



## LXXXIX. The recombination of ions made by $\alpha$ rays

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central position, and to about 700 gauss in the others. Observations were made somewhat differently from those given above, the motions of the electromagnets not being reversed and the pointings being made with the magnets alternately in slow motion and in rapid motion.

The mean values of the deviations, corresponding to  $\frac{1}{2}D$  in the experiments described above, were  $+0.01$  mm.,  $-0.02$  mm., and  $-0.01$  mm. for the three positions, with a mean error between  $0.01$  mm. and  $0.02$  mm.

Finally, it was thought worth while to see if any appreciable change in the trend of a line of induction occurred when the electromagnets were both set into rotation in the same direction with the same speed as before—slight as was the probability of obtaining a positive result. For this purpose the indicating magnet was placed outside the region between the poles, though near to one of them, and in such a position that its axis (and the lines of induction through it) made a considerable angle (about  $35^\circ$ ) with the axis of the field, and the rod supporting the magnet was placed approximately perpendicular to the plane containing the axis of the field and the lines of induction passing through the magnet. Observations made like those just described gave a mean deviation, corresponding to  $\frac{1}{2}D$  in the earlier work, of  $+0.03$  mm., with a mean error of  $0.04$  mm.; indicating therefore that no appreciable bulging out of the lines was produced by the rotation.

For the construction of most of the special apparatus used in the experiments described here, I am indebted to Mr. Arthur Freund, mechanic in the physical laboratory.

The Ohio State University,  
July 9, 1913.

LXXXIX. *The Recombination of Ions made by  $\alpha$  Rays.*  
By H. OGDEN, *Research Scholar in the University of Leeds* \*.

**B**RAGG & KLEEMAN observed in 1905 that the field required to obtain the full ionization current in a gas in which a given number of ions were being produced each second was always very much greater if the ions were produced by  $\alpha$  rays than if they were produced by  $\beta$  rays. They attributed this difference to "Initial Recombination." They supposed that when ions were formed by  $\alpha$  rays the separation between the charges was less complete than when they were formed by  $\beta$  rays, so that there was a marked tendency for

\* Communicated by Prof. W. H. Bragg, F.R.S.

the pair of ions to recombine before they could be separated by the field.

The matter has been further studied by Langevin, Moulin, and others, and attempts have been made to dispense with any special hypothesis concerning the recombination of ions produced by  $\alpha$  rays by attributing the difference in the field required to produce saturation entirely to the difference in the initial distribution of the ions. Ionization by  $\alpha$  rays is "columnar"; the ions are not distributed uniformly through the gas but concentrated along the path of the rays. The effective intensity of the ionization determining the amount of recombination is much greater than the average intensity. The difference between the effective and the average intensities of ionization will be much less if the field acts perpendicular to the column of ions, and tends to destroy the column by separating the opposite charges, than if it acts parallel to the column. The view that the magnitude of the saturation-field in the case of  $\alpha$  rays could be explained on this hypothesis of columnar ionization received support when Moulin \* found that the saturation-field was less when it acted perpendicular than when it acted parallel to the path of the rays.

However, this hypothesis of columnar ionization does not seem capable of explaining the whole matter. Wheelock † concludes that the saturation-field parallel to the rays is greater than that predicted by theory. Moreover the theory does not seem capable of explaining the very great difference observed by Bragg ('Studies in Radioactivity,' vii.) in the degree to which Initial Recombination is displayed in different gases. It appeared, therefore, that a further investigation of the problem was desirable, especially in the direction of observations with different gases.

The apparatus used was the same as that used by Bragg ‡ in his experiments on the ranges of alpha particles from radium and its products, and was only altered in a few minor details to meet the climatic conditions which in Leeds differ from those in Australia, where the apparatus was first used. Only a brief description is therefore necessary. A layer of radium R (fig. 1) was used as the source of  $\alpha$  rays. The gas of which the ionization was measured was contained between an insulated brass plate, Q, connected through a key-box to a Dolezalek electrometer, and a sheet of gauze, *g g*, parallel to the plate and distant 2.1 mm. from it. This gauze could

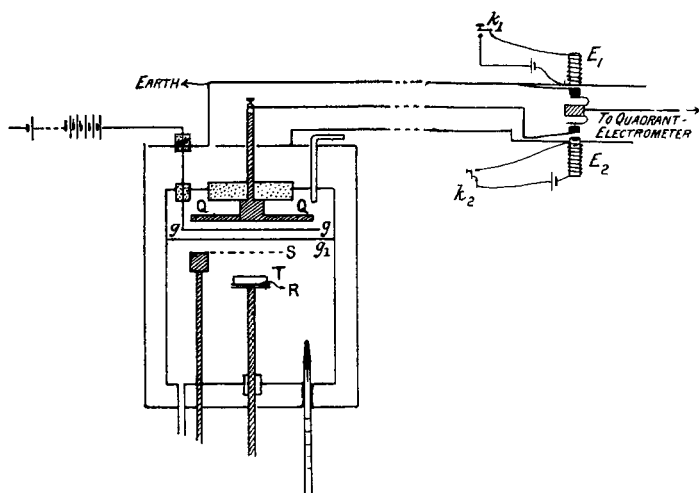
\* Moulin, *Comptes Rendus*, cxlviii. p. 1757 (1909).

† Wheelock, *Am. J. Sci.* [4] xxx. p. 233 (1910).

‡ *Phil. Mag.* x. p. 318 (1905).

be maintained at any desired potential. To prevent diffusion of the ions, another sheet of gauze,  $g_1$ , which was earthed was placed parallel to the high potential gauze and on the side remote from the plate. The  $\alpha$  rays were canalised by a set

Fig. 1.



of copper tubes, T, 1 cm. long by 1 mm. diameter placed over the radium. A screen, S, could be brought over the radium to cut off these  $\alpha$  rays, so that the ionization due to the  $\beta$  and  $\gamma$  rays might be measured. The whole of this apparatus was enclosed in a nearly gas-tight vessel, which in turn was enclosed in an outer vessel. Both were filled with the gas under examination, the outer vessel serving to prevent diffusion of air into the inner.

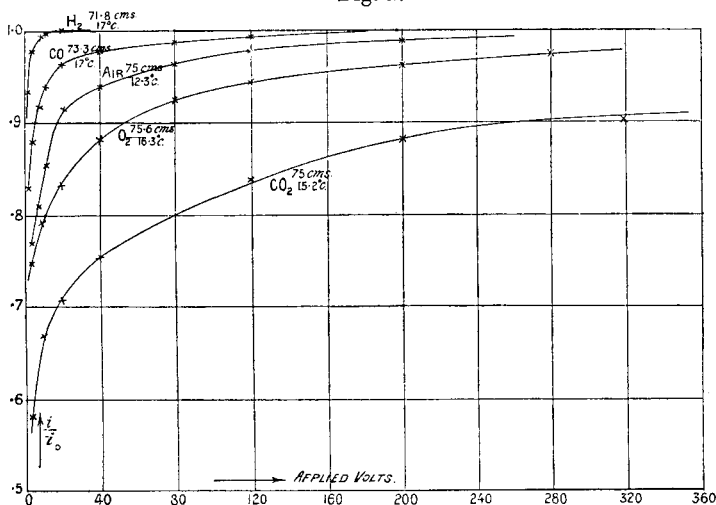
The ionization current was measured by the method used by Bragg. On the tick of a clock the key  $k_1$  was pressed, which operated an electromagnet  $E_1$  and so disconnected the electrometer and plate Q from earth. After 20 ticks of the clock (10 secs.) or other convenient interval a key  $k_2$  was pressed, which disconnected the plate from the electrometer by the agency of another electromagnet,  $E_2$ . The mean of the two ends of the first swing of the needle was taken to be proportional to the current. In an experiment on any pure gas, the chamber was first exhausted in order to get rid of any emanation which chanced to have escaped from the radium. The chamber was then filled slowly with dry air

and afterwards re-exhausted. Then the experimental gas was allowed partly to fill the outer chamber, which therefore contained the impure washings of the small connecting pipes. Then the inner chamber was filled, and, when the nature of the gas permitted it, was re-exhausted and filled again. All the gases were dried where possible by passing over long tubes of  $P_2O_5$  after bubbling through concentrated  $H_2SO_4$ . Ammonia was dried by quick-lime. Potentials from 0 to 640 volts were applied to the high potential plate and the ionization current measured :—

- (a) When the radium was covered. (The  $\beta$ ,  $\gamma$  ray effect.)
- (b) When the radium was uncovered.

The difference between the two gave the effect of the  $\alpha$  rays alone. The following gases were investigated :—air, oxygen, carbon dioxide, carbon monoxide, hydrogen, sulphur dioxide, methane, and ammonia. Some of the results obtained are given on figs. 2 & 2 A. The abscissæ give the P.D. in volts, the ordinates the corresponding currents expressed as fractions of the saturation current.

Fig. 2.



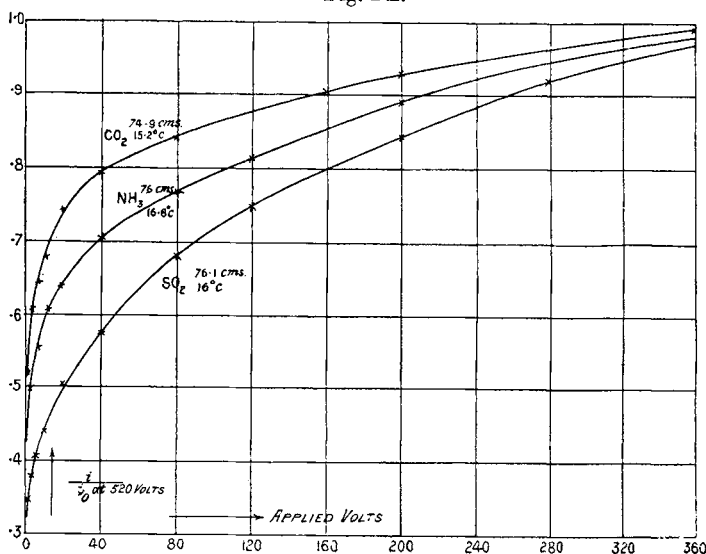
On the basis of the columnar hypothesis Wheelock has deduced the following relationship between  $i$ , the current through the gas, and  $X$ , the electric field acting on it :—

$$i = c_1 X \log_e \left( 1 + \frac{c_2}{X} \right).$$

$c_1$  and  $c_2$  are functions of the following constants :

- N, the number of pairs of ions generated by one  $\alpha$  particle in the chamber ;
- $a$ , the radius of a column ;
- $b$ , the depth of the chamber ;
- $k$ , the mobility of the ion.

Fig. 2 A.



In calculating the relationship the effects of the diffusion of the ions are neglected. Diffusion must tend to decrease the field necessary to obtain saturation by causing a diminution in the density of ionization, and so decreasing recombination. Nevertheless, Wheelock found more recombination than was indicated by his formula ; if the constants  $c_1$  and  $c_2$  were chosen so as to make the part of the curve corresponding to small voltages coincide with the theoretical curve, the part corresponding to high voltages was always below the theoretical curve. [Wheelock, Am. J. Sci. 1910, p. 233.] In all the gases except hydrogen and CO, saturation is more difficult to obtain than can be accounted for by that formula. But, in the case of hydrogen and CO, gases which show least "initial recombination," the experimental results can be fitted to the theoretical curve with some accuracy. The amount of agreement attained depends on what part of the curve is chosen to determine the constants

$c_1$  and  $c_2$ . Since the formula neglects diffusion, it will be best to determine these constants from that part which is least affected by diffusion, that is, from the part corresponding to high voltages. When  $c_1$  and  $c_2$  are determined from this part of the curve, the agreement between the theoretical and experimental values is good in the case of the gases mentioned, as is shown by the following table:—

Carbon monoxide,  $14^{\circ}2$  C., 29.5 cm. Hg pressure.

Theoretical curve,  $i = 170.8 \text{ V} \log_{10} \left( 1 + \frac{1.66}{\text{V}} \right)$ .

Applied volts.	$\alpha$ ray current in arbitrary units.	Calculated current.
{ 120 volts	116.4	116.4
8	112.5	112.5
0	0	0
2	106.6	90.5
4	110.5	104
20	114.8	114
40	115.8	115.8
360	116.5	116.5

It will be noticed that the calculated values are never higher in this case than the observed, and that for the lower voltages they fall below the observed. Such a deviation is to be expected, since with the lower voltages the time for gathering the ions is comparatively long and diffusion, always operative, here manifests its maximum effect in diminishing the density of ions within the column. However, no agreement could be found for curves for  $\text{CO}_4$ ,  $\text{CO}_2$ ,  $\text{SO}_2$ , &c., the ions of which seem to show an abnormal tendency to recombine.

A second test of the applicability of Wheelock's formula can be made. The formula can be put in the form

$$y = \frac{i}{i_0} = \frac{X}{c_2} \log_e \left( 1 + \frac{c_2}{X} \right), \text{ since } c_1 c_2 = i_0 \text{ the saturation current,}$$

which is the same as Langevin's equation

$$y = \frac{1}{x} \log_e (1 + x).$$

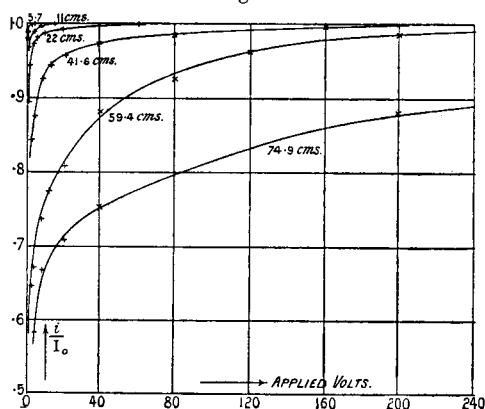
Accordingly  $\frac{i}{i_0}$  should be a function of  $\frac{c_2}{X}$  only, where  $c_2$

depends on the nature of the gas, and hence the saturation curves of two gases, characterized by different values of  $c_2$ , ought to be reduced to the same form by orthogonal strain parallel to the axis of  $V$ , that is by altering the abscissæ in a given ratio while the ordinates are left unchanged. An attempt has been made to reduce all the curves of fig. 2 to the same form by such straining, but coincidence of the curves representing different gases cannot be obtained by such means. Some experiments were made with  $\text{CO}_2$  at different pressures, but it was found that even when the same gas was used at different pressures, the saturation curves could not be brought into coincidence by straining. The ratio

$$\left(\frac{V_1}{V_2}\right) \frac{i}{i_0} = \text{constant}$$

was not found to be approximately constant, as is evident from inspection of fig. 3. This test was also applied to

Fig. 3.



curves for hydrogen at different pressures, and in this case the values

$$\left(\frac{V_1}{V_2}\right) \frac{i}{i_0} = \text{constant}$$

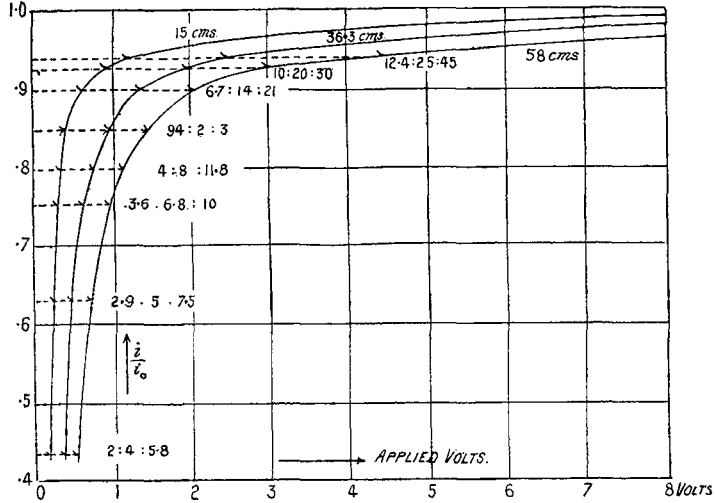
were found to be approximately constant, as is shown by the examples on fig. 4.

But the most convincing evidence of the inapplicability of a simple hypothesis of columnar ionization is afforded by



the comparison of the saturation curves for oxygen, carbon monoxide, and ammonia. According to any such hypothesis the form of the saturation curve with a given apparatus (the

Fig. 4.



effect depending of course on the dimensions of the chamber) must be determined wholly by the constants mentioned on page 995. These constants are given in the following table :—

Property.	Constant of Equation dependent on property.	Oxygen.	Carb on monoxide.	Ammonia.
Density .....	.....	32	28	17
Stopping-power .....	} N, the number of pairs of ions made in the chamber by one $\alpha$ particle.	10.6 S	98 S	90 S
Total ionization .....		11.0 S	101.5 S	90 S
Pressure.....		75.6 cm.	73.3 cm.	76 cm.
Temperature .....		16° 3 C.	17° C.	16° 8 C.
Mean mobility .....	$k$	1.58 L	1.12 L	.78 L
Coeff. of diffusion with respect to $H_2$ .....	.....	.722 L	.642 L	
Molecular diameter deduced from viscosity.	} Diameter of $\alpha$ ray track.	$3.36 \times 10^{-8}$ cm.	$3.5 \times 10^{-8}$	} L
Molecular velocity .....		$4.61 \times 10^4$ cm./sec.	4.93	
Mean Free Path .....		9.95.	9.27	

S='Studies in Radioactivity.' L=Laby & Kaye's Tables.

It will be seen that all of the constants are very nearly the same in oxygen and carbon monoxide, and yet a glance at fig. 2 will show how completely different are their saturation-curves. Thus, at 120 volts 1 per cent. of the carbon monoxide ions, 7 per cent. of the oxygen ions, whilst more than 19 per cent. of the ammonia ions, recombine. It is clear that some factor not considered by Wheelock's theory is of great importance in determining the form of the curves. Some further experiments which have been performed seem to indicate the nature of this constant.

A large quantity of carbon monoxide was prepared and was kept in a water-sealed reservoir. On testing this gas some weeks afterwards it was found to show a greater readiness to recombine than the freshly though similarly prepared specimen.

Thus :—

Volts applied across chamber.	$\frac{i}{i_0}$ Freshly prepared. 73.3 cm. 16° C.	$\frac{i}{i_0}$ Old specimen. 76.1 cm. 16° C.
4 volts	·878	·792
12	·947	·87
20	·952	·91
40	·97	·95
80	·988	·979

The difference was very marked and could not be attributed to impurities in the old gas ( $H_2O$  excepted). The experiments showing this difference were repeated many times. This result suggested investigation of the effect of degree of dryness of the gas, and hence a series of experiments on air dried by various reagents was made. In these experiments, as in other experiments where the gas liberates the emanation from the radium, the latter was enclosed in a closed box with mica or waxed tissue-paper as lid. These lids were air-tight, transparent to the long-range  $\alpha$  rays, and were also able to withstand considerable differences of pressure. Air, bubbled through water, could be used with this precaution. It was found that in damp air the ions recombined more easily than in dry air, but the difference was not so great as in the case of carbon monoxide.

V=Applied volts.	$\frac{i}{i_0}$ Dry air ( $H_2SO_4$ & $P_2O_5$ ).	$\frac{i}{i_0}$ Moist air (water).
8	·856	·84
20	·92	·91
40	·943	·93
80	·97	·951

Now it is known that the effect of water-vapour on the ions of a gas is to decrease their mobility, and hence these observations suggest that an explanation of the phenomenon of "initial recombination" may possibly be found in the presence of a small proportion of ions of very small mobility in the gases which display it to a marked degree. It is easy to see that the presence of such ions will tend to increase recombination and so make saturation more difficult. For if a column of positive ions is flowing through a similar column of negative ions, recombination ceases when the columns get clear of each other. If the ions are all of the same mobility this happens somewhere near the central plane of the chamber. But if there is present an ion of one-tenth the mobility of the ordinary ion, it will take ten times as long to cross the chamber, and hence will be in danger of recombination for almost twice as long a time. During half of this time recombination is very likely to occur, since the ion will be the only one of its sign in a dense column of opposite sign. And again, such an ion, being larger than the ordinary ion, would make more collisions.

According to this hypothesis the extent to which a gas shows "initial recombination" should increase with the extent to which it forms heavy ions of low mobility. Now, since the formation of such ions is likely to be due to attractions between the molecules, it is likely to be more frequent the nearer the gas is to its boiling-point. If, then, observations are made all under similar conditions as regards apparatus, temperature, and pressure, a gas which has the higher boiling-point should always show more "initial recombination." In the following table several gases are tabulated in the order of the degree in which they show "initial recombination"; hydrogen shows the phenomenon least, sulphur dioxide most. In the second column the boiling-points are given; it will be observed that, in accordance with the hypothesis, they increase regularly throughout the table. In the third column the solubilities in water are given, for it was thought that the formation of heavy ions might conceivably be dependent on this property to some extent. It will be observed that in the only case (ammonia) in which the order of solubility is different from that of boiling-point, "initial recombination" appears to be determined rather by the latter than by the former. The observations refer to dry gases; solubility might be of greater importance if the gases were moist.

Gas.	Boiling-point.	Solubility in water.
Hydrogen .....	-253° C.	19 parts in 1000.
Carbon monoxide .....	-190	25
Oxygen .....	-183	34
Methane .....	-164	..
Carbon dioxide.....	- 65	1019
Ammonia .....	- 33.5	802,000
Sulphur dioxide .....	- 10	56,600

*Summary.*

In the foregoing paragraphs an attempt has been made to show the shortcomings of an unamplified columnar theory in explaining all the phenomena of "Initial Recombination." The arguments are based on the failure of mathematical deductions of the theory, whether tested directly or indirectly, to predict experimental results; and also on the great diversity shown by various gases with respect to this phenomenon. Thus ammonia, a light gas, should theoretically show little recombination, but it is found to show "initial recombination" in a very marked degree. Moisture was found to enhance recombination, which is attributed to the decrease in mobility of the ions due to the presence of moisture. The suggested reason for the deviation from the exact laws is the presence of a small percentage of ions of small mobility in the gases. This receives support from the fact that the nearer the temperature of a gas is to its boiling-point, the more does the gas exhibit initial recombination.

My thanks are due to Professor Bragg and Dr. Campbell for invaluable assistance and encouragement during the time in which the foregoing work was in progress.

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XC. *On the Stability of the Laminar Motion of an Inviscid Fluid.* By Lord RAYLEIGH, O.M., F.R.S.\*

THE equations of motion of an inviscid fluid are satisfied by a motion such that  $U$ , the velocity parallel to  $x$ , is an arbitrary function of  $y$  only, while the other component velocities  $V$  and  $W$  vanish. The motion may be supposed to be limited by two fixed plane walls for each of which  $y$  has a constant value. In order to investigate the stability

\* Communicated by the Author.