RADIATION PRODUCED BY PARTIAL IONIZATION.

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SYNOPSIS.

Emission of light by gases; a partial ionization theory.—In certain cases light seems to be emitted at the instant of ionization of the gas atoms; in other cases it seems to be emitted at the instant of recombination of gas ions; and in still other cases, the light emission seems to be associated with neither ionization nor recombination. These cases are discussed and an explanation is suggested which is based on Bohr's assumption that radiation occurs when an electron falls from an outer to an inner orbit, combined with the assumption that complete ionization is produced much less frequently than partial ionization, that is, the displacement of an electron from an orbit to one farther out. Partial ionization would not affect the current or the electric field, so its existence cannot be directly proved but is rendered probable by the recent demonstration of radiation without ionization. The readjustment following it may be expected to produce radiation similar to that produced by recombination after complete ionization. The evidence given by canal rays is briefly discussed. The author's theory apparently explains all the phenomena cited.

Low-voltage discharge in Hg vapor.—If a Wehnelt cathode is used, a low-voltage discharge may be maintained which is relatively non-luminous for some distance from the cathode.

THERE are many reasons for believing that a gaseous body radiates energy when it is ionized. It is not, however, certain whether radiation occurs at the time when the atoms are ionized, or when the ions recombine. Indeed certain facts appear to indicate that the radiation is not produced by either ionization nor recombination. The following is a discussion of these facts and a suggestion that at least the phenomena pertaining to monatomic gases may be explained, if we assume that radiation is indeed caused by the recombination of parts of atoms, but that in the majority of cases the recombination takes place between parts of an atom that have been only partially separated from each other, the electron falling back to the same nucleus as that to which it was originally attached. Many of the phenomena of gases which are not monatomic can, no doubt, be explained in the same way, but since these are more complicated, they will not be discussed at this time.

Phenomena Indicating that Radiation is Due to Recombination.—In the discussion of the atom given by Bohr it is assumed that radiation occurs when an electron falls from an outer to an inner orbit, that is, radiation is produced when recombination occurs. Whether we accept this particular view of the atom or not, it is reasonable to expect that radiation will occur at such a time, for the sum of the potential and kinetic energies of the system decreases when the electron combines with a positive ion, and it is natural to suppose that the energy thus lost to the system is radiated.

Moreover, there is experimental evidence that in certain cases radiation is produced by a recombination of ions as has been shown by the experiments on the light emitted by the vapor above the mercury arc[1] and by the fact that light is emitted from a mercury arc for a brief time after the current has ceased.[2] Apparently there is no way of explaining either of these phenomena except by assuming that the light is produced at the time of recombination.

Phenomena Indicating that Radiation is Due to Ionization.—On the other hand certain phenomena are more easily explained by assuming that the light is emitted at the time of ionization. The following is an example of such phenomena. If electrical discharge is passed from a hot calcium oxide cathode, *C* (Fig. 1), to a mercury anode, *A*, through mercury vapor, it is possible to adjust the conditions so that there will be a glow at *g* with no light that can be observed between *C* and *g*. There is then a very definite line of demarkation between the nonluminous and the luminous regions. The luminous part is in fact the same as the first striation of an ordinary striated discharge, except that in the case here described there is no glow in the immediate neighborhood of the cathode.

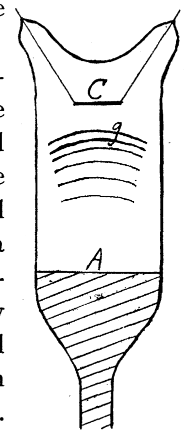

Fig. 1.

This glow shows approximately the same spectrum as that shown by the light radiated from the vapor above the mercury arc and yet it appears where we would expect ionization to occur and not where we would expect the greater part of the recombination. The electrons emitted from the cathode will not ionize in the immediate neighborhood of the cathode. In order to ionize they must first pass through a definite potential difference and this required voltage no doubt exists between *C* and the region in which the glow commences.

On the other hand the number of recombinations between *g* and *C* must be large. This number varies as the product of the number of the positive ions and of the electrons. The positive ions move toward *C* and hence are more numerous near *C* than near *A*. Since the electrons

[1] Phil. Mag. (6), 26, 906, 1913.
[2] PHYS. REV. (2), 9, 1, 1917.

come from C, there must also be a large number of electrons there. As a result there is a large number of recombinations near C.

In any case it is difficult to see how the number recombining can suddenly increase at a definite region. We, therefore, have good reason for believing that the light appears where the ionization and not where the recombination occurs. It is natural to draw the conclusion from this that the light is produced at the time of ionization rather than at the time of recombination.

While this appearance may be obtained with different conditions, a typical case is the following. The tube was 2.8 cm. in diameter. The distance from C to A was 3 cm. A was a mercury anode. The pressure of the gas as measured by a McLeod gauge was .002 mm. The tube was heated to approximately 80° C. The discharge was principally through mercury vapor as was shown by its spectrum. The potential difference between A and C was 16 volts. The current was .6 milliampere. In order to obtain the glow without light between C and g, it was usually necessary to raise the voltage slightly above 16 volts until the discharge became luminous and then gradually lower it until the region between C and g ceased to be luminous.

An attempt was made to measure the potential at g by inserting a platinum wire at that point. The potential difference between C and g as thus indicated was about 2 volts. It is probable, however, that the excess of electrons in this region and their high velocity give to the exploring wire a negative charge, so that its potential is below that of the region about it. The result would be to make this measurement of no value.

When the pressure of the mercury vapor was raised by allowing a slight amount of air to leak into the pump a higher voltage was required between C and A. However, when the voltage was so regulated as to bring the head of the striation to some fixed point the current between C and A and also the apparent voltage between C and g was always approximately the same provided the temperature of C was kept constant.

A similar result is shown when a stream of electrons (a cathode ray) or of positive ions (a canal ray) passes through a gas. As far as can be determined, the luminosity is limited to the region traversed by the moving particles. This is what would be expected, if the light is caused at the moment of ionization, for the ionization takes place in the path of the particles. It would not be expected, if the light were produced by recombination, for the recombination occurs not only where there is ionization, but also in the neighboring region to which the ions diffuse.

Phenomena Indicating that Light is due neither to Ionization nor to

Recombination.—There are other phenomena which seem to show that light is due neither to ionization nor to recombination. One of these is the fact that the amount of light emitted by a gas through which electrical discharge is passing is approximately proportional to the current flowing through the gas. It has been shown by the writer[1] that if the light were due to recombination of ions, it should vary approximately as the square of the current, since the number of recombinations varies as the product of the number of positive and of negative ions and each of these varies as the current.

Moreover the number of atoms ionized must be the same as the number recombining and, therefore, the number of atoms ionized varies approximately as the square of the current. If the light were due to ionization instead of recombination, it would still vary as the square of the current. Since the light does not in reality thus vary, it apparently is not caused by either ionization or recombination.

In the article to which reference has been given the writer made an attempt to reconcile these facts with the idea that the light is produced by recombination of the ions, but the work which has since been done on the elastic impact between electrons and the atoms of certain gases has made that attempt appear unreasonable as far as the discharge through such gases as mercury is concerned and improbable in all cases. Consequently if we accept the view that radiation is produced by either ionization or recombination, some explanation of this difficulty must be found.

Again when certain substances, as for example copper salts, are introduced into a non-luminous flame, it is possible to produce a line spectrum without any corresponding increase in the conductivity of the flame. That is we have radiation without ionization or recombination.

In the preceeding we have discussed the occurrence of light which is apparently not produced by either ionization or recombination. There is also one instance recorded in which there is apparently an abundance of ionization and recombination without any light. Graham[2] states that a current of 7 milliamperes was passed through a tube containing pure nitrogen at a pressure of 4 mm. without producing any light except in the immediate neighborhood of the electrodes, while with lower pressures a large amount of light was produced. We would certainly expect as much ionization with the higher pressures as with the lower, so that it would appear that here was an example of ionization and recombination without any resulting light.

[1] Phil. Mag. (6), 27, 278, 1914.

[2] Wied. Ann., 64, 49, 1898.

An Explanation of these Phenomena.—We have in the preceding paragraphs described two experiments which apparently show that radiation is due to recombination, two showing that it is due to ionization, and several showing that it is due neither to ionization nor recombination. It can, however, be shown that the suggestion made at the beginning of this article will explain these apparent contradictions. The assumption of Bohr and others that there is radiation whenever an electron falls from an outer to an inner orbit is there accepted, but to this is added the assumption that in the majority of cases of electrical discharge the electron falling from one orbit to another has never been entirely separated from its nucleus. It has received a shock which has driven it from its normal position, but not entirely away from the influence of the atom to which it belonged, so that it falls back to the same nucleus. Neither ionization nor recombination in the proper sense has occurred. It is rather partial ionization with a consequent return of the electron to its original position. Such an action would produce light, but would have no effect on the number of free ions. Neither the current nor the electric field would be influenced by such an occurrence.

There is the same effect, if the electron impinging on the atom is caught by the nucleus from which it has displaced an electron, so that there is merely an interchange of electrons without any increase in the number of those that are free.

It may first of all be noticed that such an incomplete ionization is what we should expect to occur in many, if not in the majority of cases. It requires more energy to separate an electron to a great distance than to remove it from an inner to an outer orbit. This is shown experimentally by the work of Davis and Goucher[1] and others on the voltage required to produce the single-lined spectrum. It is natural to expect that even a many-lined spectrum may be produced more easily than complete ionization. If such a difference exists, even though it is but small, many atoms will be hit by electrons which have attained sufficient velocity to displace an electron belonging to the atom to a considerable distance from its nucleus and will still not have sufficient velocity to ionize the atom completely. There will thus be many cases of incomplete ionization.

Such an assumption of course explains the appearance of light in the vapor above the mercury arc and of the continuance of light after the current has ceased, since in these cases we have recombination of the most complete type.

It explains the experiment in which light does not appear at the

[1] PHYS. REV. (2), 10, 101, 1917.

cathode, but begins at a definite region a few millimeters from it, namely at a point where ionization occurs and not in the region where the greatest recombination might be expected. We have no means of determining in this case the exact number of recombinations between completely separated ions, but it is probably much smaller than the number necessary to produce light that can be seen by the eye. This is probable since there are few positive ions present with which the electrons can combine. With non-luminous discharge the voltage is below that which is required to ionize the gas. When the discharge becomes luminous there is still no large increase in the current. This shows that with the current here used there is little ionization of the gas and consequently few positive ions present.

On the other hand the number of partial ionizations is probably much larger. Since the voltage is high enough to produce some complete ionization, it is probable that nearly every electron leaving the cathode produces either partial or complete ionization in this region. The number of recombinations of both the complete and the partial ionizations are sufficient to produce a visible amount of light. Since the recombination of the partially ionized atoms occurs where the ionization takes place and are thus concentrated to a greater extent it is not surprising the former should produce light while the later does not.

A similar explanation would account for the fact that the light produced by a stream of electrons or of positive ions is limited to the path of the ions.

The assumption made in the preceding explains the fact that the amount of light given by the mercury arc and other form of discharge is proportional to the current and not to the square of the current. While the number of recombinations resulting from complete ionization depends on the product of the number of positive and of negative ions and is consequently proportional to the square of the number of electrons present, the number of partial ionizations depends only on the number of electrons present and consequently is proportional to the first power of this number. Since the current is proportional to the number of electrons present (providing the electrical force is constant) the number of partial ionizations must be proportional to the current. The number of recombinations resulting from partial ionizations must be equal to the number of partial ionizations. If finally the light is proportional to such recombinations, it must also be proportional to the current, which is approximately what is found to occur.

This, of course, requires us to assume that nearly all of the light comes from partial ionizations, that is, that the number of partial ionizations is much larger than the number of complete ionizations. While we might not have anticipated this conclusion, it is not unreasonable to accept it, if by so doing one can explain the phenomena here considered.

Again such an assumption explains the occurrence of a line spectrum when certain salts are introduced into a non-luminous flame even though there is no increase in the conductivity. As the single-lined spectrum of mercury may be produced without producing ionization, so the thermal or chemical action of the flame may be sufficient to displace an electron from an inner orbit to one further out without producing complete ionization.

In regard to the experiment of Graham's the explanation is not so evident. While several explanations might be suggested, one can not at present be certain that any of them is correct. In all probability the recombinations between completely ionized atoms taken alone were too small to produce a visible amount of light. Whether partial ionization was absent or whether it occurred under conditions such that no radiation in the visible spectrum occurred can not be stated. Certainly change in the density of a gas often produces large changes in the character of the spectrum. Until there has been further investigation of this phenomenon it is unwise to attempt any explanation. It would also be unwise at present to consider this as a proof that any large amount of ionization may occur without the production of radiation.

Evidence given by Canal Rays.—One might expect that decisive evidence regarding this subject would be given by a study of canal rays, but unfortunately those who have experimented most with these rays have failed to reach any agreement as to what they prove. Since there is this disagreement, the writer ventures to give the following reasons for believing that the light given by the canal rays which shows the Doppler effect is produced by recombination.

The following facts have a bearing on this discussion. First, when the light produced by the canal rays is properly examined the lines of the line spectrum of hydrogen and many lines of other gases are split into two parts, one being displaced and showing the Doppler effect, and one part being unaffected, there being a region of minimum intensity between the two parts.

Second, in order to have any luminosity in the region through which the rays are passing there must be some gas in that region.[1]

Third, the carrier of the displaced lines are the positive ions of the canal rays (the hitting atoms). Possibly the best proof for this is given by the spectrograms shown by Fulcher.[2] Thus spectrogram No. 160 shows that when hydrogen canal rays bombard air molecules, the dis-

[1] Fulcher, Astrophys. Jour., 33, 31, 1911.

[2] Astro-phys. Jour., 35, 103, 1912.

placed line of hydrogen alone is obtained. This would seem to be clear evidence that the light showing the Doppler effect is emitted by the hitting atoms.

Further the vibration which produces the light can not be started at the time the ion is produced. First because if it were so started, it would be necessary for it to continue until a high velocity were attained. Otherwise it would show no Doppler effect. If it were thus started and continued, we should have the greatest amount of light emitted when the ion was first agitated, that is, when the ion had a small velocity and the light would gradually fade out as the velocity was increased. This would produce an undisplaced line in the spectrum together with a displaced part of less intensity with no minimum between the parts.

Secondly if the vibration were started at the time of ionization, the light given by the canal rays would be quite independent of the presence of any molecules aside from the positive ions (that is the hitting ions). As has been stated the opposite of this has been observed by Fulcher.

We are apparently compelled to accept the view that the carrier of the displaced lines are the hitting ions and that these ions are set in vibration after they have acquired a high velocity. This agitation might be due to an impact which would leave the ion charged positively, or to a recombination with an electron which would leave it uncharged. There is apparently no proof as to which of these is the correct explanation, but since the latter supposition is more in harmony with all the other phenomena which are known, it is but reasonable to accept it as the correct one. We conclude, therefore, that the evidence thus far given by the canal rays is in harmony with the view that light is produced by recombination.

Spectra taken under Different Conditions.—According to this explanation there should be a difference between the spectrum of light produced by the recombination of completely ionized atoms and that resulting from partial ionization. Such a difference is found to exist. The spectrum of the vapor arising from the mercury arc, where there is recombination between completely separated ions, is slightly different from that of the mercury arc where there is partial ionization. The two spectra show approximately the same lines but the relative intensity of the lines is different, so that the light from the vapor about the arc is yellower than that of the arc itself.

The greater part of this article was written while the writer was at Cornell University. He, therefore, desires to express his thanks to Professor Nichols and to the members of the physics department of Cornell University for the privileges which were granted him while there.

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