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THE LUMINOSITY OF MERCURY VAPOR DISTILLED FROM
THE ARC IN VACUO.

A Dissertation
Presented to the Faculty of
THE RICE INSTITUTE
in candidacy for the degree of
DOCTOR OF PHILOSOPHY

by

NORMAN HURD RICKER

The Rice Institute

June----1920

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THE LUMINOSITY OF MERCURY VAPOR DISTILLED FROM THE ARC IN VACUO.

1. Introduction.

It has been observed by a number of experimenters that, when an electrical discharge has been passed through a gas, the luminosity frequently persists for some time after the discharge has ceased. In many cases this luminosity has been shown to be due to a readjustment of chemical equilibrium in the gas, which has been upset by the discharge. This is very noticeably the case in the electrical discharges in oxygen, in hydrogen, and in nitrogen. Strutt (1,2,3,4,5,6,7,8,9) has extensively investigated the discharge in these gases and shown that the persistence of luminosity in oxygen is due to the chemical action of ozone, formed in the discharge, with traces of impurities present in the gas. The afterglow in nitrogen was shown to be due to the formation of atomic nitrogen which gives off light upon recombining to form molecular nitrogen, or in reaction with impurities in the gas. Also an active form of hydrogen seems to be formed by the discharge in hydrogen, which active modification, upon interacting with impurities in the gas, produces an afterglow.

However there are many other cases in which a chemical action could hardly be expected to explain the phenomenon. Of this type of afterglow, one of the most interesting examples is the case of mercury vapor.

It was observed by Stark and Reich (10) in 1903, that, if a side tube were connected to a mercury arc in vacuo, so that the mercury vapor in the arc could, by virtue of its vapor pressure, be blown out into a condensation chamber (figure 1), that this vapor which distills away remains luminous during its journey away from the arc. If this side tube is not of too small a diameter, the vapor may, under proper conditions, be made to remain noticeably luminous for a considerable distance along its journey. Stark (11,12,13) showed that this vapor was intensely ionized, and that the intensity of its luminosity could be diminished by having the vapor move through an independent electric field. This vapor was later studied by Mathies (14,15) and by Child (16,17,18). The fact that the luminosity may be quenched by means of an electric field indicates that the luminosity is intimately connected with the ions present in the vapor. Just how these ions are responsible for the luminosity is a more difficult question to answer.

A series of very careful, important and interesting experiments have been done by Strutt (19,20,21) on this vapor, as well as the vapors from other substances in the electric discharge. Strutt (21) has shown that, if the vapor is allowed to flow past the electrodes of an independent electric circuit, (as in figures 2 and 3), the luminosity of the vapor stops abruptly at the cathode, regardless of

fig 1.

fig 2.

fig 3.

whether the anode or the cathode is upstream. That is to say, the luminosity is unaffected upon passing the anode, but is quenched upon passing the cathode. Moreover the current in this independent circuit depends only upon the position of the cathode --- regardless of the disposition of the anode. Strutt reasons in the following manner. Since the luminosity stops abruptly at the cathode and does not reappear after the vapor has passed out of the electric field, the quenching of the luminosity must be due to the removal of the positive ions at the cathode. An equal number of negative ions must be removed at the anode or else the independent electrical circuit would continually charge up. The removal of these negative ions at the anode (figure 3) does not apparently affect the luminosity. Now, if the light were produced by the recombination of positive and negative ions, the rate of production of light would be proportional to the rate of recombination of ions, which, in turn, is proportional to the product of the numbers of positive and negative ions per unit volume of the vapor. Thus the removal of either positive or negative ions should stop the luminosity. Since this is not observed, Strutt comes to the conclusion that the positive ions themselves emit the light as positive ions --- the radiation being started while the ions are in the arc. This necessitates that the emission last during the time the vapor takes in moving from the arc to the place of observation --- a time which

Strutt (21) calculates to be of the order of one thousandth part of a second, which is not to be expected if the electrons in the atom radiate according to Lorentz's calculations. Lorentz (22) calculates that an electron radiating light of wave-length 6×10^{-5} cm. should lose amplitude in the ratio $\frac{1}{e}$ in 4×10^{-8} seconds, and could not therefore carry its luminosity with it for any appreciable distance. However, as Strutt (21) remarks, if the radiation is due to a uniformly revolving ring of equally spaced electrons, the system will radiate its energy very much more slowly than a single electron, and might therefore travel a considerable distance before extinction. Strutt (21) also suggests that perhaps the positive ion, while in the arc, is set into a sort of unstable state, such that it may later emit radiation by some "hang-fire" mechanism --- the actual radiation taking place over a very short interval of time, during which the ion does not travel an appreciable distance. That is to say, a positive ion leaves the arc with a certain amount of stored up energy, but does not radiate. Due to its critical state it may radiate later. After it has moved some distance, it emits its radiation in a sort of "flash" which indicates its position at the time. (The length of time before the light is emitted might be expected to be controlled by the laws of probability.) Thus the numerous ions emitting light after different intervals of time have elapsed, give an apparently continuous decay in

luminous intensity along the column of distilled vapor. This might be expected on the Bohr theory of the atom. In any case, because of the electrical properties of the vapor, as cited above, Strutt holds firmly to the view that the light is emitted by the positive ions as positive ions, and rejects the recombination theory.

Child (23) criticises these conclusions of Strutt by suggesting that, while the total number of negative ions (see figure 3) may be decreased by the removal of a fraction of them at the anode, that the density of the ions in the space between the electrodes will be unchanged if the velocity of the ions in this space is decreased by the same fraction. The number of ions passing through unit area perpendicular to the stream per second is the product of the density of the ions by their velocity. If this number of ions is altered by a given factor, the density of the ions will be unchanged if their velocity is altered by this same factor. Moreover the direction of the electric field is such as to oppose the motion of the negative ions, and so decrease their velocity.

Child (18) describes an experiment in which the luminosity is diminished in the neighborhood of an electrode charged positive with respect to the arc circuit, but offers no explanation of the phenomenon. He also notices that, if the potential of this electrode is sufficient, the luminosity is increased, being now of a greenish color. Later, by

means of an alternating current arc and a stroboscopic wheel, Child (24) finds that the luminosity persists for about a thousandth of a second after the current has ceased. Child (25) again criticises Strutt's work in a later paper. In another paper Strutt (26) presents evidence to the effect that the emitting centers are negatively charged particles, in contradiction to his previous conclusions.

In view of this difference in opinion as to the manner in which this luminosity is produced, it was thought advisable to investigate this luminosity further, with the view of deciding between several possible sources of the radiation.

II

EXPERIMENTAL ARRANGEMENTS

In the investigation of this vapor, the first apparatus used is shown in figure 4. In this apparatus, (made of glass) the arc was maintained between the mercury pool, K, and the cylindrical anode, An, made of nickel, and sealed into the glass by means of a platinum wire. The vapor from the arc passed through this anode and into the larger tube in which the four auxiliary electrodes A, B, C, D, made of a nickel wire grid of rather coarse mesh, were sealed. These electrodes were made by stretching fine nickel wires across a nickel ring 3 cms. in diameter. The wires were all parallel and spaced about 2 mms. apart. The vapor condensed at the end of the tube at K', and, by means of the connecting tube, flowed back to the cathode, K. A mercury reservoir was connected to this system, so that, by varying the pressure of the air over the mercury, the level of the mercury could be altered. The wide tube, containing the auxiliary electrodes, was surrounded by a cylindrical electric heater to prevent the mercury condensing on the walls of the tube. A slit about one centimeter wide was cut along the side of this heater parallel to its axis, through which the luminosity of the vapor could be observed. The tube in which the arc was maintained was about 2 cms. internal diameter, and the arc was about 10 cms. long. The large tube was 3.7 cms. internal diameter and 23 cms. long. The heated portion of

fig. 4.

this tube was 16 cms. long, and the auxiliary electrodes were spaced 3.5 cms. apart. A coil of nichrome wire was wound about the mercury cathode so that it could be heated, and the vaporization of the mercury thereby controlled. The apparatus was evacuated by means of a combination motor-driven oil pump and Langmuir condensation pump made by the General Electric Company. With this pump an extremely high vacuum could be obtained. The arc was started by heating the cathode until the mercury was vaporizing rapidly, and a discharge from an induction coil was then passed between the anode, An, and the electrode, A. The arc was maintained by a battery of Edison storage cells, giving about 80 volts, with a suitable resistance in series. An ammeter was inserted to measure the current through the arc, and a voltmeter was placed across the arc to measure the potential drop across the arc. The arc had a great tendency to form between the anode, An, and the mercury pool, K', but, by repeated trials, the arc could be made to "strike" in the proper manner. When running steadily with a current of three amperes, the drop in potential across the arc was about 12.9 volts.

When the arc is in operation, the vapor pressure in the arc is quite appreciable, and causes some of the vapor to be blown through the cylindrical anode, An, into the wider tube in which the auxiliary electrodes are placed. As the vapor flows down this tube, it can be clearly seen

by its reddish luminosity, for the entire length of the tube. The luminosity is, under proper conditions, quite bright, and its reddish color stands out in sharp contrast to the light from the arc itself, which is of a bluish color. However, when examined with a small pocket spectro-scope, it is seen that the spectra are the same, except for the relative intensities of the lines. If the cathode heater is stopped, so that the cathode may cool down, the luminosity of the distilled vapor becomes very faint. Thus it seems that it is necessary to supply more mercury vapor than the arc normally forms, if the luminosity is to be at all intense. Keeping the current through the arc constant, as the cathode is heated, so as to supply more vapor to the arc, the potential drop across the arc increases, and, if the cathode is very hot, so that the mercury vapor in the arc is very dense, the potential drop mounts to about 25 volts or slightly more, when the arc suddenly goes out. If the cathode heater is stopped, so that the vapor is distilling very slowly, the arc frequently goes out. Thus it seems that it is best to have the heater running for the steady maintenance of the arc as well as for producing a bright stream of distilled vapor. As well as the author is aware, this is the first time that, in such experiments, the cathode has been independently heated.

An inductance was placed in series with the arc to further steady it. It was observed that the auxiliary

electrodes, A, B, C, D, tend to charge up to a negative potential of about a volt, with respect to the anode, An, which was connected to earth.

The effect was tried of applying various potentials to the auxiliary electrodes.

III

THE POSITIVE EFFECT

If any one of the electrodes is made positive, and this positive potential slowly increased, while all other electrodes are left insulated so as to take up what potential they may, the following effects are observed. First there is a quenching of the luminosity near the electrode on the upstream side, which quenched region broadens, reaching further and further upstream until the luminosity in almost the entire region between the electrode and the arc's anode, An, has been quenched. While this has been going on, a quenching of the luminosity near the electrode on the downstream side is noticed, and, as the potential is increased, this region of quenching reaches further and further downstream. Thus there is a quenching of the luminosity in the neighborhood of the electrode and on both sides of it. All of these effects have occurred at potentials up to two volts. At two volts the luminosity in the region between the electrode and the anode, An, has become too faint to observe. It may be mentioned here that the boundary of the quenched region is not at all sharp, but is a gradual shading off. If the potential is further increased a bluish glow starts on the upstream side of the electrode, and reaches further and further upstream as the potential is increased, becoming brighter all the while. Also, during this process, the bluish luminosity passes through the elec-

trode, and, as the potential is increased, reaches further and further downstream. The important thing to notice is that the reddish luminosity is diminished on both sides of the electrode, but is not permanently quenched, for it reappears further down the tube. Moreover the bluish luminosity which in all probability is due to ionization by collision, occurs on both sides of the electrode, in its immediate neighborhood. Both of these effects may be easily explained in the following manner. As the potential of the electrode is increased, the electric field on the upstream side is increased, and the electrons in the vapor are accelerated. As the velocity of the electrons is increased the density is accordingly diminished and (assuming that the light is produced by the recombination of positive and negative ions) the luminosity is therefore decreased. As this increased velocity probably persists for some time after the electrons have left the field, the quenching on the downstream side is explained. As the electrons gradually lose this increased velocity the density increases, and the luminosity is restored. If, during this procedure, the velocity of the electrons relative to the vapor has reached a sufficient value to ionize, the production of the bluish glow is explained----the glow marking the region in which the velocity of the electrons relative to the vapor is equal to or greater than the ionizing velocity. This explanation of the quenching may be objected to on

the grounds that the number of electrons going to the electrode is greatly increased by the electric field drawing a large number of ions out of the arc, which, as we shall see later, is most certainly the case. However the increase in velocity under the electric field is of higher order than the increase in the number of electrons, so that the explanation still holds. This will be discussed again later. This positive effect is, in all probability, the effect observed by Child (18) when the auxiliary electrode is made positive with respect to some part of the arc circuit. The current to this electrode is rather large, as may be seen from the curve in figure 5, which shows the variation of the current to the electrode with the potential of the electrode. The current for five volts is seen to be over one ampere. As will be seen later, this is very much larger than when the electrode is negative.

In figure 6 is shown the manner in which the luminosity is altered as the potential of the auxiliary electrode is increased.

fig 5.

fig 6.

IV

THE NEGATIVE EFFECT

If any one of the auxiliary electrodes is given a negative potential, and this potential is slowly increased (negatively), while all other electrodes are left insulated so as to take up what potential they may, it is found that the luminosity on the upstream side is unaffected even with potentials as high as 300 volts, except within about half a millimeter of the electrode. However the luminosity on the downstream side is diminished by this procedure. If the density of the stream of distilled vapor is not too great, the luminosity on the downstream side may be, as well as can be judged, completely quenched. The potentials required for this effect vary greatly with the density of the vapor stream. If the density of the vapor stream is very small, so that the luminosity is feeble, small potentials of the order of one to three volts are sufficient to quench the luminosity. On the other hand, if the density of the vapor stream is large, potentials as high as 300 volts will not completely quench the luminosity. This seems to run parallel with the current to the electrode. In figure 7 is shown the way in which the current to the electrode varies with the potential of the electrode for negative potentials. From these curves it may be seen that, if the vapor density is small, a few volts seem to be sufficient to saturate the

fig 7.

current. However, as the density of the vapor increases, it becomes more and more difficult to obtain saturation, and the curve then resembles the curves obtained in the conductivity of flames. As the potential difference is increased the current continues to increase and the luminosity continues to decrease. However the current never becomes saturated and the luminosity is never completely quenched. This behavior of the current with respect to the potential is, in all probability, to be explained in the same manner as in the case of flames, by the large drop in potential in the neighborhood of the cathode. This is supported by the observations of Strutt (21) to the effect that almost the entire drop in potential occurs within a region very close to the cathode. It is to be expected that, as the density of the vapor increases, there are more ions swept out of the arc by the vapor stream, and as the density of the ions increases the effect should become more prominent. From figure 7 it will be noticed that the currents obtained in the negative effect range from ten milliamperes or lower to about twenty-five milliamperes. This is about one hundredth of the current obtained in the positive effect.

If the electrode, B, in figure 4, is maintained at a certain negative potential, with a milliammeter in series to measure the current, and the electrode, A, then given a negative potential, the current to B is seen to decrease.

This effect is much more marked when the density of the vapor is small. If the vapor density is large, the application of a negative potential to A does not appreciably affect the current to B. This is what we should expect from the above consideration of the currents to the electrodes, for with a dense vapor flowing past the electrode, A, only a very few positive ions are removed, and so the number of ions reaching the electrode, B, is practically the same as when A is uncharged. The important thing to notice in the case of the negative quenching is that, once the luminosity has been quenched, its quenching is permanent. That is to say, the luminosity does not reappear after the vapor has passed out of the electric field. This, together with the parallel relations of the quenching of the luminosity and the current to the electrode, seems to indicate that the quenching of the luminosity is dependent, in some manner, upon the removal of the positive ions at the negative electrode.

V

THE STRUTT ARRANGEMENT

In Strutt's (21) experiments the distilled vapor was allowed to flow past the electrodes of an independent circuit, insulated from the arc circuit, as is indicated in figures 2, and 3. These experiments of Strutt's have been discussed to some extent in the introduction. Strutt (21) found that, as the vapor flowed past the cathode of an auxiliary circuit, it had part of its luminosity removed; while, as it flowed past the anode, no change in luminosity was observed. Also the current in the auxiliary circuit is determined by the potential difference between the electrodes, and the position of the cathode. That is to say, regardless of the position of the anode, the current, for a given cathode, is the same. Also, if the vapor is made to flow past two such independent circuits in succession, increasing the current in the first circuit by increasing the potential difference between the electrodes of that circuit, decreases the current in the second circuit as is to be expected, as then more ions are removed by the first circuit, and so fewer reach the second. All of these experiments of Strutt have been repeated by the present writer and his observations verified. Moreover the current in the auxiliary circuit seems to be exactly the same, for a given potential difference, as the current in the circuit formed by the same electrode as cathode, and the anode of

the arc itself as anode. That is to say, the current is the same in the Strutt arrangement as in the negative effect, if the electrode used in the negative effect is the same electrode as the one used as cathode in the Strutt arrangement. Also, as well as can be judged, the quenching of the luminosity in the Strutt arrangement is the same as in the negative effect. It may be well to remark here that the presence of the mercury pool, K', at the end of the tube and in metallic connection with the cathode of the arc, does not seem to interfere with any of the electrical effects, either positive effect, negative effect, or the Strutt arrangement; for the connecting tube was later removed and all previously described work repeated. No differences in the results were noticed. From the shape of the curves in figure 7 it does not seem that an appreciable amount of ionization by collision goes on in connection with the negative effect. This is to be expected, as the large drop in potential occurs only in the immediate neighborhood of the negative electrode, and only the positive ions, which have small mobilities, are accelerated here. This also is the case with the Strutt arrangement. Occasionally, however, in working with the negative effect, ionization by collision does become appreciable, and then an arc forms. Whenever this happened the circuit was quickly broken to extinguish the arc and the circuit reformed. This does not happen often however. Whenever

the arc forms the color of the light is bluish, quite different from the reddish luminosity of the distilled vapor. An arc was never formed in working with the Strutt arrangement.

VI

DISCUSSION OF THE ELECTRICAL EFFECTS

The positive effect has already been discussed in some detail and an explanation of the effect given. There are, however, a few points of difficulty. In the first place we assumed that the negative ions are accelerated as they approach the positive electrode. By this we mean merely that they have their velocities relative to the vapor increased. Of course the electrons are suffering collisions during their motion, but their velocities relative to the vapor will be the product of their mobilities into the strength of the electric field. In order that this average velocity of the electrons should increase it is necessary that the electric field near the positive electrode be stronger, which is not to be expected if a large drop in potential occurs at the negative electrode. Now it is found in the conductivity of flames that placing an easily ionized salt on the cathode increases the current enormously, and makes the potential gradient more nearly uniform along the flame. In the positive effect the cathode of the auxiliary circuit is the anode of the arc itself. This anode, being in the arc itself, is surrounded by intensely ionized vapor. This should produce the same effect as a salt on the cathode of a circuit through a flame. Thus it is reasonable to suppose that, in this case, the largest drop in potential should occur at the auxiliary electrode used in the positive effect.

Now it may be seen by comparing currents in the positive and negative effects, that the currents involved in the positive effect are from twenty to one hundred times the currents involved in the negative effect. This increased conductivity must certainly be due to the cathode of the auxiliary circuit (anode of the arc) being surrounded by intensely ionized vapor. Now from later considerations it follows that there are 1.51×10^{16} molecules of mercury vapor per cubic centimeter in the distilled vapor. This corresponds to the number of molecules per cubic centimeter of any gas at 0°C . and at a pressure of .418 mm. Now if we assume that, when the positive quenching occurs, we have an electric field intensity of one volt per centimeter, the value of $\frac{X}{p}$ is 2.4 . Townsend (27) gives a series of values for the velocities of electrons in air at low pressures as a function of $\frac{X}{p}$. For $\frac{X}{p} = 2$, $U = 1.75 \times 10^6$ centimeters per second. For $\frac{X}{p} = 5$, $U = 3 \times 10^6$ centimeters per second. Now the velocity of electrons through mercury vapor might be expected to be smaller than through air, because the mercury atom is larger than the atoms making up air. However the mercury molecule consists of a single atom, while the molecules in air consist of two atoms, and so there is probably not a great amount of difference between the sizes of the mercury and air molecules. It is then probably safe to assume that the velocities of electrons in mercury vapor are the same as in air: at least they are of the same order. If we interpolate between Townsend's

values of the velocity we have $U = 2 \times 10^6$ centimeters per second, approximately. Initially the velocity of the electrons is the same as the velocity of the distilled vapor, which, from later considerations, is 3740 centimeters per second. When the electric field has been established the velocity of the electrons is 2×10^6 centimeters per second. This means that the velocity has been increased 535 times. Now by a comparison of the currents obtained in the positive and negative effects it is seen that the current in the positive effect is about thirty times the current in the negative effect, when the luminosity has been quenched. Since the current in the negative effect is a measure of the total number of positive ions flowing past per second (when the vapor density is not too large), and therefore a measure of the number of electrons when no electric field is acting (since there must then be equal numbers of positive and negative ions), it follows that, by virtue of the electric field, the total number of electrons flowing has been increased thirty times, while the velocity has been increased 535 times. The density of the electrons has then been decreased about 18 times. As the number of positive ions is probably not altered, due to their small mobilities, the luminosity should, as a first approximation, be proportional to the density of the electrons. Therefore the intensity of the luminosity

should be decreased about 18 times. This explains the decrease in luminosity on the upstream side of the electrode. In regard to the diminution of the luminosity on the downstream side there are several possibilities.

In the first place, if the mean free paths of the electrons in the vapor are sufficiently large, the electrons which do not strike the electrode (which are equal in number to the positive ions that pass through the electrode) will continue with their high velocities for a certain distance before their increased velocities are lost by collisions with the vapor. Jeans ⁽²⁸⁾ gives a series of numerical values for the mean free paths of molecules in various gases. His table does not include mercury vapor, but, for the heavy gases, it may be seen that the values are not widely different. The value given for xenon is 3.5×10^{-6} centimeters at 0° C. and 760 mms. pressure. Now both xenon and mercury vapor are monatomic gases, and their atomic weights do not differ so very widely. We can therefore take the mean free path of mercury atoms in mercury vapor to be 3×10^{-6} centimeters at 0° C. and 760 mms. pressure (if such were possible). The density of the vapor in the experimental tube was $\frac{1}{1816}$ of the value under standard conditions. We must therefore increase the mean free path 1816 times (since the mean free path, λ , is inversely proportional to the density) so that we have $\lambda = .0545$ millimeters. This is for mercury atoms. For

electrons this value must be increased by the factor $4\sqrt{2}$, which gives $\lambda = .309$ millimeters. This means that, in going one centimeter, the electron must make about 32 collisions. So, unless the electron could suffer a number of collisions without having its velocity and direction sensibly altered, we should not expect the quenching to extend this far. There are, however, several ways in which this region of quenching could be increased.

- (1) A considerable fraction of the electrons, of a given mean free path, will have actual free paths several times the mean free path. This should lengthen the region and produce a gradual shading off of the luminosity, as is actually observed.
- (2) When the velocity of an electron relative to the vapor is large it is difficult for recombination to occur, and, if the velocity is not too high, the collisions between the electrons and molecules of mercury vapor will be almost perfectly elastic. Therefore, while collisions will deflect the path of the electron in all possible directions, so that its velocity relative to the vapor is zero, still the numerical value of its velocity will decrease very slowly. By the time its velocity has dropped to a value at which recombination can take place, it has been carried along by the vapor as it flows along the

- tube. (This effect might also occur to some extent on the upstream side).
- (3) If the electric field on the upstream side of the electrode increases near the electrode there must be an excess of negative charge in the vapor. The vapor is therefore acted upon by a force in the direction of the electrode----resulting in a decrease in density of both positive and negative ions, with the corresponding decrease in the luminosity.
 - (4) The absolute temperature in the experimental tube is probably twice the absolute temperature at 0° C., and this should increase the mean free path slightly.
 - (5) It is perhaps not unreasonable to suppose that, at high velocities, the electrons may collide with the atoms without being greatly deflected, for electrons of much higher velocities, (β rays) most certainly do. This would have the same effect as lengthening the free paths of the electrons.

These five explanations are all in the right direction to explain the large region of downstream quenching. They probably all do help to increase this region----the extent to which they actually contribute is however debatable. At any rate the downstream quenching is decidedly real, and the quenched region extends downstream from a few millimeters

to two or three centimeters. It is difficult to explain the positive effect on the theory that the positive ions are the light emitters, as positive ions.

The negative effect is easily explained on either theory. If the light emitters are the positive ions themselves, the removal of the positive ions at the electrode should quench the luminosity. If the light is due to the recombination of positive and negative ions, the removal of the positive ions at the electrode will prevent them later recombining with negative ions, and so stop the luminosity.

The only effect that seems at all to stand in the way of the recombination theory is the quenching of the luminosity with the Strutt arrangement. Referring again to figures 2 and 3 on page 3, it is easy enough to explain the case (figure 2) where the negative electrode is upstream on either theory, for the removal of the positive ions should quench the luminosity. In the case shown in figure 3, however, the two theories, on first consideration, predict different effects. On the theory that the light is given out by the positive ions we should expect that the luminosity should be unaffected until the vapor has reached the negative electrode, where the positive ions are removed and the luminosity accordingly quenched, as is observed. However on the recombination theory, the removal of either positive or negative ions should diminish the

luminosity. Since the number of electrons removed at the positive electrode must be equal to the number of positive ions removed at the negative electrode, we should expect that the luminosity should be diminished at the positive electrode when the electric field is established. This, however, is not observed. The conclusions drawn from this by Strutt ⁽²¹⁾ have already been discussed, as well as Child's ⁽²³⁾ criticism of them. It appears to the present writer that Child's criticisms are just. Due to the high mobilities of the electrons at low pressures it is possible for their velocities to be very greatly altered by the electric field, even when it is weak. This will tend to prevent a decrease in the density of the electrons. We can show that the densities of the positive and negative ions must be very nearly equal in the following manner.

Suppose that all of the electrons were removed at the upstream anode. The positive ions will then continue on their path until they reach the cathode. The density of the positive ions in the space between the electrodes will probably then not vary greatly from point to point since recombination cannot occur. Let there be n ions per cubic centimeter in this region, and let e be the charge on each. Then if X be the electric field, and x the distance from the anode, measured toward the cathode, we will have

$$\frac{dX}{dx} = 4\pi ne$$

and so

$$X = 4\pi n e x + X_0$$

and

$$V = \int 4\pi n e x \cdot dx + \int X_0 \cdot dx$$

or

$$V = 2\pi n e x^2 + X_0 x + V_0$$

where V is the potential difference between the anode and the point x . Let us take $V_0 = 0$, and let $x = a$ at the cathode. Also suppose that X_0 is negligible.

Then

$$V = 2\pi n e a^2$$

Now $n e u$ is of the order of the maximum current involved in the experimental work, and is about 10 milliamperes across a cross section of about 10 square centimeters, or one milliampere across unit area.

Therefore
$$n e = \frac{i}{u} = \frac{3 \times 10^6}{3740} \text{ E.S.U.} = 8 \times 10^2 \text{ E.S.U.}$$

since the velocity, u , of the positive ions is the same as the velocity of the vapor, which, from later considerations, is shown to be about 3740 centimeters per second. Since $a^2 = 10$, this gives

$$V = 5 \times 10^7 \text{ E.S.U. or } 15 \times 10^7 \text{ volts.}$$

The actual potential difference between the electrodes is of the order of 50 volts, however. To give this actual value $n e$ should be 2.7×10^3 E.S.U. or 3.3×10^6 of the value obtained on the assumption that no electrons entered the space between the electrodes. That is to say, the value 2.7×10^3 E.S.U. represents $(n_+ - n_-)e$, where n_+ is the number of positive ions per cubic centimeter, and n_- is

the number of electrons per cubic centimeter.

We then have
$$\frac{(n_1 - n_2)}{n_1} = 3.3 \times 10^{-6}$$

which shows that the number of positive ions per cubic centimeter and the number of electrons per cubic centimeter are very nearly equal. If n_1 and n_2 are nearly equal it follows that the velocities of the electrons must be decreased by the electric field. Now a very weak field is sufficient to make a great change in the velocities of the electrons, as stated before. This can be shown in the following manner. The initial velocity of the electrons is the velocity of the vapor, 3740 centimeters per second. The velocity of the electrons relative to the vapor is the product of the mobility of the electrons into the electric field. As the field tends to retard the electrons, the actual velocity of the electrons will be $(u - kX)$ where k is the mobility. This velocity can thus be reduced to zero by a field of .0018 volts per centimeter, if we assume that the mobility of the electrons is 2×10^6 centimeters per second for a field of one volt per centimeter. The electrons are not brought completely to rest, and so the actual field must be less than this. This is in agreement with Strutt's observations that almost the entire drop in potential occurs within a region very close to the cathode. Thus, in spite of the large drop in potential at the cathode, the weak field between the electrodes

would be sufficient to slow down the electrons so that their density is unchanged. With these considerations, then, the quenching with the Strutt arrangement can be explained on either theory.

In the case in which the cathode is upstream, the electrons will be accelerated by the electric field, and their density will accordingly decrease about one thousand times. Thus if only one thousandth of the positive ions reaching the cathode enter the region between the electrodes the densities of positive and negative ions in this region will be equal. The luminosity will then be reduced to one millionth of its previous value.

The conclusions to be drawn from the electrical effects are these. The negative effect and the quenching of the luminosity with the Strutt arrangement can be explained on either theory. The positive effect can be explained very easily on the recombination theory, but an explanation on the other theory does not immediately present itself.

VII

RELATIVE QUENCHING OF THE LINES IN THE VISIBLE PART OF THE SPECTRUM.

The following lines may easily be observed in the spectrum of the distilled vapor.

*	yellow	$\lambda = 5790.$	$\text{\AA.U.}$
*	yellow	$\lambda = 5769.$	$\text{\AA.U.}$
*	green	$\lambda = 5461.$	$\text{\AA.U.}$
*	violet	$\lambda = 4358.$	$\text{\AA.U.}$
	violet	$\lambda = 4078.$	$\text{\AA.U.}$
	violet	$\lambda = 4047.$	$\text{\AA.U.}$

The lines marked with an asterisk are the most prominent, and are accordingly the ones upon which observations were made. In addition to these are two rather faint orange lines and a somewhat faint greenish-blue line.

These lines are the same lines as occur in the spectrum of the mercury arc itself, the only difference in the spectra being in the relative intensities of the lines.

The question that immediately arises is whether all lines are quenched in the same ratio, or whether some lines are more easily quenched than others. To be sure the color of the luminosity, as observed by the eye, does not seem to change when the luminosity is diminished by the electric field. Strutt also is of the opinion that the lines are quenched in the same ratio, but no quantitative measurements to determine this point were made by him. The present writer has measured the relative intensities of the four

most prominent lines before quenching to their intensities after the application of an electric field, by means of a Nutting polarization photometer in connection with a Hilger wave-length spectroscopy. The conclusions reached in these experiments were that all lines are quenched in the same ratio; or, if not, the differences are very small.

VIII

INTENSITIES OF THE VISIBLE LINES IN THE SPECTRUM
OF THE BLUISH GLOW AS COMPARED WITH THOSE IN THE LUMINOSITY
OF THE DISTILLED VAPOR

When observed with a spectroscope the light from the bluish glow shows the same lines as the reddish luminosity of the distilled vapor. However, since there is a marked difference in the color of the two types of luminosity as viewed by the eye, one would expect that this difference is due to a difference in the relative intensities of the lines in the two cases. These relative intensities have been measured by means of the Nutting polarization photometer in connection with a Hilger wave-length spectroscope. The results of these experiments showed that, when the yellow line $\lambda = 5790$. was of the same intensity in the two cases, the yellow line $\lambda = 5769$. was about six per cent more intense in the blue glow than in the reddish luminosity, the green line $\lambda = 5461$. was about 76 per cent more intense in the blue glow, and the violet line $\lambda = 4358$. was about three times as intense in the blue glow as in the reddish luminosity of the distilled vapor. It seems then that the process producing the blue glow is different from the process concerned in the production of the persistent reddish luminosity.

IX

THE ADDITION OF UN-IONIZED MERCURY VAPOR TO THE
LUMINOUS VAPOR.

The previously described experiments on the electrical quenching of the luminosity show that the luminosity is intimately connected with the positive ions present in the vapor, so that the removal of the positive ions stops the luminosity. This would indicate that the light is not produced by the influence of the intense light from the arc, for if this were the case the luminosity should occur beyond the electrodes used in the negative quenching effects. It was thought, however, that this point might well be investigated in a different manner. Accordingly the apparatus shown in figure 8 was used. In this apparatus, also made of glass, the arc was maintained between the mercury cathode and the cylindrical anode made of nickel. The cathode was provided with an independent electrical heater so that the volatilization of the mercury could be controlled. The vapor from the arc moves up the vertical tube leading to the pump. Connected with this tube on one side was a tube containing mercury which could be heated by an independent electrical heater. The mercury vapor from this tube passes through a glass jet and is blown across the main tube where it is exposed to the direct action of the light from the arc itself. It then passes into the side tube at the left where it finally condenses.

figure 8

Grids of fine nickel wire forming the electrodes A and B were placed in this tube so that the vapor passing through them could be studied.

The arc was run with about 2.4 amperes with the heater only hot enough to prevent the arc going out. In this condition the luminosity in the vertical tube above the anode was too faint to observe. The part of the tube in which the arc was formed was wrapped with asbestos, as was the first experimental tube (figure 4), to prevent the brilliant light from the arc interfering with observations. When the mercury in the side tube was heated, the mercury vapor was forced through the jet and into the side tube to the left where it could be seen condensing. A very faint luminosity appeared in this tube in the region near the electrodes A and B. This luminosity was too faint for its color to be determined, but it was found that it could be quenched by establishing a difference in potential between the electrodes A and B. It is highly probable that this luminosity is due merely to the horizontal stream of mercury vapor carrying with it some of the luminous vapor which has distilled away from the arc. This vapor was too faint to observe when it was in the vertical tube, for there was considerable light from the arc itself which had been reflected from the walls of the tube. This light is probably brighter than the faint luminosity of the distilled vapor, and so the luminosity of the latter is obscured.

However as soon as this vapor has been carried into the side tube where it is fairly dark, its luminosity is more easily observed.

When the cathode of the arc was strongly heated, a very bright column of distilled vapor could be seen in the vertical tube. In this case, when un-ionized mercury vapor was forced through the glass jet, the resulting stream of un-ionized vapor was deflected upwards and carried along by the current of luminous vapor. The stream of un-ionized vapor could be traced through the luminous vapor by its lack of luminosity. The effect is illustrated in the

figure 9.

adjoining figure (figure 9). This seems to show that the intense light from the arc itself does not produce any great amount of luminosity in unionized mercury vapor.

In this connection the dependence of the intensity of the luminosity in the distilled vapor upon the rate of volatilization of the mercury at the cathode of the arc is worthy of consideration. Due to the more rapid volatilization of the mercury the potential drop across the arc increases and, in consequence, the energy expended in the arc increases. If this energy is used up in ionization we should expect the number of ions to be increased. However the potential

drop across the arc is only increased by a few per cent by the increased vaporization of the mercury, and as the intensity of the luminosity is increased many times, we should not expect that the corresponding increase in ionization should account for the increase in luminosity. The part played by this increased supply of mercury vapor is probably to place a larger number of neutral molecules between the positive and negative ions, and so diminish their rate of recombination. This permits them to travel a greater distance away from the arc before recombining, and thereby losing their ability to produce light. When very little vapor is distilling away from the arc there are not many neutral molecules between the ions, and so the ions recombine quickly. Accordingly they have become very few in number before they have left the arc for any appreciable distance. The change in the velocity of the vapor for the different rate of volatilization and the corresponding alteration in the densities of the ions also contributes to the effect.

X

THE VELOCITY OF THE VAPOR

In all of these experiments with the luminosity of the distilled vapor it is highly desirable to know the velocity with which the vapor flows along the tube. The velocity of this vapor was calculated by Stark (11) from the potential gradient set up in the vapor due to a magnetic field perpendicular to the direction of flow. The value given by Stark is 28000 centimeters per second. Strutt (21) calls attention to the fact that the velocity of the vapor cannot exceed the molecular velocity of agitation at the temperature of the lamp. Taking this temperature to be 273° centigrade Strutt gives 50000 centimeters per second for the velocity of molecular agitation and therefore sets this as an upper limit for the velocity of the vapor.

It was thought highly desirable to attempt a direct measurement of the velocity of the vapor. Accordingly the first apparatus (figure 4) was arranged as illustrated in figure 10. The anode of the arc was earthed and an audion oscillator arranged so as to cause the potential of one of the electrodes (B) to vary harmonically from zero to about 100 volts negative potential. In this way the electrode would alternately stop the luminosity and let it through. Accordingly "puffs" of luminosity were sent down the tube with the velocity of the vapor. The tube was then observed through the holes of a stroboscopic wheel. When the strobo-

Potential of electrode B made to fluctuate between 0 and -100 volts by means of the audion oscillator. Luminosity observed through a stroboscopic wheel with frequency of intermittance same as frequency of oscillator. Luminous puffs then appear to stand still and can be measured.

figure 10

scopic wheel was run at such a speed that the frequency of intermittance of vision was the same as the frequency of the audion oscillator the "puffs" of luminosity appeared to remain stationary so that the distances between them could be measured. This of course is because when a hole in the stroboscopic wheel passes, the luminosity in the tube is seen during a very short interval of time, during which the vapor has not moved appreciably. When the next hole passes, the "puffs" immediately behind have moved into the same position as the previous "puffs" and the appearance is the same. If n is the frequency of the oscillator and λ the distance between similar parts of two successive "puffs", then the velocity, U , of the vapor in the center of the tube is given by

$$U = n \cdot \lambda$$

The "puffs" as experimentally observed appeared to be equally spaced, showing that the velocity of the vapor did not change rapidly as the vapor moved along the tube. However only three or four "puffs" could be seen at one time, and so this point deserves further consideration. The frequency of the oscillator was adjusted until λ was 2.0 centimeters. The frequency of the oscillator was then found to be 1870 vibrations per second. This gives

$$U = 3740 \text{ centimeters per second.}$$

It is planned to make use of this method to study very carefully the way in which the velocity of the vapor varies as the vapor moves along the tube. It is also hoped to be able to study the transition from viscous to turbulent flow. All of these may be very conveniently studied as the motion of the vapor can be traced visually.

In the determination of the velocity the current through the arc was 3 amperes and the cathode was just sufficiently hot to produce a good distillation of luminous vapor. This was the condition under most of the conductivity and quenching effects were studied.

XI

THE DENSITY OF THE VAPOR.

If we know the velocity of the vapor as it flows along the tube, and the cross-sectional area of the tube, we can calculate the density of the vapor by measuring the rate of distillation of the mercury. To measure the rate at which the mercury distills, the original apparatus (figure 4) was altered as shown in figure 11. The tube connecting the mercury pool K' with the cathode K , was cut and separate tubes forming barometric columns were run down from each to the vessels R and S filled with mercury. In the side of the vessel S was an overflow tube which led to the beaker, T . The arc was run at a current of one ampere with the cathode heater at the same temperature as when the previous experiments were done. With the apparatus in normal operation the mercury in the vessel R was kept at a fixed level by pouring mercury in as it distilled away from the cathode. As the mercury condensed at the end of the tube at K' it flowed into the vessel S , and the overflow was caught in the beaker, T . The mercury which overflowed in a known time was caught and weighed. The rate of distillation of the mercury could then be determined. Let r be the rate of distillation of the mercury in grams per second. Then if a is the cross-sectional area of the tube and V the average velocity of the vapor over the cross-section, the density, d , of the vapor is given by

figure 11

$$r = a \cdot V \cdot d$$

Now V will be $\frac{1}{2} U$ if the flow is not so fast as to be turbulent, or 1870 centimeters per second. The diameter of the tube was 3.7 centimeters, which gives $a = 10.76$ square centimeters. In one hour 356.91 grams of mercury distilled over---giving $r = .0991$ grams per second.

Thus $d = 4.95 \times 10^{-6}$ grams per cubic centimeter.

The mass of the mercury atom is 3.25×10^{-22} gram.

There are then 1.51×10^{16} molecules of mercury per cubic centimeter of the vapor.

XII

THE NATURE OF THE FLOW OF THE VAPOR ALONG THE TUBE

It has been shown by Reynolds ⁽²⁹⁾ that, when a fluid flows along a uniform circular tube, the flow will be governed by the laws of steady viscous flow provided the average velocity of the fluid across a cross-section does not exceed a certain critical velocity. If the average velocity exceeds this critical velocity, the flow will be turbulent. If W is this critical velocity, W is given by

$$W = \frac{1000 \mu}{a \rho}$$

where μ is the viscosity; a , the radius of the tube; and ρ , the density of the fluid. Taking the viscosity of the mercury vapor at 273° centigrade to be 5×10^{-4} , the radius of the tube 1.85 centimeters, and the density of the vapor 4.95×10^{-3} grams per cubic centimeter, we have

$$W = 54000 \text{ centimeters per second,}$$

which is many times our experimentally determined velocity. Thus we are safe in assuming that the flow of the vapor is governed by the ordinary viscous equations. If a gas of viscosity μ flows along a uniform circular tube of radius a and length L , then, if p_1 is the pressure at one end and p_2 the pressure at the other end, the relation connecting these quantities is

$$\mu p v = \frac{(p_1^2 - p_2^2)}{8L} (a^2 - r^2) \quad (30)$$

where v is the velocity of the vapor at a point where the pressure is p --- remembering that pv must be constant along a stream line to prevent the accumulation of gas at a point. r is the radial distance of the point from the axis of the tube. Since we know v at some point near the beginning of the tube, and from the density and temperature can calculate p , we know pv and can take p here to be p_1 . We then have

$$p_1^2 = p_2^2 - \frac{8\mu p_1 v_1}{a^2} L \quad \text{at the center of the tube.}$$

Now a density of 4.95×10^{-6} grams per cubic centimeter at a temperature of 273° centigrade corresponds to a pressure p of .836 millimeters of mercury, or 1.116×10^3 dynes per square centimeter.

$$\begin{aligned} \text{So} \quad p_1^2 &= 1.245 \times 10^6 \\ v_1 &= 3740. \\ \mu &= 5 \times 10^{-4} \\ a^2 &= 3.42 \end{aligned}$$

$$\text{So} \quad p_2^2 = 1.245 \times 10^6 - 4.88 \times 10^3 L$$

$$\text{When } L = 0 \text{ centimeters,} \quad p_2 = 1.116 \times 10^3$$

$$\text{When } L = 40 \text{ centimeters,} \quad p_2 = 1.026 \times 10^3$$

$$\frac{p_1 - p_2}{p_1} = \frac{.09}{1.116} \quad \text{or } 8 \text{ per cent.}$$

Thus there is not a very great decrease in density in a distance of forty centimeters along the tube. It must also be borne in mind that a decrease in density necessitates an increase in velocity. However the velocities with which we are dealing are of the order of $\frac{1}{7}$ th of the velocity of molecular agitation, and therefore of the maximum possible velocity. This approach toward the limiting velocity should tend to prevent the velocity increasing as much as our theory indicates. Attention might well be called to the fact that the relation between the pressure and the distance along the tube is parabolic, and so if the pressure falls by 8 per cent in forty centimeters, the fall in pressure for the first part of the tube will be less than the proportional amount given by a uniform pressure gradient.

These calculations, together with the experimental observations that the luminous "puffs", in the velocity determinations, are equally spaced should permit us to take the velocity of the vapor along a streamline as constant, without any great error. We may then use the simpler equations for the case of an incompressible liquid.

XIII

THE THEORY OF THE DECAY IN THE INTENSITY OF THE LUMINOSITY
AS THE VAPOR FLOWS ALONG THE TUBE

Let us consider a number of possible ways in which the positive ions could be responsible for the luminosity of the distilled vapor.

- (1) In the first case let us assume the hypothesis that the positive ions do not emit the light during their entire journey from the arc, but that they are set into some sort of unstable state by the arc, such that when they emit light it is by some "hang fire" method. That is to say, the ions travel away from the arc without emitting light. Suddenly, while they are still positive ions, they emit light---the time during which the light is emitted being so small that the ion does not travel an appreciable distance during emission. The ions are, however, continually disappearing by recombination. The light intensity is thus proportional to the number of positive ions per cubic centimeter at any point.
- (2) In the second case we will take as our hypothesis that the light is produced during recombination of the positive ions to form neutral molecules. Thus the light intensity is proportional to the rate of recombination, which in turn is proportional to the square of the number of positive ions per cubic centimeter (since there are equal numbers of positive and negative ions).

- (3) In the third case we will take as our hypothesis that the positive ions themselves emit the light---the emission occurring continually during their journey from the arc. The number of ions, however, is continually decreasing because of recombination. Thus the intensity of the light should be proportional to $n e^{-\lambda t}$, where n is the number of positive ions per cubic centimeter, and t is the time.

These various ways in which the positive ions could produce the luminosity should give rise to different laws of decay as the vapor flows along the tube. Accordingly it was hoped that, by comparing the rate at which the luminosity decayed experimentally with the rates predicted by these several hypotheses, the correct hypothesis could be determined. For the present we shall consider only cases (1) and (2). Case (3) will be discussed in the next chapter.

Let us consider a tube of uniform circular cross-section along which the vapor is flowing. Let us suppose also that the velocity, v , of the vapor is constant at all points in the tube. Let x represent the distance of any point in the vapor from some fixed plane placed perpendicular to the axis of the tube, the distance being measured in the direction of flow of the vapor. Let there be N_0 positive ions per

cubic centimeter at $x = 0$. At any point at a distance x along the tube we will have,

$$\frac{dn}{dt} = -\alpha n^2 \quad (1)$$

where n is the number of positive ions per cubic centimeter.

But $\frac{dx}{dt} = v$

so $dn = -\alpha n^2 dt$ becomes

$$dn = -\frac{\alpha}{v} n^2 dx$$

Integrating

$$\int_{N_0}^n \frac{dn}{n^2} = -\frac{\alpha}{v} \int_0^x dx$$

$$\frac{1}{N_0} - \frac{1}{n} = -\frac{\alpha}{v} x$$

from which $n = \frac{1}{\frac{1}{N_0} + \frac{\alpha}{v} x}$ (2)

Case (1) then gives $I \propto \frac{1}{(A + Bx)}$ (3)

Case (2) then gives $I \propto \frac{1}{(A + Bx)^2}$ (4)

Neither of these relations agree with the observed experimental variation of the intensity of the luminosity along the tube---even approximately. We should not have

expected agreement, however, for we have assumed that the velocity of the vapor is uniform across a cross-section, while we have good reason to believe that the flow of the vapor is governed by the equations of steady viscous flow. Nevertheless the above equations will hold regarding the luminosity along a fine elementary tube of infinitesimal cross-sectional area with it's axis along a streamline of the actual tube.

Let us now consider the vapor as flowing along the tube as governed by the equations of steady viscous flow. Let us also suppose that the velocity is independent of x , and that at $x = 0$ the number of positive ions per cubic centimeter is uniform across the cross-section of the tube and is equal to N_0 . Then, if U is the velocity of the vapor along the axis of the tube, the velocity v at a radius r from the axis will be given by

$$v = U \frac{a^2 - r^2}{a^2} \quad (5)$$

where a is the radius of the tube. The number of ions per cubic centimeter now becomes a function of both x and r .

$$n = \frac{1}{\frac{1}{N_0} + \frac{1}{U(a^2 - r^2)} x} \quad (6)$$

which may be written as

$$n = \frac{A}{C - Dr^2} - \frac{Br^2}{C - Dr^2} \quad (7)$$

where $A = U N_0 a^2 \quad (8)$

$$B = U N_0 \quad (9)$$

$$C = U a^2 + N_0 \alpha a^2 x \quad (10)$$

$$D = U \quad (11)$$

Now in making observations on the intensity of the luminosity in the tube, the light which is observed is the light from all points on a diameter of the tube. The total

light observed may then be written in the form of an integral

$$I = 2 \int_0^a I_r dr \quad (12)$$

where I_r is the intensity of the light from a point at a radial distance r from the axis of the tube. In the

figure 12

above, x is held constant.

Let us now take case 1, where I_r is proportional to n . Except for a constant we may then write

$$I_1 = \int_0^a n \cdot dr$$

the subscript 1 referring to case 1.

$$I_1 = A \int_0^a \frac{dr}{C - Dr^2} - B \int_0^a \frac{r^2 dr}{C - Dr^2} \quad (13)$$

We may, at any time, drop any constant factor, since the unit in which I is measured is arbitrary.

$$I_1 = \frac{A}{D} \int_0^a \frac{dr}{\frac{C}{D} - r^2} - \frac{B}{D} \int_0^a \frac{r^2 dr}{\frac{C}{D} - r^2}$$

Let $\frac{C}{D} = b^2$ and for r substitute $r = b \cos \beta$
 then $dr = -b \sin \beta \cdot d\beta$

$$I_1 = \frac{A}{D} \int_{r=0}^{r=a} \frac{-b \sin \beta d\beta}{b^2 - b^2 \cos^2 \beta} - \frac{B}{D} \int_{r=0}^{r=a} \frac{-b \sin \beta b^2 \cos^2 \beta \cdot d\beta}{b^2 - b^2 \cos^2 \beta}$$

$$I_1 = \frac{-A}{Db} \int_{r=0}^{r=a} \frac{d\beta}{\sin \beta} + \frac{Bb}{D} \int_{r=0}^{r=a} \frac{\cos^2 \beta}{\sin \beta} \cdot d\beta$$

$$I_1 = -\frac{A}{Db} \int_{r=0}^{r=a} \frac{d\beta}{\sin \beta} + \frac{Bb}{D} \left[\int_{r=0}^{r=a} \frac{d\beta}{\sin \beta} - \int_{r=0}^{r=a} \sin \beta \cdot d\beta \right]$$

$$I_1 = \left[\left(\frac{Bb}{D} - \frac{A}{Db} \right) \log \tan \frac{\beta}{2} + \frac{Bb}{D} \cos \beta \right]_{\cos \beta = 0}^{\cos \beta = \frac{a}{b}}$$

$$I_1 = \left[\left(\frac{Bb}{D} - \frac{A}{Db} \right) \log \sqrt{\frac{1 - \frac{a}{b}}{1 + \frac{a}{b}}} + \frac{Ba}{D} \right]$$

$$I_1 = \left[\frac{1}{2} \left(\frac{Bb}{D} - \frac{A}{Db} \right) \log \frac{b-a}{b+a} + \frac{B}{D} a \right]$$

But $\frac{B}{D} = N_0$ and $\frac{A}{D} = N_0 a^2$ so

$$I_1 = \frac{1}{2} \left(N_0 b - \frac{N_0 a^2}{b} \right) \log \frac{b-a}{b+a} + N_0 a$$

$$I_1 = \frac{b^2 - a^2}{2b} \log \frac{b-a}{b+a} + a. \quad \text{Taking out any constant multiplier of } I.$$

$$I_1 = 1 + \frac{b^2 - a^2}{2ab} \log \frac{b-a}{b+a}$$

but $b^2 = \frac{C}{D} = a^2 + \frac{N_0 \alpha}{U} x a^2 = a^2 \left(1 + \frac{N_0 \alpha}{U} x \right)$

$$I_1 = 1 + \frac{a^2 \left(1 + \frac{N_0 \alpha}{U} x \right) - a^2}{2 a^2 \left(1 + \frac{N_0 \alpha}{U} x \right)^{\frac{1}{2}}} \log \frac{a \left(1 + \frac{N_0 \alpha}{U} x \right)^{\frac{1}{2}} - a}{a \left(1 + \frac{N_0 \alpha}{U} x \right)^{\frac{1}{2}} + a}$$

$$I_1 = 1 + \frac{kx}{2(1+kx)^{\frac{1}{2}}} \log \frac{\sqrt{1+kx}-1}{\sqrt{1+kx}+1}. \quad \text{Calling } \frac{N_0 \alpha}{U} = k$$

So

$$I_1 = 1 - \frac{kx}{2(1+kx)^{\frac{1}{2}}} \log \frac{\sqrt{1+kx}+1}{\sqrt{1+kx}-1} \quad (14)$$

==

Let us now take case 2, where I_p in (12) is proportional to n^2 . Except for a constant factor we may then write

$$I_2 = \int_0^a n^2 dr$$

and from (7)

$$I_2 = A^2 \int_0^a \frac{dr}{(C - Dr^2)^2} - 2AB \int_0^a \frac{r^2 dr}{(C - Dr^2)^2} + B^2 \int_0^a \frac{r^4 dr}{(C - Dr^2)^2} \quad (15)$$

$$I_2 = \frac{A^2}{D^2} \int_0^a \frac{dr}{(\frac{C}{D} - r^2)^2} - \frac{2AB}{D^2} \int_0^a \frac{r^2 dr}{(\frac{C}{D} - r^2)^2} + \frac{B^2}{D^2} \int_0^a \frac{r^4 dr}{(\frac{C}{D} - r^2)^2}$$

Let $\frac{C}{D} = b^2$ then, if $r = b \cos \beta$
 $dr = -b \sin \beta \cdot d\beta$

$$\int_0^a \frac{dr}{(b^2 - r^2)^2} = -\frac{1}{b^3} \int_{r=0}^{r=a} \frac{d\beta}{\sin^3 \beta}$$

$$= -\frac{1}{b^3} \left[-\frac{\cot \beta}{2} + \frac{1}{2} \log \tan \frac{\beta}{2} \right]_{r=0}^{r=a}$$

$$= \frac{1}{b^3} \left[\frac{\cot \beta}{2} - \frac{1}{2} \log \tan \frac{\beta}{2} \right]_{r=0}^{r=a}$$

Note: There is a mistake in this work.
 For the correct presentation, see
 the reprint of this work at the back
 of this book.

H. N. K.

$$\begin{aligned}
\int_0^a \frac{r^2 dr}{(b^2 - r^2)^2} &= -\frac{1}{b} \left[\int_{r=0}^{r=a} \frac{d\beta}{\sin^3 \beta} - \int_{r=0}^{r=a} \frac{d\beta}{\sin \beta} \right] \\
&= -\frac{1}{b} \left[-\frac{\cot \beta}{2} + \frac{1}{2} \log \tan \frac{\beta}{2} - \log \tan \frac{\beta}{2} \right]_{r=0}^{r=a} \\
&= -\frac{1}{b} \left[-\frac{\cot \beta}{2} - \frac{1}{2} \log \tan \frac{\beta}{2} \right]_{r=0}^{r=a} \\
&= \frac{1}{b} \left[\frac{\cot \beta}{2} + \frac{1}{2} \log \tan \frac{\beta}{2} \right]_{r=0}^{r=a}
\end{aligned}$$

$$\begin{aligned}
\int_0^a \frac{r^4 dr}{(b^2 - r^2)^2} &= -b \left[\int_{r=0}^{r=a} \frac{d\beta}{\sin^3 \beta} - 2 \int_{r=0}^{r=a} \frac{d\beta}{\sin \beta} + \int_{r=0}^{r=a} \sin \beta \cdot d\beta \right] \\
&= -b \left[-\frac{\cot \beta}{2} + \frac{1}{2} \log \tan \frac{\beta}{2} - 2 \log \tan \frac{\beta}{2} - \cos \beta \right]_{r=0}^{r=a} \\
&= -b \left[-\frac{\cot \beta}{2} - \frac{3}{2} \log \tan \frac{\beta}{2} - \cos \beta \right]_{r=0}^{r=a} \\
&= b \left[\frac{\cot \beta}{2} + \frac{3}{2} \log \tan \frac{\beta}{2} + \cos \beta \right]_{r=0}^{r=a}
\end{aligned}$$

Substituting these values in (15) we have

$$I_1 = \left\{ \frac{A^2}{D^2 b^3} \left[\frac{\cot \beta}{2} - \frac{1}{2} \log \tan \frac{\beta}{2} \right] - \frac{2AB}{D^2 b} \left[\frac{\cot \beta}{2} + \frac{1}{2} \log \tan \frac{\beta}{2} \right] + \frac{B^2 b}{D^2} \left[\frac{\cot \beta}{2} + \frac{3}{2} \log \tan \frac{\beta}{2} + \cos \beta \right] \right\}_{r=0}^{r=a}$$

$$I_1 = \left\{ \frac{\cot \beta}{2} \left[\frac{A^2}{D^2 b^3} - \frac{2AB}{D^2 b} + \frac{B^2 b}{D^2} \right] + \frac{1}{2} \log \tan \frac{\beta}{2} \left[3 \frac{B^2 b}{D^2} - \frac{A^2}{D^2 b^3} - \frac{2AB}{D^2 b} \right] + \cos \beta \left[\frac{B^2 b}{D^2} \right] \right\}_{r=0}^{r=a}$$

$$I_1 = \left\{ \frac{\cot \beta}{2} \left[N_0^2 \left(\frac{a^2}{b^3} - 2 \frac{a^2}{b} + b \right) \right] + \frac{1}{2} \log \tan \frac{\beta}{2} \left[3 N_0^2 b - \frac{N_0^2 a^4}{b^3} - 2 \frac{N_0^2 a^2}{b} \right] + N_0^2 b \cos \beta \right\}_{r=0}^{r=a}$$

$$I_2 = \left\{ \frac{1}{b^3} \frac{\cot \beta}{2} (a^4 - 2a^2b^2 + b^4) + \frac{1}{2b^3} \log \tan \frac{\beta}{2} [3b^4 - a^4 - 2a^2b^2] + b \cos \beta \right\}_{r=0}^{r=a}$$

$$I_2 = \left[\frac{\cot \beta}{2} \left(\frac{(b^2 - a^2)^2}{b^3} \right) + \frac{(3b^2 + a^2)(b^2 - a^2)}{2b^3} \log \tan \frac{\beta}{2} + b \cos \beta \right]_{r=0}^{r=a}$$

But $b^2 = a^2 \left(1 + \frac{N_0 \alpha}{U} x \right)$ and if $k = \frac{N_0 \alpha}{U}$

$$b^2 = a^2 (1 + kx)$$

$$b^2 - a^2 = a^2 kx$$

therefore

$$I_2 = \left[\frac{(kx)^2 a^4}{2(1+kx)^{3/2}} \frac{\cot \beta}{a^3} + \frac{(4a^2 + 3a^2 kx)(a^2 kx)}{2a^3 (1+kx)^{3/2}} \log \tan \frac{\beta}{2} + a(1+kx)^{1/2} \cos \beta \right]_{r=0}^{r=a}$$

and taking out a factor a .

$$I_2 = \left[\frac{(kx)^2}{2(1+kx)^{3/2}} \cot \beta + \frac{(4+3kx)kx}{2(1+kx)^{3/2}} \log \tan \frac{\beta}{2} + (1+kx)^{1/2} \cos \beta \right]_{\cos \beta = 0}^{\cos \beta = \frac{a}{b}}$$

$$I_2 = \left[\frac{(kx)^2}{2(1+kx)^{3/2}} \frac{\cos \beta}{\sqrt{1-\cos^2 \beta}} + \frac{4+3kx}{2(1+kx)^{3/2}} kx \log \sqrt{\frac{1-\cos \beta}{1+\cos \beta}} + (1+kx)^{1/2} \cos \beta \right]_{\cos \beta = 0}^{\cos \beta = \frac{a}{b}}$$

$$I_2 = \frac{(kx)^2}{2(1+kx)^{3/2}} \frac{a}{(1-\frac{a^2}{b^2})^{1/2}} + \frac{(4+3kx)kx}{4(1+kx)^{3/2}} \log \frac{1-\frac{a}{b}}{1+\frac{a}{b}} + (1+kx)^{1/2} \frac{a}{b}$$

$$I_2 = \frac{(kx)^2}{2(1+kx)^{3/2}} \frac{a \cdot b}{b(b^2-a^2)^{1/2}} + \frac{(4+3kx)kx}{4(1+kx)^{3/2}} \log \frac{b-a}{b+a} + (1+kx)^{1/2} \frac{a}{b}$$

$$I_2 = \frac{(kx)^2 a}{2(1+kx)^{3/2} a(kx)^{1/2}} + \frac{(4+3kx)kx}{4(1+kx)^{3/2}} \log \frac{\sqrt{1+kx}-1}{\sqrt{1+kx}+1} + \frac{(1+kx)^{1/2} a}{a(1+kx)^{1/2}}$$

$$I_2 = \frac{1}{2} \left(\frac{kx}{1+kx} \right)^{3/2} - \frac{(1+\frac{3}{2}kx)}{(1+kx)^{3/2}} kx \log \frac{\sqrt{1+kx}+1}{\sqrt{1+kx}-1} + 1$$

$$I_2 = 1 + \frac{1}{2} \left(\frac{kx}{1+kx} \right)^{3/2} - \frac{(1+\frac{3}{2}kx)}{(1+kx)^{3/2}} kx \log \frac{\sqrt{1+kx}+1}{\sqrt{1+kx}-1} \quad (16)$$

XIV

EXPERIMENTAL VERIFICATION OF THE THEORY

In order to measure experimentally the rate of decay in luminous intensity with the distance along the tube, the apparatus shown in figure 13 was made. This apparatus consisted of a glass tube 2.5 centimeters outside diameter in which the arc was formed. The vapor from this arc distills upward through the anode and into a tube 3.7 centimeters inside diameter and 65 centimeters long. In the lower part of this tube is an auxiliary grid, A, for use in measuring the velocity of the stream. A long cylindrical electric furnace was placed about the greater part of this tube to prevent the mercury vapor condensing on the walls. There was a long slit along the side of the furnace, parallel with its axis, and about one centimeter wide, through which the luminosity was observed. The arc was "struck" by vaporizing the mercury at the cathode by means of the cathode heating coil, and starting the arc by means of an induction coil between the electrode A and the anode of the arc. The arc operated well with a current of three amperes with the cathode heater going. The potential drop across the arc varied from 13 volts to 20 volts, depending upon the rate of volatilization of the mercury at the cathode. The potential drop was generally about 15 volts.

figure 13

The luminous vapor could be traced for the entire length of the tube. The inside walls of the furnace were carefully blackened, and in this way reflected light from the walls was almost completely done away with. In fact when very little vapor was distilling, the upper part of the tube appeared quite dark. The mercury vapor condensed on the cold parts of the tube well above the furnace. These condensed drops of mercury rain down and fall back to the cathode. However the drops have to be fairly large before they can do this. If the extreme upper part of the tube is carefully observed, the small droplets may be seen to fall into the tube. However, before they have descended more than about a centimeter, the uprushing current of mercury vapor strikes them and sends them up again. Thus the mercury must descend in a few large drops instead of a large number of small ones. This is a good thing, for if there were a large number of small droplets continually raining down into the tube, the light from the arc, which they would reflect, would interfere with the observed luminosity of the distilled vapor. An occasional large drop does not matter. For a given mass of mercury, the area of the reflecting surface is much smaller when the mercury is in one large drop than when it is divided up into a large number of small ones.

The luminosity as a function of the distance along the

tube was measured in the following manner. A Nutting polarization photometer made by Adam Hilger was turned on it's side and mounted on the carriage of a cathetometer.

figure 14

Aluminium tubes 10 centimeters long were affixed to the apertures of the photometer as shown in figure 14. These tubes were carefully blackened on the inside with soot in order to minimize the effect of scattered light entering the photometer. The apertures on the photometer were

3.8 centimeters apart. The device was so arranged that the light from the lower aperture could be decreased by the crossed nicols and so matched with the light from the upper aperture. In order to measure the intensity of the luminosity along the vapor stream the ratio of intensities between these two points was observed. The photometer was then moved up so that the lower tube came into the position previously occupied by the upper tube. The ratio was again determined, and so on for about two thirds of the length of the tube. Ten such ratios were observed along the tube at intervals of 3.8 centimeters. The ends of the tube were avoided as it was feared that conditions might not be steady and uniform near the ends. The distance between the

photometer tubes, 3.8 centimeters, was taken as unit distance, and at $x = 0$ the intensity of the light was taken as unity. So the intensity at any point could be calculated as the product of all previous ratios. Several series of readings were made----a typical curve being shown in figure 15. Two series of readings were made with the mercury green line alone----one series being shown by the curve in figure 16. These readings were taken by holding a mercury green line filter before the eyepiece while matching intensities.

Now to compare these experimental curves with the theory of the previous chapter. It will be seen in the expressions for I_1 and I_2 that their graphs both pass through the point $0, 1$, and that the luminosity vanishes as x becomes infinite. There is, however, one arbitrary constant in each of the expressions (14) and (16). This means that, by properly choosing these constants, we can make the curves pass through one arbitrary point on the experimental curve. If in (14) we take $k = 1.6$ and in (16) we take $k = .20$ the graphs of these equations both pass through the point $5, .076$ approximately, as in figure 15. It will now be seen that the graph of I_2 lies very close to the experimental curve, while the graph of I_1 cannot be made to fit the experimental curve. This also applies to the curves on figure 16 for the green line alone. This seems to point very strongly toward the view

figure 15.

figure 16.

that the light is produced by the recombination of positive and negative ions. The following table showing the better agreement of I_2 with the experimental values may be interesting.

x	I_1	I_2	$I_{exp.}$	$\frac{I_2 - I_1}{I_1}$	$\frac{I_2 - I_1}{I_2}$
0	1.000	1.000	1.000	.000	.0000
1	.280	.494	.535	+ .477	+.0767
2	.168	.290	.300	+ .440	+.0333
3	.113	.2006	.1838	+ .386	-.0914
4	.094	.117	.1150	+ .183	-.0174
5	.077	.0805	.0762	- .013	-.0564
6	.062	.0655	.0504	- .231	-.30
7	.054	.0383	.0351	- .543	-.0212
8	.050	.022	.0246	-1.275	+.102
9	.042	.0165	.0175	-1.40	+.0752
10	.037	.0140	.0135	-1.78	-.0370

These results show that recombination explains the production of the luminosity much more satisfactorily than the first case considered in the previous chapter. In the previous chapter it was stated that the third case would be considered later. This case assumes that the positive ions emit the light continually during their journey from the arc. If the light from each ion decays exponentially with respect to the time we should expect the luminosity at a

point to be proportional to $n e^{-kt}$.

So

$$I \propto \frac{e^{-kx}}{1 + Ax}$$

Equations of this form will involve two arbitrary constants, and after an integration procedure as in cases 1 and 2 has been carried out the two arbitrary constants will enable us to pass the curve through two arbitrary points of the experimental curve. Thus this theory might be made to fit the experimental curve. However it must be borne in mind that as soon as a number of arbitrary constants enter we can make the equation fit almost any sort of curve. Thus the equation becomes little more than an empirical one. The ease with which the equation for I_1 fits the experimental curve with a single arbitrary constant is very encouraging.

In matching intensities with the Nutting photometer it was found that there was a color difference in the lights entering the two apertures. The light entering the lower aperture appeared to be yellower than that at the upper aperture. Thereupon the following experiment was tried. The photometer was kept in a fixed position and the separate lines matched separately. This was done by holding filters before the eyepiece so that only the light under observation was transmitted. In this way the decay in the intensities of the separate lines over the distance between the photometer tubes could be measured.

These ratios were measured for the yellow lines, the green line, and the violet line-- $\lambda = 4358$.

The average of a large number of observations showed that for equal intensities starting at the first aperture, for each unit of the violet luminosity reaching the second aperture, .873 units of the green luminosity, and .786 units of the yellow luminosity reach the second aperture. This shows that the violet line persists longer than the green line, and that the green line in turn persists longer than the yellow lines.

XV

CONCLUSION

In the preceeding chapters of this work it has been shown that all observed phenomena with the luminosity and electrical conductivity of the distilled vapor can be explained on the assumption that the luminosity is produced during recombination of positive and negative ions to form neutral molecules, and that the intensity of the luminosity is accordingly proportional to the rate of recombination of the ions. Some of the phenomena can be explained through the positive ions themselves emitting the light; and with one ^{phenomenon} it does not seem possible to explain the effects except on the recombination theory. On the whole the evidence is very much in favor of the recombination theory.

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VITA.

Norman Hurd Ricker, son of John R. Ricker and Julia (Shaw) Ricker, was born in Galveston Texas on October 11th, 1896. His early training was received in the public schools of Galveston and Waco Texas. His high school work was done in the preparatory department of Reynolds College, Albany Texas. In the Autumn of 1912 he entered The Rice Institute with the opening of that institution, as a member of the first class. In his second, third, and fourth years he was student assistant to the departments of mathematics and physics. During this time he enrolled in the Honors Course in Physics, and in the Spring of 1916, received the degree of Bachelor of Arts with Honors in Physics. For the following year he received an appointment as fellow in mathematics at Rice, and, in the Spring of 1917, received his Master of Arts degree. During the session 1917-18 he held an appointment as fellow in physics at Rice, and, during the last half of the year 1918, served in the U.S. Air Service as a flyer----being reappointed to a fellowship in physics at Rice upon his discharge from the service at the close of the year 1918. During the summer of 1919 he was engaged in research work on Modulation by Thermionic Tubes at the research laboratories of the Western Electric Company----New York City. He received an appointment as instructor in physics at Rice for the year 1919-20. During his undergraduate and graduate work at Rice he has been under the immediate supervision of Profs. H.A. Wilson, G.C. Evans, P.J. Daniell, and A.L. Hughes, from whom he has received much inspiration and guidance, and to whom he wishes to express his most sincere appreciation.