CONDUCTIVITY OF VAPOR FROM THE MERCURY ARC.

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THE ease with which an electric current passes through the vapor of a mercury arc is well known. The experiments here described show that the vapor in the neighborhood of the arc also has a high conductivity and that the cause of the ionization there found is perhaps different from the causes of ionization which have heretofore been studied. The experiments were commenced for the purpose of finding the velocity of the ions in the mercury arc by the method which had been used in studying their velocity when drawn from a flame,¹ but it was found that in the case examined new ions are produced in all regions in the neighborhood of the arc, so that the method is not applicable. The investigation was, therefore, turned to a study of these ions.

Apparatus. — The apparatus used is shown in Fig. 1. *A* and *B* are two bulbs containing the mercury, the arc being formed by the common method of tipping the tube. *C* is a platinum wire used to draw the ions from the arc, *D* is one to determine the potential near to *C*, and *E*, to determine the potential of the arc.

Fig. 1.

The potential difference between *C* and *E* was produced by the battery *F* and the current between these points was measured by the galvanometer *G*. *P* is the connection to the pump.

¹ PHYS. REV., 12, 65.

There is an objection to this arrangement in that E does not have the same potential as the arc about it, except when no current is flowing from E . A different arrangement was tried by putting a shunt between A and B and placing the battery and galvanometer between C and the middle of this shunt. But it was found that the middle of the arc did not have the same potential as the middle of the shunt. This was shown by placing an electrometer between the two points. Moreover the potential of E was continually varying. Whenever the mercury in A or B moved or even when the end of the arc shifted over the mercury, the potential of E changed. As a result the arrangement shown in the figure was used. This at least, gave results somewhat consistent with themselves and its disadvantages did not interfere with showing the principal facts for which this form of the apparatus was used.

The length of the tube was 13 cm. and the inside diameter 2.1 cm. The platinum wires were .45 mm. in diameter. The branch tube was 1.4 cm. in diameter. The distance of C from the middle of the tube AB was 6 cm.

Current between C and E Dependent upon Time.—On examining the current between C and E , it was found that when the arc was first started, the current was small, that it rapidly increased, and then decreased. This increase varied much at different times, but as an example a set of readings taken when the potential difference between C and E was 13 volts is given in Table I. The current through the arc was 4.5 amperes, and the pressure of the gas .2 mm. The first column gives the length of time that the arc had been running; column 2, the current when C was positive; and column 3, when it was negative.

TABLE I.

Time in Sec.	Current when C was Positive.	Current when C was Negative.
5	28×10^{-4}	5.7×10^{-4}
10	55	2.8
20	130	1.7
30	110	1.2
60	51	.57

The change in the current was not caused by the charge on C , for the conductivity was found to vary the same whether C was charged positively or negatively or was uncharged. It was found that the current became large much sooner, if the tube was hot when the arc was started, also that a glow gradually crept up the tube from the arc, and the conductivity became much greater when the glow reached C . The front of this appeared to be the boundary region between the hot mercury vapor and the residual gases which it was pushing out, for in this region the drops of mercury first began to appear on the sides of the glass.

Effect of Changing the Potential Difference.—Next the potential difference between C and D was varied, keeping the other conditions the same as before. With each potential difference the largest current which was observed at any time is given. Column 1 gives the potential difference; column 2, the current when C was positive; column 3, that when it was negative.

TABLE II.

Potential Difference between C and E .	Current with C Positive.	Current with C Negative.
1.5		5.1×10^{-4}
2.5		5.1
5	20×10^{-4}	5.4
8	68	5.4
11	100	5.4
13	128	5.4

With the first two voltages given with C connected to the positive side of the battery the current flowed against the E.M.F. of the cells, showing that there was an E.M.F. between C and E greater than 2.5 volts. E.M.F.'s of more than 13 volts were not used, because with so large currents the potential difference between E and the arc must become appreciable.

When the battery was placed between C and the middle of a shunt about AB , the results were much the same, except that with potential differences about 12 or 13 volts and with C positive, an arc was liable to form having C for the positive end.

The Internal E.M.F. between C and E .—The internal E.M.F.

between C and D was examined by balancing it against a variable potential difference. C was found to be negative at first, becoming positive, however, before the maximum conductivity of the gas occurred, and remaining positive.

A set of data taken are given in Table III. Column 1 gives the time in seconds from the starting of the arc and column 2, the E.M.F. in volts. The minus sign indicates that C was negative with respect to E . After the first four observations C was positive.

TABLE III.

Time in Sec.	E.M.F. in Volts.	Time in Sec.	E.M.F. in Volts.
9	-2	99	3.3
16	-3	106	3.5
33	-1.5	112	3.6
40	-1	121	3.8
44	+ .5	133	4
52	2.3	144	4.3
67	2.6	163	4.5
75	2.7	178	4.6
89	3	209	4.4

Several sets of observations were taken all similar to this. In general the change from negative to positive occurred sooner than in the data given above. It occurred at approximately the same time as that at which of maximum conductivity occurred.

The Potential Difference between C and D . — The potential difference between C and D when a current was flowing between C and E was examined by a quadrant electrometer. It was found that when the arc was first started the potential difference between C and D was nearly as great as that between C and E . After a few seconds it gradually decreased until the former was about half of the latter. This shows even more conclusively that the gas itself, aside from the layer about the electrode C , has a very high conductivity.

The experiments thus far bring out clearly three facts ; first, that the gas in the branch tube is highly conducting ; second, that this conductivity is greatest when the luminous part of the vapor first reaches the electrode ; and third, that there is an E.M.F. in the branch tube.

Ions do not Come from the Arc.—The next experiments were undertaken for the purpose of determining whether the current between *C* and *E* was carried by ions coming from the arc, or by ions produced in the neighborhood of *C*. The branch tube was replaced by one having four electrodes as shown in Fig. 2. *CD* and *EF* were connected to separate E.M.F.'s which could be varied at will. If the current was carried by ions coming from the arc, it was expected that they would all be drawn out of the vapor by *CD* leaving none for *EF*.

Fig. 2

In the experiment as tried the distance from *C* to the middle of the main tube was 5 cm.; from *D*, 5.5 cm.; from *E*, 8.3 cm.; and from *F*, 8.8 cm. The wires were platinum wires .45 mm. in diameter and coiled as in the diagram. The pressure of the gas remaining in the tube was .1 mm.

The current through *CD* was first examined and it was found that this current varied appreciably with the time and that it also depended on the direction of current between *C* and *D*. There is given in Table IV. the current at different times. Column 1 gives the number of seconds after the arc was started; column 2, the corresponding current in amperes, when *C* was positive; and column 3, that when it was negative. The E.M.F. in the circuit was 13 volts.

TABLE IV.

Time in Sec.	Current with <i>C</i> Positive.	Current with <i>C</i> Negative.	Time in Sec.	Current with <i>C</i> Positive.	Current with <i>C</i> Negative.
10	2.8×10^{-4}		85		17×10^{-4}
15		23×10^{-4}	90	5.1×10^{-4}	
20	14		95		10
25		45	100	2.8	
30	28		105		8.5
35		68	110	2.3	
40	40		115		5.7
45		85	120	1.7	
50	45		125		4.5
55		91	140	1.1	
60	34		145		3.4
65		63	160	1.1	
70	14		165		2.8
75		28	180	1.1	
80	8.5		185		2.3

It was noticed in making these observations that the time of maximum conductivity occurred a few seconds after the luminous part of the tube reached CD . Again the maximum current between E and F occurred shortly after the luminosity first reached that part of the tube.

The current through CD was then tested to learn whether it was "saturated." The data are given in Table V. Column 1 gives the potential difference between C and D in volts; column 2, the maximum current in amperes which flowed at any time with C positive; and column 3, that with C negative.

TABLE V.

Potential Difference.	Current with C Positive.	Current with C Negative.
1.2	24×10^{-4}	32×10^{-4}
2.5	42	62
5	42	83
9.5	49	97
13	57	110

The current between C and D would then appear to be "saturated" with only 5 volts, the increase after this, no doubt, being due to the fact that with stronger fields ions which are produced at greater distances from the electrodes are drawn up to them.

The current between E and F was found to vary in the same way, although it was at all times less than that between C and D , and the difference between the current flowing from E to F and that from F to E was not nearly as great as the difference in the two directions between C and D . The maximum current between E and F was 14×10^{-4} ampere.

The current through EF was further examined first when a current was flowing through CD and then with this current removed. The potential difference between C and D was 13 volts. This was more than enough to "saturate" the current, so that we had reason to believe that all of the ions passing between C and D were removed when this potential difference was applied. The current between E and F was, however, found to be the same whether any was flowing between C and D or not.

The current through EF was next tried together with a current through CF , EF being connected to an E.M.F. of 1 volt and CF to 13 volts, F being positive with respect to both C and E . In this case the current through EF was decreased from .95 to .85 milli-ampere, when the connection was made for the current to flow between E and D .

It would thus appear that none of the ions which carry the current between E and F come from the part CD and that but few of them are produced between C and F ; that is, in general the ions found outside of the arc do not come from the arc, but are produced in the immediate neighborhood of the place where they are found.

Current not over Surface of Glass.— In all of these experiments there has been nothing to prove that the current did not flow over the surface of the glass. It is conceivable that the hot mercury vapor should make the surface a conductor. A coil of steel wire which pressed tightly against the surface of the glass, was, therefore, inserted between C and D as in Fig. 3. This was connected by a platinum wire to the outside at E . C was also extended so as to pass through the coil without touching it. C and D were then

Fig. 3.

Fig. 4.

connected as before through a galvanometer and a cell, a storage cell of 2 volts was used in this case. It was found that the current between C and D was the same (approximately .002 ampere) whether E was kept at the potential of C or at that of D . This showed conclusively that the current passed through the gas and not over the surface of the glass.

Current not Caused by Rays from Arc. — It was thought that possibly rays were being given off from the arc that were making the space above it conducting. An experiment was, therefore, tried with a tube as in Fig. 4. The distances between *C* and *D* and between *E* and *F* were both approximately .5 cm. The distance from *D* to *G* was 3.5 cm. and that from *F* to *G* 4 cm. *P* was connected to the pump. Both *CD* and *EF* were connected to a galvanometer and a gravity cell.

It was found that an appreciable current first began to flow through *CD*, but that after 15 or 20 seconds the current between *E* and *F* became the larger. These experiments indicate that the ions are not produced by rays from the arc, otherwise the current between *C* and *D* in Fig. 4 would be the larger.

Fig. 5.

A tube was made as in Fig. 5, but with this there was no luminosity between *C* and *D*, nor was there any appreciable current between them at any time.

The experiments, therefore, show that the current does not flow over the surface of the glass, that it is not carried by ions from the arc, and is not produced by rays from the arc.

E.M.F. between C and D. — Examination was then made of the E.M.F. between *C* and *D*. It was measured by balancing it against a variable potential difference as when measuring E.M.F. between *C* and *E*. It was found that this E.M.F. behaved quite differently under different circumstances. When the electrodes were two coils of wire as in Fig. 2, the upper one was continually negative.

In one experiment it happened that the E.M.F. was observed when the upper electrode was a coil of platinum wire as before and the lower one a straight platinum wire as *C* in Fig. 1. With this arrangement the upper one was first positive and then negative, and finally positive again. This was found with three different tubes.

However in another tube with a similar coil above and a straight wire below and with other conditions the same, as far as was known, there was only one change of sign of the E.M.F., the coil being first positive and then negative. The data taken with this tube are given in Table 6, column 1 giving the time in seconds, and column 2, the E.M.F. in volts.

TABLE VI.

Time in Sec.	E.M.F. in Volts.	Time in Sec.	E.M.F. in Volts.
30	+ .30	108	— .17
38	+ .07	119	— .28
55	+ .07	125	— .38
68	+ .04	155	— .43
80	— .04	185	— .40
89	— .07	220	— .35
98	— .11		

It is not known why these different results were obtained. The pressure of the gas left in the tube was approximately .1 mm. in each case. There were some reasons for believing that the amount of water vapor left in the tube had some effect, but this has not yet been proven. The effect is no doubt due in some way to the greater mobility of the negative ions, but it is difficult to see just how this could produce the observed results. It needs, in fact, a much more careful study than I can at present give it, in order to give any satisfactory explanation.

Cause of the Ionization.—We see that the experiments have shown that the conductivity of the gas is produced neither by the ions from the arc, nor by rays from the arc. At first it was thought that the ions were produced by the high temperature, mercury vapor possibly ionizing more easily than other gases. The temperature, however, is not very high, and we have as yet no proof that even very high temperatures will produce ionization.

A different explanation has been suggested by Prof. Ernest Merritt, one which has much in its favor. According to this, when ions first recombine, their union is more or less incomplete. Each ion before recombining may have been a cluster of atoms with a positive or negative charge added. Two such oppositely charged clusters might become attached without the charges coming into the intimate relation which is needed for complete equilibrium. Some of these incomplete combinations might again break up much as the atoms of radium are supposed to do when subjected to some unusual atomic force. We might look upon such a group of atoms as radio-active matter produced artificially. Such a group would not be acted on by electrical forces, so that they would pass *CD* in

Fig. 3 and yet might be split up again into ions by the time they had reached EF .

It seems quite possible that such groups would be more apt to be formed with a mixture of gases at comparatively low temperature than with a single gas at high temperature. This would explain the fact that the conductivity of the gas is the greatest in the region where the mercury vapor is condensing. This is the boundary region consisting of the residual gases left in the tube and the mercury vapor which would be pushing them on. In the parts of the tube nearer the arc the continual flow of mercury vapor would have carried the other gases out and there would be nothing but mercury vapor and this would be at a high temperature. This is the region which we find has but small conductivity.

The E.M.F. Oscillatory. — When working with the arrangement shown in Fig. 3, it was noticed that the wire extending from D vibrated rapidly. It has already been found that the current through the mercury arc has rhythmic variations. A telephone was therefore connected directly between C and D . This gave a very distinct tone. The current through the arc was then passed through the primary of an induction coil and the secondary was connected to the telephone. This gave the same tone that had been produced when the telephone was connected between C and D . These experiments were tried with the current from a storage battery, in order that the fluctuations of the dynamo might be eliminated.

It was thought that possibly this rapid variation of the current through the arc might be aiding in the ionization of the gas, and an attempt was therefore made to get rid of these variations. The tube shown in Fig. 2 was used. Tin-foil was wrapped around the tube between EF and the main tube and C and D were connected to this foil, and this was then connected to the ground, but as far as could be detected this arrangement made no difference with the humming in the telephone. It certainly made no appreciable difference whether the tin-foil was connected to the ground, or left insulated. This experiment, therefore, showed nothing, except that it is very difficult to get rid of the effect due to the fluctuation of the current.

The effect could, however, be entirely stopped by connecting C and D by wire outside of the tube, showing that the humming was

produced by an E.M.F. within the tube and not by a magnetic induction outside of it.

Summary. — The following facts have been brought out by this investigation. The space in the tube connected with a mercury arc becomes highly conductive. A luminous space gradually spreads out from the arc and the front of this region has the greatest luminosity and the highest conductivity. This conductivity is not due to ions coming from the arc, nor to rays sent out by it. It is not due to any leakage over the surface of the glass. It is probably not due to the high temperature of the gas. A probable explanation is that when ions first recombine, they are in a condition of unstable equilibrium much like the atoms of radio-active matter, and often break up again, this being a form of ionization which has not heretofore been studied.

There is an E.M.F. between electrodes inserted in different parts of the tube. This is possibly due to the more rapid diffusion of the negative ions.

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