths, at which distance he could use the plates as a condenser. Using the formula, $C = S/4\pi d$, and finding the capacity and measuring the area of the plates, he could calculate the distance, d , between the charges. Comparing the distance between the charges with the known distance between the metallic surfaces, he found them very nearly coincident, and decided that an atmosphere of free

(10 F.C.Brown, Phys.Rev.(2) 2, p.314, 1913.

(11 C.R.England, Phil.Mag. (6) 27, p.457, 1914.

(12 F.F.Householder, Phys.Rev. (12) 4, p.47, 1914.

electrons could not extend more than two wave-lengths beyond the metallic surfaces, themselves. Householder prepared metal films similar to those used by Wood, but much narrower, only .6 mm. wide, and found that when they were cut completely across once in such a manner that no metallic bridges could be observed with a very high power microscope, the resistance was greater than 100 megohms. The cuts varied from $.3\mu$ to $.6\mu$ in width.

The PURPOSE of the PRESENT INVESTIGATION.

Although the method of Carr is not given, it should be noticed that every other experimenter mentioned as having worked with conduction across small gaps before Wood performed his experiments with electron atmospheres, found his points of true metallic contact with conduction at very low voltages. That is, they applied a potential, sometimes as low as .0002 volt and sometimes as high as 1 volt, and bringing their electrodes together very slowly, they took that point at which a galvanometer was deflected, at which a voltmeter fell to zero, or at which a telephone receiver was made to sound, as the point of metallic contact between the electrodes. Once having established this point of zero separation, they were able to measure any further separation very easily and accurately by interferometer methods. But if Wood's conclusion were true, if there were really an atmosphere of free electrons beyond the solid surface of a metal, there was evidently such a fundamental error in the observations of these previous experimenters that their results could not be taken to disprove those of Wood. The latter found his films were conducting when cut across by twenty complete rulings with applied potentials as low as .001 volt. If there were conduction across a gap between two very small areas such as those formed by a cross-section of a thin metal film, the conductance should, as Wood points out, be very much greater between two opposed planes of any considerable size. Since

either opposed planes or electrodes composed of a sphere and a plane were used by the previously mentioned experimenters with conduction across small gaps, and since they took as points of metallic contact the points at which conduction was secured with small voltages, their observations only began, if Wood's assumption be applied, at the points at which the electron atmospheres about the surfaces of their electrodes came into contact, and not with true metallic contact at all. It is true that Almy⁽⁴⁾ used very tiny spherical electrodes with radii as small as .0035 cm., but he took metallic contact as coincident with conduction with applied potentials of from 2.2 volts to 10 or 20 volts. Then so far there had been nothing which could be taken as real evidence of the lack of the existence of free electrons about the surface of a metal.

After the experiments by Wood,⁽¹⁰⁾ Brown,⁽¹¹⁾ England,⁽¹²⁾ and Rother⁽⁹⁾ have submitted papers having a direct bearing upon the subject. Rother, however, determined his points of metallic contact by the method of conduction with low voltages, in the same manner as Wood's predecessors. As for England's experiment, the reference given does not state how he determined metallic contact, but since he used interferometer methods for measuring the increase in the extent of the gap, it is reasonable to suppose that he may have determined the point of no separation in much the same manner as those other experimenters who used the interferometer in the same way. Brown's method for ascertaining that an electric charge does not extend beyond the surface of a metal is very ingenious and quite simple in theory, but since he found it impossible to secure insulation

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when his electrodes were separated by less than nine wave-lengths of light, it seems scarcely justifiable conclusively to decide that there could not have been an atmosphere of free electrons extending to that distance. Householder's experiment was very simple and direct, and was a very good indication of the non-existence of electron atmospheres. However, the surfaces exposed in his case were very small, and an effect which might have been observed with large opposed planes might easily have passed unnoticed in this case, although Wood had observed conduction in a case quite similar. Moreover, the reference given does not state the resistance of the films before the cuts were made, nor does it state the precautions taken in making contact with the films. The writer has found it quite nearly impossible to make contact directly with very thin films, so that if precautions were not taken in that respect, there may have been no conduction across the films under discussion before the cuts were made, in which case, of course, the cuts would make no difference at all.

After this survey, it seems that the question of the existence of an atmosphere of free electrons has been left a matter of some doubt. It was at the suggestion and under the supervision of Dr. W. F. G. Swann that the writer undertook the investigation of the phenomenon by a method in which all the questionable features previously referred to should be eliminated. The main problem, then, was to secure electrodes of considerable area and with extremely smooth surfaces, to establish their point of true metallic contact by other than electrical means, and to be able to measure the distance be-

tween them very accurately, as well as to be able to change this distance by very small steps. It seemed also desirable to carry out the investigation in a manner which should reproduce as nearly as possible the conditions which Wood employed, in order that it might be determined whether or not his observations could have been due to some peculiarity of the surfaces he used.

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APPARATUS.

The objectionable features mentioned were eliminated in the following apparatus:

A number of double convex lenses of large radii of curvature, and a number of double concave lenses of somewhat larger radii, all supposedly quite good optically, were examined in pairs under reflected sodium light, with regard to the system of Newton's rings secured when a convex surface was placed against a concave surface with a larger radius of curvature. No lenses were selected which did not give quite uniformly circular rings, no matter at what point on their surfaces the center of the system happened to be, and the edges of the lenses were so marked that the two most perfect surfaces might always be used together. The convex lens was 5 cm. in diameter, and the concave lens was cut down until it was 3 cm. in diameter. The edge of the concave lens adjacent to its perfect surface was then ground down and polished until the edge of the lens was a continuation of the polished concave surface throughout its circumference. The selected surfaces of the two lenses were each covered by a deposit of gold thrown down by a cathode discharge in vacuum. The cathode was a plate of gold about 4 cm. square. The concave lens was placed with its selected face upward at a distance of about 1 cm. directly beneath the cathode, and the discharge was allowed to take place for about four hours, with a vacuum of about .5 to 1 mm. pressure,

a potential of 600 to 700 volts, and a current of .4 to .8 milli-ampere. At the end of this time, the upper surface of the lens was completely covered with a uniform film slightly heavier than that known as semi-transparent. Films which did not appear uniform were rejected. The selected surface of the convex lens was covered in much the same fashion, excepting that the central portion was first protected by a metal disc (a thin brass plate supported by three pointed legs) and a heavy ring about .5 cm. in width was deposited around it. The plate was then removed and the entire surface was covered with a film like that on the concave lens, excepting that in this case the deposition was allowed to continue for only about three hours, so that the central film was quite transparent. Great care was taken to have the lenses very clean before the deposit was made, and immediately upon their removal from the vacuum they were placed under cover and carefully protected from all dust particles. The convex and concave films thus prepared served as the electrodes for the present investigation. The radius of curvature of the concave film used for most of the observations was about 206 cm., while that of the corresponding convex film was 78.5 cm. less.

The form of the apparatus made to hold the electrodes and to adjust the extent of their separation can be observed from the photographs, pp. 10, 11, and from the partial cross-sectional diagram, Fig.1, p.12. The base of the instrument consisted of two brass rings about 4 mm. thick and with external diameters of 10 cm., firmly held at a distance of 2.5 cm. from each other by three stout brass rods of .5 cm. diameter, the

continuation of these beyond the lower ring forming the legs upon which the instrument stood. These rods were fitted tightly into the two rings in the manner shown by the dotted lines in Fig. 1, and were well soldered, thus making that part of the apparatus very rigid. The upper surface of the second ring was cut down so that a raised collar was left about its inner circumference. As shown in the diagram, the top of this was cut down so that the concave lens would just fit into it, leaving a circular ledge 1 mm. in width to support the lens, and allowing it to sink only to such an extent that a little over half the thickness of the lens extended above the highest point of the collar. In one place the collar was filed away for a distance about 4 mm. in width and about 2 mm. deep, so that a small clamp, fastened to the lower side of the second ring and extending up along the cylindrical side of the lens, could be made to hold a small piece of tin foil tightly against that side without exposing any metal at an altitude as great as that of the upper surface of the lens which held the gold film. A binding post placed on the bottom ring provided direct electrical contact with the concave film.

The convex film was supported above the concave film in the following fashion. A third ring with exterior diameter the same as that of the lower two, was made with a collar along its inner circumference into which the convex lens fitted in precisely the same manner as the concave lens fitted into its collar, excepting that in this case the lens rested against the lower instead of the upper surface of the ring, the gold-covered surface being downward. The lens was held in place by

three small clamps symmetrically placed about the collar. The clamps extended only about 3 mm. over the edge of the lens, so that they did not reach farther than the heavy ring first deposited upon the convex film. A binding-post placed upon this top brass ring provided direct contact with the convex film, through the pieces of tin foil held against it by the clamps. In order that the third or top ring might be supported above the second and still be insulated from it, in a manner which would provide for the adjustment of the distance between the two, three brass rods were inserted in the base in the manner shown in Fig. 1. The ends entering the lower ring were cut down and fitted snugly into and against it, while the rods passed through holes in the second ring which were just large enough to allow them to turn freely. Thumbscrews of 2.3 cm. diameter were clamped tightly to the rods just below the second ring, and fitted snugly against it. In this fashion, the three rods could be turned slowly about vertical axes, and were still quite rigidly fixed to the base. The portions of the rods extending above the second ring, about 2.4 cm., were threaded so that there were forty threads per inch. In the third ring, holes were drilled corresponding in position to the three threaded brass rods, but with diameters considerably larger than those of the rods. Above each of these holes small bone plates were attached to the brass ring, and holes threaded to receive the threaded rods were made in them. These bone plates entirely insulated the top ring from the lower part of the apparatus, and as the convex lens was lowered, metallic contact could occur only between the opposed convex and concave films. Moreover, although the threaded rods must necessarily be turned quite nearly together, there was sufficient laxity that the films

could be brought into contact at any point desired. Three fibre plates were fastened to the top ring and from these spiral springs extended to the legs of the base, thus eliminating much of the back-lash in the screws.

By means of a small plate of glass placed in a frame at an angle of 45 degrees to the planes of the rings, the green light from a mercury arc lamp was reflected against the lenses so that a system of Newton's rings was formed by the reflections from the two gold films. In effect, then, two very thin and very smooth sections of spherical gold shells could be made to approach each other in a uniform manner. The center of the system of rings formed was observed through a traveling microscope between parallel hairs. Metallic contact was taken as occurring when the center of the system remained light and only spread out over the field when greater pressure was exerted upon the lenses. As the thumbscrews were turned in a direction which would separate the films, the center of the system was followed with the microscope. Each change in the center of the system from light to dark or from dark to light indicated an increase in the separation of the points of nearest contact between the films, of one-fourth wave-length of the green light of mercury. (The wave-length of the green light of mercury is .0000546 cm.)

By means of this apparatus it is seen that all the difficulties pointed out were eliminated. Two electrodes with large areas much smoother than could have been secured by polishing were obtained, the position of true metallic contact was established by optical means, and the distance between the points nearest contact could be delicately controlled and

measured. During part of the observations, currents passed through small insulated coils wound about the fixed legs of the base of the instrument were used for adjusting the distance between the electrodes. Very fine adjustments could be made in this manner, but after the writer had gained some experience in the manipulation of the thumbscrews, he ordinarily preferred the mechanical means because it seemed more tractable.

MEASUREMENTS.

The apparatus was first set up as is shown diagrammatically in Fig. 3, p. 12. The apparatus holding the films was connected as the unknown resistance in a Leeds and Northrup portable bridge, and the resistance of the gap was measured as the films were moved together or separated. Observations were made of the resistance of the films when true metallic contact had been made certain in the manner before described, i.e., when the center of the system of Newton's rings no longer changed color but spread out as a uniform light area. Under such conditions the resistance was quite constant, varying only as points of contact between the films were made nearer the conducting clamps. Observations of the resistance were then made, usually at every one-fourth wave-length increase in the shortest gap between the films, as determined by the successive changes in color at the center of the system of rings. Readings secured in this manner are given in table 7, 8, 9, and 10, pp.36,37. The potentials applied were 1.4 volts, provided by one dry cell. For the readings given in table 9, the bridge galvanometer was replaced by a very much more sensitive one of the moving-coil moving-mirror type. Infinite resistance in these tables is taken to mean that the resistance was greater than 9 000 000 ohms.

With some films, conduction continued in some cases until the films had been separated more than 50 wave-lengths. ("Wave-length" is taken, in the remainder of this discussion, to

be the wave-length of the green light from a mercury arc lamp, .0000546 cm.) The magnitude of the distance the electrodes had to be separated for no conduction varied largely with the points on the electrodes which were nearest contact, but with some films it was impossible to bring the electrodes within three wave-lengths of each other without conduction. It was only after repeated trials with the making of the deposits, and with particular care to keep the films at all times protected from dust particles, that films were secured which could be brought very nearly together without conduction

In order to obtain an indication of the nature of the medium providing conduction across the gaps, a test of Ohm's law was made for a constant gap of about $2 \frac{3}{4}$ wave-lengths at which there was a considerable resistance. The electrodes were connected in series with a milliammeter, and various voltages applied, the voltages being read by a milli-voltmeter constantly shunted across the gap. The connections were made as shown in Fig. 2, p. 12, if D were replaced by a couple of dry cells, G, by a milli-ammeter, and if R were absent. The resistance, $R=E/i$, which should remain constant according to Ohm's law, was calculated for each of the voltages applied. The results are given in table 5, p.35.

For the same reason, the electrodes were left separated by a constant gap whose resistance was about 25.5 ohms (this was in the bridge connection) and 3 milligrams of radium contained in a leaden case with a small slit were brought from a distant room to a position very near the electrodes. No change could be observed in the resistance of the gap. This is significant since

Williams found an immediate change in the conductance when ultraviolet light was introduced into the gap between his electrodes.

It should now be noted that the question of chief significance is not across how large an apparent gap between the electrodes conduction could be observed, but how nearly the electrodes could be made to approach without conduction. Since the films were observed to be continuous over the whole opposed surfaces of the lenses, and since considerable areas were at practically the same minimum distance from each other, if any one spot could be found at which the electrodes could be brought within two wave-lengths of each other without any conduction, and if it were certain that all other connections in the circuit were good at the same time, this one observation would be sufficient to show that there could not be a general and uniform atmosphere of free electrons extending more than one wave-length above each metal surface, and conduction across apparently greater gaps at other points could be explained by a probable roughness of the surfaces at those points.

Because of this consideration, observations were made of the magnitude of the gaps necessary for no conduction, without finding the values of the resistance during the intermediate steps, the connections remaining as in Fig. 3. The films were first brought into metallic contact and conduction was assured. Then they were gradually separated and the point noted at which conduction ceased. Causing the electrodes to approach in such a manner that the point nearest contact should remain as nearly as possible the same throughout the observation, the films were next made slowly to approach each other, and the magnitude of the

gap at which conduction was resumed was noted. Such observations were made at different places over all the areas of the films, the object being to find how nearly the films might be together at any point without conduction. Readings taken in this manner are given in table 1, 2, and 3, pp.34,35. In each case the potential applied was 1.4 volts, excepting for the last ten readings in table 2, where 2.8 volts were applied. For table 3, the bridge galvanometer was replaced by the sensitive galvanometer before mentioned.

As a check, similar observations were made in a different manner. The electrodes, one dry cell, and the sensitive galvanometer were connected in series, and the positions of no conduction were taken as those positions at which no deflection of the galvanometer could be observed when the circuit was closed. It should be noted that before each reading conduction was first secured by bringing the films into contact, thus making sure that the lack of conduction was not due to a break in any other portion of the circuit. Readings secured in this manner are given in table 4, p.35.

It was next decided to find just how large voltages must be applied to break down the resistance of the very short gaps which proved perfect insulators for small voltages. For this purpose, the apparatus was connected as shown in Fig. 2, p. 12. A rheostat of considerable resistance was connected directly in a D.C. lighting circuit. Between one end of this and the sliding contact were shunted the electrodes, a resistance of 62 000 ohms, (in order that the apparatus might not be short-circuited), and the sensitive galvanometer, all in series. A voltmeter was left permanently shunted across the same two points.

The films were first brought together and conduction established with very low voltages. They were then slowly separated and the point at which conduction ceased was noted, after which they were brought together with the same voltage and the points at which conduction was resumed were determined. When a spot had been found in this way where the electrodes could be made to approach very closely without conduction with low voltages, they were separated to a distance just greater than that at which conduction with low potentials was known to occur, and the magnitude of the gap kept constant. By adjusting the position of the sliding contact along the rheostat, the applied voltage was then very slowly increased. It was found that as the voltage was increased the electrostatic attraction between the electrodes became so great that they were drawn together, but by observing the rings their distance apart at any instant could be discerned. By waxing a weight to the lower surface of the bottom lens, and by slowly turning the thumbscrews in a direction tending to separate the films as the potentials were slowly increased, the magnitude of the gap could be kept quite constant. Since the magnitude of the gap could be continuously observed, the electrodes were sometimes separated by a greater distance than that at which it was desired to test the discharge potential, and then allowed to drift down to that distance, the magnitude of the gap at which conduction actually occurred being noted in each case. Conduction was understood to have taken place whenever the sensitive galvanometer began to be deflected. It was sometimes noticed, however, that tiny clicking sounds were given out when the gap was considerably greater than that at which general conduction occurred. The

sounds were interpreted to be the results of minute discharges which occurred before a general conduction sufficient to affect the galvanometer had taken place. They may have been due to minute metallic fingers which were burned up at the first spark. Data obtained in the manner just described may be found in table 6, p.36.

DISCUSSION of RESULTS.

From the readings given in tables, 1, 2, 3, and 4, pp. 34,35, as well as those readings listed in table 6, p.36, under "Preliminary Voltage," it is seen that with applied potentials between 1 and 4 volts, it was possible to bring the electrodes so close together that their nearest points were separated only by a gap equal to one-half wave-length of the green light of mercury, before conduction took place. This shows that at those points, and necessarily over a considerable area about those points, there was no conducting medium extending more than $1/4$ wave-length above the surface of each electrode. At other places, conduction occurred at very great distances, sometimes, as found with films later discarded, when the metallic surfaces were apparently separated by gaps of the order of 50 wave-lengths. With such films, however, it was usually impossible to find any spot at which the films could be brought within so short a distance as 3 wave-lengths of each other without conduction. It was only after repeated trials with the depositing of the films, and with particular care to keep the films at all times protected from dust particles, that metal surfaces were secured which could be made to approach to the minimum distance without conduction, and it was only at certain places on these that this could be accomplished. Conduction at a distance greater than that of minimum separation of the electrodes without conduction cannot, then, be explained by the

presence of any uniformly distributed medium in the gap, but might easily be due to metallic projections at certain points on the films, or to particles of conducting dust between them.

In this respect, it should be noted that when conduction was first established by bringing the electrodes into contact, after which they were slowly separated, conduction persisted in most cases across a much larger gap than that at which conduction was resumed, although great care was taken that the point nearest contact during the separation should be the same as that during the approach, final adjustments of the gap being made by the turning of only one thumbscrew. Such a lag might be explained by the presence of long dust particles which would adhere to the two surfaces as they were being separated but which, after they had been broken, would fall down so that the upper lens must descend much lower before establishing contact again. Or we might imagine the dust particles being distended due to the electrostatic forces acting upon them. Upon separation of the electrodes, this action would diminish until finally a point would be reached at which the particles could no longer be made to bridge the gap. It would be difficult to conceive of such a pronounced effect with a uniformly distributed medium.

When the magnitude of a gap was left constant and the amperage determined when different voltages were applied, the ratio of the voltage to the current was, as shown in table 5, p.35, as nearly constant as might be expected after considering the vibrations to which the electrodes were subject due to motions of the building, and the degree of accuracy with which the milli-ammeter and milli-voltmeter could be read. This evidence

that Ohm's law held indicates that the conduction was due to a solid medium rather than to an electron atmosphere, in which case a maximum current might have been expected.

Let us now consider the data given in tables 7, 8, 9, and 10, pp. 36,37, obtained, as explained under "Measurements," by observing the resistance at the gap as it was increased or decreased by minute steps. Curves 7, 8, 9, and 10, pp. 38,39,40,41, correspond to the data given in tables 7, 8, 9, and 10, respectively. In each case the conductance, $1/R$, is plotted vertically, while the magnitude of the gap in wave-lengths is plotted horizontally, the various scales being as stated on the pages containing the curves. Curves 7 and 8 show that the conductance may vary in a random fashion as the electrodes are separated. Curves 9 and 10, however, are quite significant. Curve 9 represents much the same sort of occurrence as that described as having been observed by Wood. As the electrodes are brought together the conductance increases "with beautiful regularity" until a point which may be assumed to be "metallic contact" is reached, at which the conductance increases rapidly to a maximum. Using a scale such that the maximum conductance may just be shown on the paper, the conductance decreases in a very regular manner with the increase of the gap until the latter is ~~the~~ ^{one} wave-lengths in extent, at which point the conductance falls to a practical zero on the first scale. Plotting the points from here on according to a new scale, as shown by the dotted curve, 9 (a), it is seen that the variation of the conductance below this point is much the same as that above it, although the magnitudes are much smaller. This, then, might be taken as evidence

of conduction first across an atmosphere of free electrons (or, as has been suggested, across a film of water) and then later across metal bridges as the electrodes were brought into actual contact. But such a supposition can scarcely be used to explain curve 10. Here much the same sort of thing is observed, excepting that in this case there are three distinct steps, each showing a very regular decrease in the conductance with an increase of the gap. Plotting curve 10 in such a way as to include the maximum conductance, the conductance falls to a practical zero at $3 \frac{1}{2}$ wave-lengths. Plotting the points from here on according to a scale which shall just include the first, a second curve, 10(a), is obtained according to which the conductance again shows a marked break at 6 wave-lengths. Plotting the points from here on according to a still larger scale, a third curve, 10(b), is obtained. Each of the curves has the same general form. In order to explain these curves by the electron atmosphere theory, we must imagine at least two distinctly different layers, or a layer of water and an atmosphere of electrons. It seems much more likely that the conduction between the electrodes as the gap was increased was due to metallic projections or to dust particles, part of which could conduct no farther than $3 \frac{1}{2}$ wave-lengths, part no farther than 6 wave-lengths, and none farther than $9 \frac{1}{2}$ wave-lengths. Assuming the presence of such particles, all the curves shown can be explained in the same way, while only curve 9 can be explained by the electron atmosphere or the water-film hypothesis.

Although the interpretation just given for the curves under discussion is that which first appeals to one, and which in the end proves most logical, it would not be wise to accept

this explanation without further investigation. The curve for the equation $y = \frac{1}{x^2}$ is smooth and continuous, yet if for values of the abscissae which give very small ordinates, the ordinates be plotted according to a greatly magnified scale, a new curve is obtained which is much like the first. This gives a figure quite similar to those we have been discussing, as is shown by the small curve for $y = \frac{1}{x^2}$, inserted at the upper right corner of the page containing curve 9. We see, then, that curves 10 might not be discontinuous unless the peculiar changes in their curvature near their lower portions are sufficient to make them so. After this consideration, let us turn to curve 11, p. 42. Here the logarithms of the resistances recorded in table 10 are plotted as ordinates against the distance of separation of the electrodes as abscissae, and it seems that the variation can best be represented by three distinct steps, each in the form of a straight line, the upper two lines being nearly parallel. Then if R represent the resistance and X the magnitude of the distance between the electrodes, the variation of the resistance with the separation through the three successive steps from the point of contact can respectively be represented by the following equations:

$$\log R_1 = a_1 X + b_1$$

$$\log R_2 = a_2 X + b_2$$

$$\log R_3 = a_3 X + b_3$$

or

$$R_1 = e^{a_1 X} \cdot e^{b_1}$$

$$R_2 = e^{a_2 X} \cdot e^{b_2}$$

$$R_3 = e^{a_3 X} \cdot e^{b_3}$$

Whence

$$C_1 = 1/R_1 = e^{-a_1 X} \cdot e^{-b_1}$$

$$C_2 = 1/R_2 = e^{-a_2 X} \cdot e^{-b_2}$$

$$C_3 = 1/R_3 = e^{-a_3 X} \cdot e^{-b_3}$$

We would expect the conductances, if they were due to metal projections or dust particles to be addible, and if

$$C' = K_1 e^{\alpha X},$$

$$C'' = K_2 e^{\alpha X}, \text{ where } C' \text{ and } C'' \text{ are individual conduct-}$$

ances,

$$C' + C'' = (K_1 + K_2) e^{\alpha X}.$$

This seems to be the case with the two higher steps, but the slope of the lower line is not quite the same. This might be supposed to be due to conduction at first through metallic projections, then through two dust particles of different dimensions, and finally through a single particle.. It is probable, however, that the conductance is to a great extent dependent upon the contacts, and the real significance of the curve is that it gives ample justification for the assumption of three distinct steps in the conductance as the electrodes were separated.

Turning to table 6, p.36 , we find the data secured by tests for the voltages necessary for conduction across gaps which were perfect insulators at lower voltages. (4) Almy pointed out that other experimenters who worked with small gaps between large electrodes may have found as discharge potentials only those potentials necessary to provide sufficient electrostatic attraction to bring the electrodes into metallic contact. In the present investigation the attraction was observed and made use of as explained under "Measurements." In each case recorded, the value given for the magnitude of the gap was the actual distance

between the reflecting surfaces at the time of discharge, but the gap between the highest metallic projections may have been much less. Considering reading no. (15), table 6, p. 36, we see that the potential gradient necessary for discharge if we consider the gap as being the distance between the reflecting surfaces of the films was about 640 000 v/cm., while if we consider it as the increase over the gap necessary for conduction with very low voltages, it was practically infinite. Considering that a gradient of only about 30 000 v/cm. is necessary for discharges at considerable distances, and that a much higher gradient was necessary for a discharge in each case herein observed, the readings given strongly indicate that a minimum potential such as that found by Carr, Almy, and others^{(2) (4)} may exist. In this respect it is important to note that in this experiment the actual distances between the metal surfaces were observed at every instant during which the potentials were applied. The phenomenon has been explained as being due perhaps to a film of denser air about the surfaces of the electrodes, perhaps to the resistance of a film of pure water adhering to them.

CONCLUSION.

Because of the fact that two metallic electrodes could be brought within a distance of from $1/2$ to 1 wave-length of the green light of mercury from each other without any conduction with applied potentials as high as 36 volts, it is plainly evident that no uniform atmosphere of free electrons conducting for low voltages, can extend more than half that distance beyond the true metallic surface of a gold electrode.

Because of the fact that Ohm's law held over a constant gap; because the introduction of radium had no effect on the conductance of the gap; because conduction persisted over a longer gap upon separation than that across which it was resumed when the electrodes were brought together; because electrodes could be brought nearer contact without conduction when great care was taken to keep them entirely free from dust; because of the tiny clicks heard during the operations made in securing the data for table 6, before general conduction was observed; and because of the peculiar forms of the curves showing the relations between the magnitudes of the gaps and their resistances, we must conclude that the conduction observed across the minute gaps was due to infinitesimal metal projections or to dust particles, rather than to any uniformly distributed medium.

The data showing the value of the voltages necessary

33

for an electrical discharge across small gaps serving as perfect insulators for small voltages, indicates that a minimum potential may be required to force an electrical discharge across minute air gaps, or at least that the potential gradient required is much greater than that required across larger gaps.

TABLE # 1.

Wave-lengths Separation of Electrodes for no Conduction.

$2\frac{1}{2}$
 1
 10
 $2\frac{1}{2}$
 $2\frac{3}{4}$
 $13\frac{1}{2}$
 $3\frac{3}{4}$
 $1\frac{1}{2}$
 $3\frac{1}{2}$
 $1\frac{1}{2}$
 $2\frac{1}{2}$
 $1\frac{1}{2}$
 3
 $2\frac{1}{2}$
 $3\frac{1}{2}$
 $3\frac{3}{4}$

TABLE # 2.

Wave-1 Sep. for no Cond. Wave-1 Sep. for Resumption of Cond.

(E.M.F.=1.4 V.)

$1\frac{1}{2}$		
$3\frac{1}{2}$		
$1\frac{1}{2}$		
$2\frac{1}{2}$		
$1\frac{1}{2}$		
3		
$2\frac{1}{2}$		
$3\frac{1}{2}$		
2	-	$1\frac{1}{2}$
2		4
$3\frac{3}{4}$		
$9\frac{1}{2}$		$7\frac{1}{2}$
6		
$3\frac{1}{2}$		$3\frac{1}{2}$

(E.M.F.=2.8 V.)

8	2
2	$1\frac{1}{2}$
$6\frac{1}{2}$	$1\frac{1}{2}$
$1\frac{1}{2}$	$1\frac{1}{2}$
$1\frac{1}{2}$	$1\frac{1}{2}$
$1\frac{1}{2}$	1
$2\frac{1}{2}$	$1\frac{3}{4}$
$4\frac{1}{4}$	2
2	$1\frac{1}{2}$
2	$1\frac{3}{4}$

TABLE # 3.

Wave-1 Sep. for no Cond.

Wave-1 Sep. for Resumption of Cond.

$1\frac{1}{8}$									
2 $\frac{3}{4}$									
$\frac{3}{4}$	-	-	-	-				$\frac{5}{8}$	
$\frac{3}{4}$								$\frac{1}{2}$	
1									
1								1	
$1\frac{1}{8}$ -								$1\frac{1}{4}$	
$3\frac{1}{2}$								2 $\frac{3}{4}$	
$5\frac{1}{4}$								4 $\frac{3}{4}$	
$3\frac{1}{2}$								3 $1\frac{1}{8}$	
$2\frac{1}{2}$								-	

TABLE # 4.

Wave-1 Sep. for no Cond.

Wave-1 Sep. for Resumption of Cond.

3									2
2									1
2									$1\frac{1}{4}$
3									$2\frac{3}{8}$
2									$1\frac{1}{4}$
3									$1\frac{1}{2}$
2									1
2									$1\frac{1}{2}$
$1\frac{1}{8}$									1
2-									$1\frac{1}{4}$

TABLE # 5.

<u>Volts.</u>	<u>Amperes.</u>	<u>Ohms.</u>
.06	.00066	91
.07	.00070	100
.10	.00060	166
.15	.00086	174
.20	.00120	166
.175	.00105	157
.22	.00130	170
.23	.00135	170
.24	.00140	170
.25	.00170	150
1.238	.00820	150
1.345	.00840	160

TABLE # 6.

<u>For Preliminary Voltages.</u>			<u>For High Voltages.</u>	
<u>Volts.</u>	<u>W-1 Sep. no Cond.</u>	<u>W-1 Sep. Res. C.</u>	<u>Test Made</u>	<u>Volts.</u>
3	$1\frac{1}{2}$			40
3	$4\frac{1}{2}$	2	$2\frac{1}{2}$	23
4	$2\frac{1}{2}$	$1\frac{1}{2}$	2	30
4	3	$1\frac{1}{2}$	$3\frac{1}{2}$	40
3	$1\frac{1}{2}$	$1\frac{1}{2}$	$1\frac{1}{2}-2$	31
4 $3/4$	2	$1\frac{1}{2}$	2	40
3 $3/4$	2	1	$1\frac{1}{2}$	38
$3\frac{1}{2}$	$1\frac{1}{2}$	$1\frac{1}{2}$	$4\frac{1}{2}$	60
2 $3/4$	2	$1\frac{1}{2}$	2	64
$3\frac{1}{4}$	$2\frac{1}{2}$	$1\frac{1}{2}$	$1\frac{1}{2}$	27
3	$1\frac{1}{2}$	1	$2\frac{1}{2}-2$	70
3	4	$2\frac{1}{2}$	3	60
$3\frac{1}{4}$	$2\frac{1}{2}$	$1\frac{1}{2}$	$2\frac{1}{2}$	52 $3/4$
$2\frac{1}{2}$	$1\frac{1}{2}$	1	1-1 (Noise) $3\frac{1}{2}$	36 $1/2$
(15) 3	2	1	1 (Noise) 4	36
3	2	$1\frac{1}{2}$	$1\frac{1}{2}$	25
3	2	$1\frac{1}{2}$	$1\frac{1}{2}$	15
4	$3\frac{1}{2}$	$1\frac{1}{2}$	5-6	$67\frac{1}{2}$

TABLE # 7.

<u>Wave-lengths Separation</u>	<u>Ohms R.</u>
0	8-
$\frac{1}{4}$	8
$\frac{1}{2}$	9
$3/4$	9 $1/3$
1	$9\frac{1}{2}$
$1\frac{1}{4}$	10
$1\frac{1}{2}$	$11\frac{1}{2}$
1 $3/4$	13
2	15
$2\frac{1}{4}$	50
$2\frac{1}{2}$	inf.

TABLE # 8.

<u>Wave-lengths Separation.</u>	<u>Ohms R.</u>
0	13.4
$\frac{1}{4}$	23.6
$\frac{1}{2}$	29.4
$3/4$	31.8
$1\frac{1}{2}$	inf.

TABLE # 9.

<u>Wave-lengths Separation.</u>	<u>Ohms R.</u>
0	19
$\frac{1}{4}$	45.7
$\frac{1}{2}$	65.5
$\frac{3}{4}$	200
1	40 000
$1\frac{1}{4}$	3 000 000
$1\frac{1}{2}$	inf.

TABLE # 10.

<u>Wave-lengths Separation.</u>	<u>Ohms R.</u>
0	16.4
$\frac{1}{4}$	19.6
$\frac{1}{2}$	21
$\frac{3}{4}$	23.1
1	25.2
$1\frac{1}{4}$	28.8
$1\frac{1}{2}$	31.7
$1\frac{3}{4}$	34.7
2	37
$2\frac{1}{4}$	37.5
$2\frac{1}{2}$	45.8
$2\frac{3}{4}$	4 600.
3	9 999.
$4\frac{1}{4}$	14 100.
$4\frac{1}{2}$	20 000.
5	33 000.
$5\frac{1}{4}$	160 000.
$5\frac{1}{2}$	250 000.
6	450 000.
$6\frac{1}{4}$	1 200 000.
$6\frac{1}{2}$	3 200 000.
7	inf.
$7\frac{1}{4}$	
$7\frac{1}{2}$	
8	
$8\frac{1}{4}$	
$8\frac{1}{2}$	
9	

No 7

CURVE NO 7

Conductance Plotted as Ordinates
Wave-lengths Separation Plotted as Abscissa

Scale of Ordinates:

31.0000 Conductance ± 10 Small Div

Scale of Abscissa:

1 Ang = 2 Large Divisions

No 8

CURVE NO. 8

Conductance Plotted as Ordinates
Wave Lengths Separation of Electrodes P.T.D. as Abs.
Scale of Ordinates
0.1 Units Conductance = 1 Large Division
Scale of Absorption
 $L_{\text{Avg}} = 2$ Large Divisions

Apr 9

40

CURVE NO 9

Conductance Plotted as Ordinates

Wave Lengths Separation of Electrodes Plotted as Abscissa

Scale of Ordinates: .01 Units Conductance = 1 Large Div.

Scale of Abscissa: 1 Ang = 3 Large Divisions

000010

000008

000006

000004

000002

000000

Apr 9 1931

CURVE NO 9 (a)

Conductance Plotted as Ordinates

Wave Lengths Separation of Electrodes Plotted as Abs.

Scale of Ordinates: .000001 Units Conductance = 5 Small Div.

Scale of Abscissa: 1 Ang = 3 Large Divisions

No 10

CURVE NO. 10

Conductance Plotted as Ordinates

Wave Lengths Separation of Electrodes Plotted as Abscissa

Scale of Ordinates: 1 Unit Cond = $1\frac{1}{2}$ Large Div

Scale of Abscissa: 1 λ_{90} = 8 Small Divisions

0.0015

0.0012

0.0008

0.0004

0.0001

CURVE NO. 10(a)

Same as No. 10 Except That

Scale of Ordinates: 10000 Unit Cond = 5 Small Div

0.00005

0.00005

0.00004

0.00003

0.00002

0.00001

No 10 (b)

CURVE NO. 10(b)

Conductance Plotted as Ordinates

Wave Lengths Separation of Electrodes Plotted as Abscissa

Scale of Ordinates: 1000000 Unit Cond = 5 Small Div

Scale of Abscissa: 1 λ_{90} = 8 Small Divisions

NaII

CURVE NaII

Log. R. Plotted as Ordinates.
Wave Lengths Separation of Electrodes Plotted as Abs.
Scale of Ordinates: 1 Unit Log. $\frac{1}{2}$ Large Division
Scale of Abscissa: 1 λ_{m} = $\frac{2}{3}$ Large Division

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