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On the Condensation Nuclei Produced in Gases by the Action of Rontgen Rays, Uranium Rays, Ultra-Violet Light, and Other Agents

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IX. *On the Condensation Nuclei produced in Gases by the Action of Röntgen Rays, Uranium Rays, Ultra-violet Light, and other Agents.*

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IN a previous communication ('Phil. Trans.,' A, vol. 189, p. 265, 1897) I described experiments proving that when dust-free air, initially saturated with water vapour, is allowed to expand adiabatically, condensation takes place, if the maximum degree of supersaturation resulting from the expansion exceeds a certain limit. Using v_2/v_1 the ratio of the final to the initial volume as a measure of the expansion, we may describe the phenomena briefly as follows :—

Condensation only takes place throughout the gas if v_2/v_1 exceeds 1·25; the drops are comparatively few, provided a second limit ($v_2/v_1 = 1·38$) is not exceeded. Beyond this second limit the rate of increase in the number of drops with increasing expansion is extremely rapid, very dense fogs resulting from expansions even slightly exceeding this limit.

The view was taken that when the degree of supersaturation (approximately eight-fold) corresponding to the second limit is reached, the vapour condenses independently of any nuclei other than its own molecules or those of the gas with which it is mixed.

The rain-like condensation which takes place in air when v_2/v_1 lies between 1·25 and 1·38 was taken as indicating the presence of some other kind of nuclei than the molecules of gas or vapour.

It was further found that when the gas was exposed to even weak Röntgen radiation, comparatively dense fogs were obtained when v_2/v_1 exceeded 1·25 (the supersaturation being then approximately four-fold), no condensation taking place with smaller expansions. Thus, exposure of the gas to Röntgen rays causes nuclei to be produced, requiring a definite degree of supersaturation in order that water may condense upon them. Later ('Proc. Camb. Phil. Soc.,' vol. 9, p. 333, 1897) it was found that nuclei, requiring exactly the same minimum expansion to catch them, are produced in air by the action of uranium rays.

In the paper just referred to the conclusion was drawn that the nuclei produced by X-rays and uranium rays are identical with one another, as well as with those always present in small numbers in moist air, and causing the rain-like condensation which results when v_2/v_1 lies between 1·25 and 1·38. It was also there suggested that these nuclei are to be identified with the "ions," to the presence of which the conducting power of gases exposed to X-rays or uranium rays is due.

The primary object of the experiments described in the present paper was the study, by comparison of their efficiency as nuclei of condensation, of the carriers of the electricity in gases, when these are made by any of the known methods to be capable of allowing the passage of electricity through them. In the course of the work certain other kinds of nuclei were unexpectedly met with, which appear not to be associated with any conducting power in the gas. The method by which nuclei carrying a charge of electricity were distinguished from such uncharged nuclei is described in § 10.

I must explain here the meaning to be attached to certain expressions frequently used throughout this paper to avoid circumlocution. I have spoken of the expansion required to "catch" nuclei, meaning the expansion required to cause water to condense on such nuclei. The expressions "larger" and "smaller" are often used of nuclei instead of "requiring a less degree of supersaturation," or "requiring a greater degree of supersaturation, in order that condensation may take place on them." Nuclei are often said to "grow" when they become larger in the sense just defined.

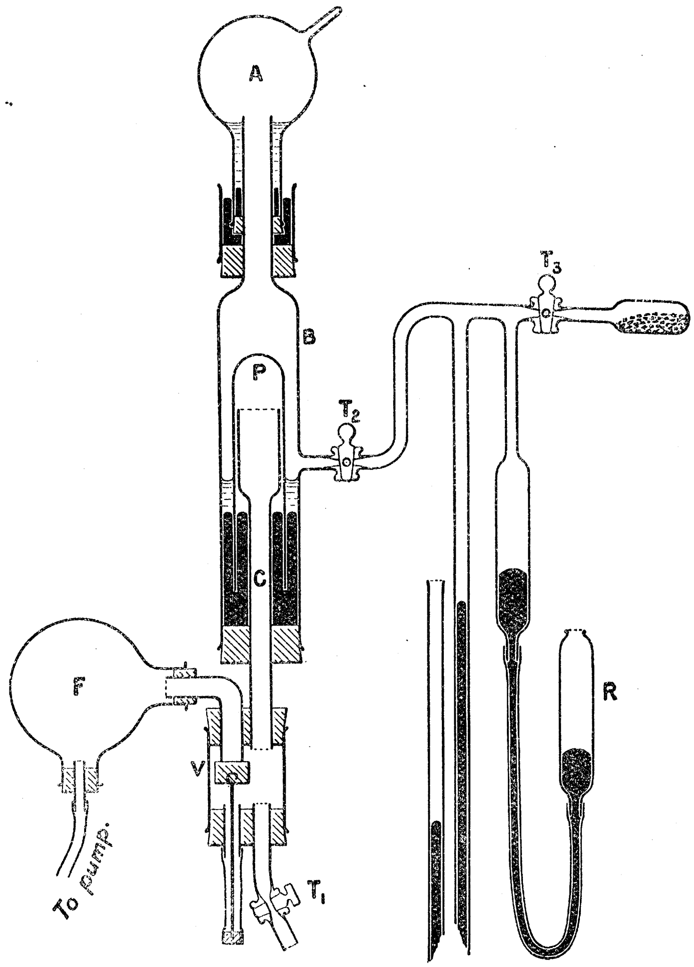
It is probable that the expressions "larger" and "smaller" may be taken literally, without error; for we may suppose such nuclei to be very small drops of water, which are able to persist in spite of their small size, because the effect of the curvature of the surface in raising the equilibrium vapour-pressure is balanced by the opposite effect produced by the drop either being charged with electricity or containing some substance in solution. An increase in the charge of electricity or of the quantity of dissolved substance, either of which would increase the efficiency of the drop as a condensation nucleus, would also result in an immediate increase in the size of the nucleus necessary for equilibrium.

2. Expansion Apparatus.

The apparatus that I have most frequently used for bringing about the sudden expansion required in these experiments is represented in fig. 1.

A is the cloud chamber, where any drops which may be formed on expansion are made visible by the light from a luminous gas flame, brought by means of a lens to

Fig. 1.



a focus within it. As the form of the cloud chamber had very frequently to be changed, it was convenient to arrange that it could readily be detached from the rest of the apparatus. An air-tight joint was made by means of the indiarubber stopper and mercury-cup arrangement shown in the diagram. The form of the cloud chamber there shown is the simplest that was used.

The cylindrical glass tube B (internal diameter = 2·7 centim.) is closed at its lower end by an indiarubber stopper, through the centre of which passes a glass tube, C, about 1 centim. in diameter, with a wider portion at its upper end serving as a guide to the light glass plunger, P, which slides freely over it. The plunger is made from a thin-walled test-tube, the open end of which has been cut perpendicular to the sides and ground smooth. Its lower edge is always immersed in the mercury which fills the lower part of B, and thus the gas in A and the upper part of B is completely cut off from the air inside P. The external diameter of the plunger is 2 millims. less than the internal diameter of the outer tube; there is thus a space of 1 millim. all round the tubes. When the tap, T_1, is open and there is thus free communication between the space inside P and the atmosphere, the plunger rises till the pressure in A only differs from the atmospheric pressure by an almost negligible amount, depending on the difference between the weight of the plunger and of the mercury displaced by the immersed part of its walls. If, now, communication with the atmosphere be cut off (by closing the tap T_1), and the space below the plunger be suddenly connected with the vacuum in F by means of the valve, V, the plunger is driven through the mercury till it strikes the indiarubber, against which it remains tightly held by the pressure of the air above it. The mercury remains practically stationary, while the thin edge of the plunger cuts its way through it.

If T_1 be again opened, re-admitting air into the space below the plunger, the latter rises to its original position, and an expansion of the same amount can be repeated as often as may be required. To arrange for an expansion of any given amount, the tap, T_2, must be opened while the plunger is in contact with the indiarubber, that is, in the position it occupies immediately after an expansion. The mercury reservoir, R, is then fixed at such a level that the pressure in A, as indicated by the gauge, is the desired amount below that of the atmosphere; the tap, T_2, is then closed and the plunger made to rise by opening the tap, T_1.

If B be the barometric pressure, then the pressure of the gas before expansion is

$$P_1 = B + m - \pi,$$

where π is the vapour pressure at the temperature of experiment, and m is the pressure (amounting to 1 or 2 millims. of mercury) required to keep the walls of the plunger immersed in the mercury (m is measured by finding the pressure which has to be applied to the air in A to keep the piston immersed to the same depth when the space below it is in communication with the atmosphere).

The pressure of the gas after expansion is

$$P_2 = B - p - \pi,$$

where p is the difference of pressure indicated by the open mercury gauge when put in connection with A before the previous contraction.

Then the ratio of the final to the initial volume of the gas is (if BOYLE'S law holds)

$$\frac{v_2}{v_1} = \frac{P_1}{P_2} = \frac{B + m - \pi}{B - p - \pi}.$$

P_2, it will be noticed, is the pressure, not at the moment when the expansion is completed, but after the temperature has risen to its original value.

As the initial pressure, P_1, in these experiments is always approximately equal to the atmospheric pressure, it is sufficient for many purposes to take $P_1 - P_2$, or p, as a measure of the expansion without further reduction.

To make, for example, $v_2/v_1 = 1{\cdot}25$, $P_1 - P_2$ must be equal to 15 centims. of mercury if the barometric pressure = 760 millims. and the temperature = 15° C.; while, as long as the atmospheric pressure lies between 740 and 780 millims., and the temperature lies between 10° and 25° C., $P_1 - P_2$ for the same expansion will always lie between 14·4 and 15·4 centims.

The gas with which the apparatus is to be charged is introduced through the stopcock, T_3, a side tube on the cloud chamber A being connected to a water air-pump, so that a stream of the gas at low pressure may pass through the apparatus. (At this stage a sufficiently low pressure must, of course, be maintained below the plunger, P, to prevent it rising out of the mercury in B.) The side tube is afterwards sealed off, and when sufficient gas has been generated to bring the pressure nearly up to that of the atmosphere, T_3 is closed.

The stopcocks, T_2, T_3, were lubricated with water only and protected by mercury cups. The mercury in B, as well as that covering the indiarubber stopper over which A is slipped, is prevented from coming in contact with the gas in the apparatus by a layer of distilled water.

In most of the experiments in which large expansions were required the expansion apparatus had the form described above. Many of the experiments with air, however, were performed with an expansion apparatus resembling that described in the 'Camb. Phil. Soc. Proc.' (*loc. cit.*). In it the plunger works in water instead of mercury, and is made to fit the outer tube like a piston, instead of working on an internal guide tube. The only advantage of the form with mercury is the absence of any risk of contamination of the gas in the apparatus by air which, when the plunger works in water, may gain entrance by solution and diffusion through the latter. The mercury apparatus is also suited for experiments with other liquids than water; such experiments, have, however, not yet been made.

Both these forms of apparatus give results almost identical with those obtained by means of the apparatus used in the earlier experiments ('Phil. Trans.,' *loc. cit.*). No considerable error appears to be produced by the yielding of the indiarubber when struck by the plunger, or by the momentum acquired by the air in the narrower part of the tube.

It will be convenient to mention here the methods used in preparing the gases required for the experiments. Oxygen was prepared by heating potassium permanganate. Hydrogen was obtained from palladium, which had previously been charged with the gas, obtained from the purest zinc and dilute sulphuric acid, the gas being passed through potassium permanganate solution before reaching the palladium.

Carbonic acid was prepared by heating potassium bicarbonate. In each case the tube in which the gas was produced was fused to the rest of the apparatus with the blow-pipe.

§ 3. Nuclei produced by X-rays.

In the experiments with X-rays described in the 'Phil. Trans.,' *loc. cit.*, the gas was only exposed to such radiation as was able to penetrate glass. It was of interest to know whether under the action of strong radiation condensation would take place with a less degree of supersaturation, or whether merely the number of nuclei would be increased. In a postscript to that paper the results of further experiments were given, showing that the latter alternative was the true one. Further experiments have confirmed this.

For the experiments with X-rays the expansion apparatus used differed from that represented in fig. 1, in being without the part A, the tube B being cut off square at the top instead of being prolonged into a narrower tube. With the help of an india-rubber washer, its upper end, which was ground smooth, was closed by a thin sheet of aluminium. This was held down by a brass diaphragm, which was screwed tight by three bolts, attached to a similar brass plate pressing against the lower surface of the indiarubber stopper which closes the lower end of B.

A "focus" tube giving out strong X-radiation was fixed a few centimetres above the aluminium plate closing the top of the tube B. In some of the experiments the expansion apparatus was wrapped in tinfoil (provided with the necessary apertures for observing the result of the expansions); this was found to be without effect on the appearance of the fogs.

The results of expansions in the immediate neighbourhood of the point where condensation first begins are given below.

I. Air exposed to X-rays.

B = barometer reading = 767 millims.; t = temperature = 18° C.; π = maximum vapour pressure at t° C. = 15 millims.; m = pressure required to sink plunger = 0 millim.

Gauge reading (in millims.) = p.	$v_2/v_1 = \dfrac{B - \pi + m}{B - \pi - p}$.	Result of expansion.
146	1·241	No drops
149	1·247	Very few drops
156	1·259	Fog

Least value of v_2/v_1, with which condensation was observed = 1·247.

When the expansion was made without exposure of the air to X-rays, only a very few scattered drops were seen even with v_2/v_1 as great as 1·279.

Similar results were obtained with oxygen.

II. OXYGEN exposed to X-rays.

B = barometer reading = 767 millims.; t = temperature = 21·5° C.; π = maximum vapour pressure at t° C. = 19 millims.; m = pressure required to sink plunger = 0.

Focus bulb 3 centims. above aluminium window.

Duration of exposure before expansion.	Gauge reading (in millims.) = p.	$v_2/v_1 = \frac{B - \pi + m}{B - \pi - p}$.	Result of expansion.
1 min.	146	1·243	No drops
$\frac{1}{2}$ "	152	1·256	Fog
1 "	149	1·249	Shower
1 "	147	1·245	No drops
10 secs.	159	1·271	Dense fog

Least value of v_2/v_1, with which condensation was observed = 1·249.

The number of drops produced even with expansions exceeding any of those given in the table is exceedingly small in the absence of the rays.

The minimum expansion required, in order that condensation in the form of drops may take place, is, it will be noticed, clearly defined; the increase in the expansion corresponding to a change in the result from entire absence of drops to dense fog being very small. It is also independent of the strength of the radiation, as is seen from the identity of the results here given with those previously obtained with weak rays ('Phil. Trans.,' *loc. cit.*). The increase of the density of the fogs with increasing expansion continues till v_2/v_1 is about 1·31; beyond that point, as far as can be judged from the appearance of the fogs, the increase in the number of the drops is slight, till the second limit v_2/v_1 = 1·37 is reached, beyond which the region of dense fogs, due to great supersaturation alone, is entered. Thus expansions exceeding v_2/v_1 = 1·31 appear to be sufficient to catch nearly all the nuclei produced by the rays.

Prolonged exposure to the rays does not cause the nuclei to grow larger (or become otherwise more effective in helping the condensation) than the limit corresponding to the expansion v_2/v_1 = 1·25. The observations given in Table II. show this, an exposure of 10 seconds producing nuclei enough to give a dense fog with v_2/v_1 = 1·271, while even after 1 minute not one nucleus has grown sufficiently to be caught by an expansion v_2/v_1 = 1·245.

The nuclei introduced by the X-rays, as has already been pointed out ('Phil. Trans.,' *loc. cit.*), rapidly diminish in number after the radiation has been cut off, but several seconds are required for their complete disappearance; thus an expansion made 5 seconds after switching off the current from the induction coil will give a shower very much denser than would have resulted had there been no exposure of the gas to the rays. No trace of the nuclei can, however, be detected 30 seconds after cutting off the rays. The rapid diminution of the number of the nuclei is readily explained, if we regard them as consisting of positively and negatively charged ions which tend to recombine and neutralize one another.

Experiments were also made with carbonic acid.

CO_2 EXPOSED to X-rays.

B = barometer reading = 768 millims.; t = temperature = 21° C.; π = vapour pressure at t° C. = 18 millims.; m = pressure required to sink plunger = 0.

Gauge reading (in millims.) = p.	$v_2/v_1 = \frac{B - \pi + m}{B - \pi - p}$.	Result of expansion.
189	1·337	No drops
190	1·339	" "
190	1·339	Very few drops
192	1·344	Slight shower
235	1·45	Dense fog showing colours

Least value of v_2/v_1 with which condensation was observed = 1·339.

Even with an expansion the same as in the last observation given in the table, only a slight shower was obtained in the absence of the rays.

The expansion, found in the previous experiments ('Phil. Trans.,' *loc. cit.*) to be necessary to cause rain-like condensation to take place in the absence of X-rays, was $v_2/v_1 = 1·36$. Dense condensation began at the limit $v_2/v_1 = 1·53$. In the experiments now described, condensation was again found to begin in the absence of the rays when $v_2/v_1 = 1·36$.

The experiments with CO_2 were made with a thin glass cloud chamber, such as is shown in fig. 1.

4. NUCLEI PRODUCED BY URANIUM RAYS.

In the experiments on the action of the uranium rays on condensation, described in a previous paper ('Camb. Phil. Soc. Proc.,' vol. 9, p. 333), the air was contained in a glass vessel which the rays had to penetrate; by far the larger part of the radiation being thus absorbed before it reached the air. Experiments were, therefore, performed in which the uranium compound was inside the vessel and thus actually in contact with the air, so that the maximum intensity of the radiation was obtained.

For this purpose the apparatus used was that shown in fig. 1, the cloud chamber being a thin glass bulb. Inside it was fixed, by means of a copper wire wound round the top of the narrow prolongation of B, a small shallow glass cup containing some uranium oxide.

AIR in contact with Uranium Oxide.

B = barometer reading = 759 millims.; t = temperature = 13° C.; π = maximum vapour pressure at t° C. = 11 millims.; m = pressure required to sink plunger = 1 millim.

Gauge reading (in millims.) = p.	$v_2/v_1 = \frac{B - \pi + m}{B - \pi - p}$.	Result of expansion.
147	1·246	0
148	1·249	1 or 2 drops
149	1·251	0
150	1·253	1 or 2 drops
154	1·261	Dense shower
174	1·305	Fog
196	1·357	Fog

Least value of v_2/v_1 with which condensation was observed = 1·249.

This is identical with the number obtained when the uranium was contained in a glass bulb outside the expansion apparatus. ('Camb. Phil. Soc. Proc.,' *loc. cit.*) The number of drops is, as was to be expected, very much greater.

Similar experiments were made with hydrogen.

HYDROGEN in contact with Uranium Oxide.

B = barometer reading = 759 millims.; t = temperature = 14·5° C.; π = maximum vapour pressure at t° C. = 12 millims.; m = pressure required to sink plunger = 1 millim.

Gauge reading (in millims.) = p.	$v_2/v_1 = \frac{B - \pi + m}{B - \pi - p}$	Result of expansion.
151	1·255	No drops
153	1·259	1 or 2 drops
161	1·277	Shower
170	1·296	Dense shower
198	1·362	Dense shower

Least value of v_2/v_1 with which condensation was observed = 1·259.

HYDROGEN exposed to Uranium Rays (through glass).

B = barometer reading = 767 millims.; t = temperature = 13° C.; π = maximum vapour pressure at t° C. = 11 millims.; m = pressure required to sink plunger = 1 millim.

Gauge reading (in millims.) = p.	$v_2/v_1 = \frac{B - \pi + m}{B - \pi - p}$	Result.
150	1·246	No drops
153	1·255	Very few drops

Least value of v_2/v_1 with which condensation was observed = 1·255.

It is remarkable that the minimum supersaturation required to cause condensation on the ions should be the same in hydrogen as in air. It must, however, be remembered that in all these experiments water vapour is necessarily present; and some of the ions may always be derived from it. It may be that those requiring the minimum expansion to make condensation take place on them are produced from this source, when hydrogen is the gas under investigation.

In hydrogen which is not exposed to Uranium rays or other nucleus-producing agent, no drops at all are produced even with v_2/v_1 as great as 1·3 (see 'Phil. Trans.,' *loc. cit.*). A small quantity of uranium oxide contained in a thin glass bulb, 16 centims. away from the glass bulb forming the cloud chamber, was found to give quite a noticeable shower with $v_2/v_1 = 1{\cdot}277$. An expansion apparatus filled with hydrogen thus forms a very sensitive detector of Uranium or X-rays. If we take the view already suggested, that these nuclei actually are identical with the ions, each individual ion being made visible on expansion by the formation of a visible drop around it, it is not surprising that the method should be more delicate than the photographic or electrical modes of detecting such rays.

§ 5. Nuclei produced by Ultra-violet Light.

In some experiments of Lenard and Wolff ('Wied. Ann.,' vol. 37, p. 443, 1889), light, rich in ultra-violet rays, was admitted through a quartz window into a vessel containing moist dust-free air. They found that if the air was allowed to expand after being exposed for some minutes to the light, a fog was produced showing that nuclei of some kind had been produced by the action of the ultra-violet rays. Similar results were obtained in steam-jet experiments. They regarded their experiments as proving that the ultra-violet rays caused the posterior surface of the quartz to disintegrate, the small particles thrown off constituting the nuclei on which condensation took place.

For the purpose of measuring the expansion required to make water condense on the nuclei produced in this way, I used apparatus identical with that made for the experiments with Röntgen rays, a quartz plate being, however, substituted for the aluminium closing the top of the cylindrical tube B.

The quartz plate was attached in the same way as the aluminium plate, being screwed tightly against an indiarubber band placed on the top of B. As in Lenard and Wolff's experiments, the source of the ultra-violet light was the spark between zinc terminals produced by an induction coil; a Leyden jar being inserted in the secondary circuit to brighten the spark. Short sparks of about 2 millims. in length were generally used. Cadmium terminals were substituted for zinc in many of the experiments, but with no great increase in the effect. The expansion apparatus was wrapped in tinfoil, provided with windows to enable the fogs to be seen, the quartz itself being covered with wire gauze, placed on the brass diaphragm which held the quartz in position.

The effects described below are certainly due to the ultra-violet rays. That they are due to light of some kind is easily shown by interposing a quartz lens, so that an image of the source is formed, which, by a slight displacement of the lens, may be made to fall either on the quartz window or just to one side of it. In the latter case all effect on the condensation ceases, while so long as the concentrated light from the quartz lens does enter the window, the effect is immensely increased by its presence. Even exceedingly thin glass or mica interposed anywhere between the source and the cloud-chamber prevents all action. It is, therefore, the ultra-violet rays alone which are active in producing nuclei.

The results of one series of experiments, extending over four consecutive days, are given in the tables which follow. Many experiments of the same kind were made with exactly similar results. Since, however, as will be seen in what follows, the absolute numbers are of no particular interest, the one series has been considered sufficient. For the same reason the value of v_2/v_1 has not been calculated, the gauge reading p (approximately equal to $P_1 - P_2$) being used as a measure of the amount of expansion. The time for which the air was exposed to the ultra-violet rays before the expansion was made is given, as well as the interval, if any, which elapsed between the cutting-off of the rays and the expansion. When the number under this last heading is zero, it is to be taken as indicating that the expansion was brought about while the sparks were still passing.

Distance of Spark from Quartz Plate = 4·5 centims.

p = gauge reading (approx. = pressure fall).	Duration of exposure.	Interval after exposure.	Result of expansion.
(1) 10 millims.	1 min.	0	Fog
(2) 112 ,,	10 mins.	5 mins.	Dense coloured fog

Distance of Spark from Quartz Plate = 17 centims.

p = gauge reading (approx. = pressure fall).	Duration of exposure.	Interval after exposure.	Result of expansion.
(3) 102 millims.	5 mins.	0	0
(4) 133 ,,	30 secs.	0	Slight shower
(5) 133 ,,	7 mins.	0	Slight shower
(6) 145 ,,	30 secs.	0	Shower
(7) 145 ,,	5 mins.	0	Shower
(8) 160 ,,	30 secs.	0	Fog
(9) 157 ,,	10 ,,	0	Very dense shower

Distance of Spark from Quartz Plate = 11 centims.

p = gauge reading (approx. = pressure fall).	Duration of exposure.	Interval after exposure.	Result of expansion.
(10) 101 millims.	30 secs.	0	Dense fog
(11) 74 ,,	30 ,,	0	Slight shower
(12) 74 ,,	3 mins.	0	Slight shower
(13) 134 ,,	30 secs.	0	Fog
(14) 68 ,,	30 ,,	0	Slight shower
(15) 38 ,,	5 mins.	0	Few drops
(16) 140 ,,	5 secs.	0	0
(17) 140 ,,	20 ,,	0	Fog
(18) 140 ,,	5 ,,	1 sec. (approx.)	1 drop seen
(19) 140 ,,	10 ,,	,, ,,	Shower
(20) 140 ,,	20 ,,	,, ,,	Very dense shower
(21) 140 ,,	1 min.	,, ,,	Fog
(22) 163 ,,	Current switched on momentarily.	...	Shower

Distance of Spark from Quartz Plate = 5·5 centims.

p = gauge reading (approx. = pressure fall).	Duration of exposure.	Interval after exposure.	Result of expansion.
(23) 85 millims.	10 secs.	0	Shower
(24) 85 ,,	5 ,,	0	0
(25) 85 ,,	10 ,,	0	Shower
(26) 85 ,,	15 ,,	about 1 sec.	Fog
(27) 41 ,,	30 ,,	,,	Shower
(28) 41 ,,	20 ,,	,,	0
(29) 41 ,,	40 ,,	,,	Fog

Distance of Spark from Quartz Plate = 32 centims.

p = gauge reading (approx. = pressure fall).	Duration of exposure.	Interval after exposure.	Result of expansion.
(30) 156 millims.	20 secs.	0	Shower
(31) 140 ,,	2 mins.	0	0
(32) 169 ,,	5 secs.	0	Fog
(33) 169 ,,	3 ,,	about 1 sec.	Dense shower
(34) 153 ,,	10 ,,	0	1 or 2 drops
(35) 185 ,,	20 ,,	10 secs.	Fog
(36) 185 ,,	20 ,,	20 ,,	Very dense shower
(37) 185 ,,	20 ,,	30 ,,	Slight shower

Distance of Spark from Quartz Plate = 42 centims.

p = gauge reading (approx. = pressure fall).	Duration of exposure.	Interval after exposure.	Result of expansion.
(38) 148 millims.	60 secs.	0	0
(39) 152 ,,	60 ,,	0	Slight shower

Distance of Spark from Quartz Plate = 21 centims.

p = gauge reading (approx. = pressure fall).	Duration of exposure.	Interval after exposure.	Result of expansion.
(40) 128 millims.	60 secs.	0	Very few drops
(41) 140 ,,	5 ,,	0	0
(42) 140 ,,	60 ,,	0	Few drops
(43) 155 ,,	3 ,,	0	Shower

The nuclei produced by the action of ultra-violet light differ in many ways from those produced by X-rays or Uranium rays.

The expansion required to make water condense upon them depends on the strength of the radiation, and when this is strong, only a very slight expansion is necessary, as is shown in Experiments (1) and (29) in the above table. The smallest expansion of which the apparatus admitted was, in fact, sufficient to form a fog with strong radiation, and indeed, in later experiments, fogs were obtained without any expansion. Under the action of the weakest rays used, however (Expts. 30–39), the expansion required to obtain condensation is as great (p = about 150 millims.) as that required to catch the nuclei produced by X-rays.

The expansion required to make condensation take place on these nuclei depends on the time during which the apparatus has been exposed to the action of the rays before the expansion, being less the longer the exposure. The number which can be caught by a given expansion also increases with the time of exposure. (See Expts. 16–21, 23–29.) The nuclei thus appear to grow under the action of the ultra-violet rays. The increase in the size of the nuclei, or in the number exceeding a given size, does not, however, continue indefinitely with increasing time of exposure, but after a time a steady state is reached, the result of a given expansion becoming independent of the time of exposure, if this be long enough. (Expts. 3–7, 10–12.)

The time for which the nuclei persist depends on the size to which they have attained. When the radiation is so weak that the nuclei are only caught if an expansion be made as great as would be required for X-ray nuclei, by far the larger number have disappeared in 30 seconds after cutting off the radiation. (Expts.

35–37.) They do, however, last longer than the nuclei produced by X-rays. When the nuclei are large enough to be caught by a very slight expansion they last for many minutes at least (Expt. 2). As will be seen later, those produced by very strong radiation last for many hours. The shorter life of the smaller nuclei is probably due mainly to their more rapid rate of diffusion.

The limit to the size attained by the nuclei for a given strength of radiation when the time of exposure is indefinitely prolonged is, perhaps, also to be explained by diffusion. For, if the radiation be weak, the nuclei may reach the walls by diffusion before any considerable growth has time to take place; whereas, with stronger radiation, not only will the drops grow more in a given time, but the slower rate of diffusion resulting from their increased size must increase the time for which they remain exposed. It is not surprising, according to this view, that a comparatively small increase in the intensity of the radiation may result in a very great diminution in the least expansion required to catch the nuclei.

Fig. 2.

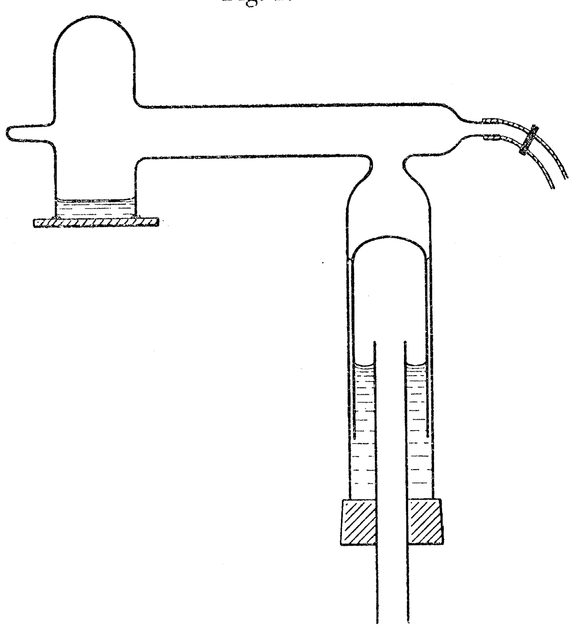
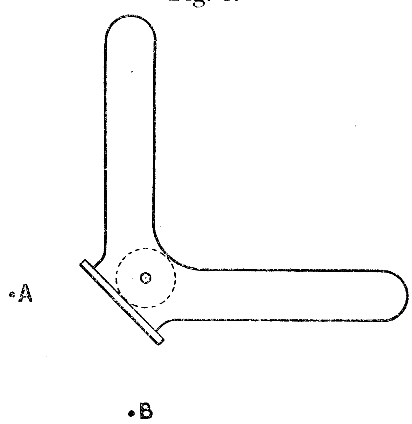


Fig. 3.



Experiments were now carried out with the object of deciding whether the nuclei are produced throughout the volume of the moist air, or, only at the surface of the quartz, as LENARD and WOLFF supposed (*loc. cit.*). For this purpose an expansion apparatus was made of the form shown in fig. 2. The ultra-violet light entered from below through a quartz plate, which was covered with water to a depth of about 5 millims. The quartz plate was held up against the ground edge of the cloud-chamber by means of two elastic bands, an indiarubber washer being used as before to make an air-tight joint. The apparatus was wrapped in tinfoil, provided with the necessary apertures.

Dense fogs were obtained under the action of the ultra-violet light (zinc-spark); the expansion being that corresponding to a pressure fall of 10 centims.

The nuclei produced under these conditions cannot have arisen from the disintegration of the quartz.

Another proof that the quartz is not the source of the nuclei is furnished by the results of experiments made with an expansion apparatus of the form shown in fig. 3. It consisted of three glass tubes meeting at right angles, two being horizontal and the third pointing downwards and containing the piston. A quartz window was fixed in a vertical plane making an angle of 45° with each of the horizontal arms. By placing the zinc points forming the source of the ultra-violet light at a position such as A, the rays may be made to pass along only one limb of the apparatus. If the source is transferred to B the air in the other limb is exposed to the rays and none of them traverse the first limb. The quartz being equally inclined to both limbs, any nuclei which are thrown off from it will find their way equally readily along either. The experiments show, however, that nuclei are only introduced into that limb along which the ultra-violet light passes.

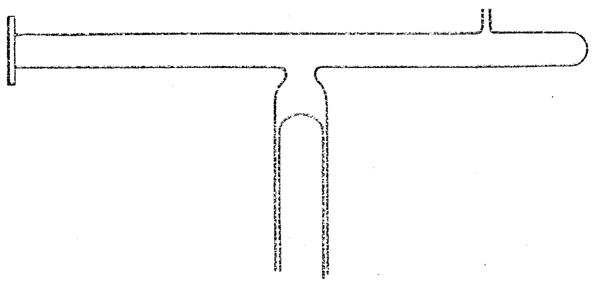
The fogs were made visible by the light from a gas flame, which could be concentrated by a condensing lens at any part of either tube. The time for which the rays were allowed to act before the expansion was made was generally 5 seconds. In some of the experiments the rays were made approximately parallel by means of a quartz lens. The expansions used, measured by the pressure fall p, varied from 13 to 16 centims. of mercury.

In every case a shower of fog was produced from end to end of the tube traversed by the ultra-violet rays, while no effect could be detected in the other branch even at a point not more than 1 centim. from the junction of the tubes. The exposure could be made twice as long without any effect being obtained in the branch not exposed to the rays.

In all these experiments attention was confined to the small portion of one tube which was illuminated by the light from the luminous gas flame, which was brought to a focus at that point; observations being made alternately with corresponding portions of the two branches successively illuminated in this way. Finally, however, experiments were made, in which, owing to the use of stronger radiation this was unnecessary, the fogs produced being well seen without any condensing lens. The sparks were produced between cadmium terminals, and a more powerful induction coil was used than in the previous experiments. A parallel beam of ultra-violet light was not used, but the cadmium points were brought to within 1·5 centims. from the quartz plate. The experiments were made with a pressure fall of 14 centims., the time of exposure being 20 seconds. Under these conditions, the tube along which the rays were directed was filled with fog on expansion, the other tube remaining empty. The fogs were well seen by means of the light from the gas flame without any condensing lens, so that a general view of the result of expansion throughout both branches was obtained at once. On displacing the cadmium points so that the rays now passed along the other tube, and repeating the experiments, the tube which before was filled with fog now remained dark, and the other was filled with a white or coloured fog.

These experiments prove that the nuclei produced by the action of ultra-violet light do not have their origin at the surface of the quartz. It might still be supposed that they are produced at the surface of the glass, where this is exposed to the ultra-violet rays. LENARD and WOLFF, however, were able to detect no effect of this kind with glass. With the object of testing this point, a T-shaped expansion apparatus was now made (fig. 4). The length of the horizontal tube amounted to

Fig. 4.



27 centims., and the internal diameter was 1·3 centim. One end of this tube was closed by a quartz plate cemented on with shellac.

The rays from a spark between cadmium terminals were sent axially along the tube, a quartz lens being inserted to make the rays converge to a point slightly beyond the far end of the tube. By observing the image of the cadmium points which was formed by the quartz lens, it was easy to test whether the light was passing axially, and also whether the points were sufficiently near together to give an image considerably smaller than the diameter of the tube. The length of the spark-gap was generally rather less than 1 millim.

In the earlier experiments made with this apparatus, the fogs, which were produced on expansion under the influence of the ultra-violet light, although very dense near the quartz plate, diminished rapidly in denseness with increasing distance from the quartz, and did not reach the far end of the tube at all. This was at first interpreted as indicating either that the nuclei arose at the surface of the quartz, or that the active rays were absorbed by a comparatively small thickness of moist air. The latter view was easily disproved by interposing a layer of moist air (in an open tube 17 centims. long) between the source and the expansion apparatus. This exercised no appreciable absorption. The whole effect was finally traced to a deposit of fine dew on the inside of the quartz plate. On removing this by gentle warming, uniform fogs from end to end of the tube were obtained on expansion. There was never any indication of any increase in the density of the fog close to the far end of the tube, where the rays strike the glass. To ensure that there should be no effect throughout the length of the tube due to rays grazing the walls, a tinfoil diaphragm with an aperture of 5 millims. was inserted in front of the quartz plate. The fogs still remained uniform from end to end. A want of uniformity in the density of the fog at once shows itself in the curvature of the upper surface of the fog, due to the more rapid settling where the drops are fewer and larger. In these experiments the time of exposure before expansion was from 3 to 5 seconds.

It is easy to understand the great effect produced by a slight dimness of the quartz plate, for scattering of the ultra-violet rays by the small droplets on the plate is likely to take place to a much greater degree than that of the luminous rays. The rays which escape scattering or deflection at the quartz may not be strong enough of themselves to produce, in the time for which the exposure lasts, nuclei large enough to be caught with the degree of expansion used, while together with the scattered rays they may be more than strong enough close to the quartz for this purpose. Now the scattered light (the quartz plate being small compared with the length of the tube) will fall off approximately inversely as the square of the distance from the quartz. It is thus readily understood why the fog extended only a short distance from the quartz when this was covered with a deposit of dew.

That the uniformity of the fog from end to end of the tube, when the contents are actually exposed to equally intense radiation throughout, is not due to diffusion of the nuclei before expansion, or mixing of the air in the tube in consequence of the expansion, is certain. For, in the experiments in which there was a deposit of dew on the quartz, no fog was produced at the far end, even with an exposure of 60 seconds; while a very dense fog was obtained near the quartz with an equal expansion, with an exposure of only 10 seconds. Similar results were obtained in experiments in which the Cadmium points were displaced to one side, so that only a small portion of the tube near the quartz was exposed to the rays. The fog obtained on expansion only extended a short distance beyond the part of the tube reached by the rays.

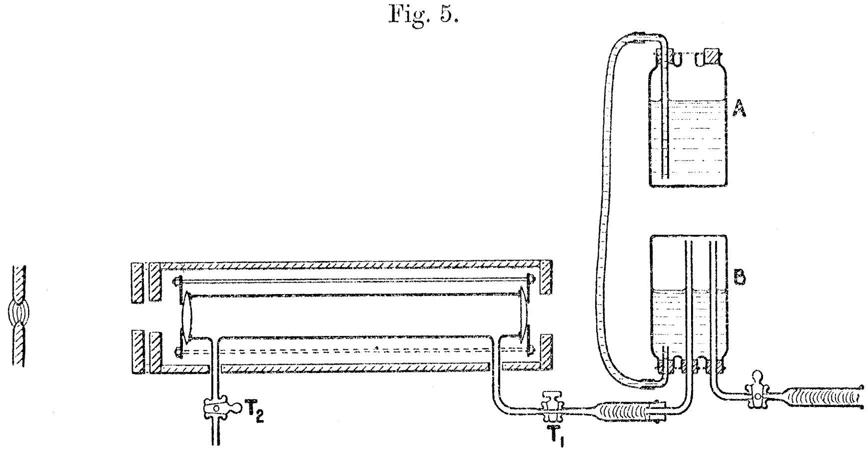
The experiments with this apparatus make the superficial origin of the nuclei very improbable; for, if they arose only where the rays fell on a surface, the fogs would have been confined to the ends of the tube. To account otherwise for the fact that whenever a fog was produced (with the light passing axially) it was uniform from end to end of the tube, we would have to suppose that on account of undetected scattering of the ultra-violet rays at the ends, the walls throughout the whole length of the tube received approximately uniform ultra-violet illumination.

Perhaps the most striking proof that the nuclei produced by ultra-violet light are formed throughout the volume of the moist air, and not at the surface of the vessel containing it, is furnished by experiments with very strong radiation. As already stated in a preliminary note on the subject ('Camb. Phil. Soc. Proc.,' vol. 9, p. 392), under the influence of very strong ultra-violet light fogs are produced without any expansion, even in unsaturated air. The nuclei which, when they are only exposed to very weak ultra-violet light, do not grow beyond the stage at which a four-fold supersaturation is required to make condensation take place upon them, grow under the influence of very strong radiation till they become large enough to scatter ordinary light.

TYNDALL, many years ago ('Phil. Trans.,' vol. 160, p. 333, 1870), showed that when the more refrangible rays from an arc lamp, such as were able to traverse blue glass but not red glass, were concentrated within a tube containing air mixed with amyl-nitrite or certain other vapours, dense clouds were produced. He was unable to obtain any such effect with pure air and water only. The experiments to be described differ in no essential respect from his, except in the fact that the rays from the arc lamp were allowed to traverse no material such as glass, which is opaque to the ultra-violet rays, before entering the tube containing the moist air. Under these conditions, air containing water vapour only, shows the phenomena that were observed by TYNDALL with other vapours.

I have found the apparatus shown in fig. 5 convenient for experiments on this

Fig. 5.



subject. It consists of a glass tube 34 centims. long, and 4 centims. in diameter, provided with a side tube near each end. The ends are closed by quartz lenses, which are fixed air-tight by means of indiarubber washers. They are pressed tightly against these indiarubber rings by means of two brass diaphragms screwed together by means of three bolts just outside the tube. By means of the two Wolff bottles, A, B, a current of filtered air can be driven through the apparatus. The air is filtered before entering B, and again on leaving it. If, while A was fixed at some height above B, the stop-cock T_2 remained closed while T_1 was open, the pressure in the apparatus was greater than the atmospheric pressure. On opening T_2 the pressure was suddenly reduced to that of the atmosphere, and the expansion produced in this way was sufficient to cause condensation on ordinary dust particles. A small quantity of water was contained in the tube to keep the air saturated. To enable even faint clouds to be seen, the tube was contained in a blackened box, open along one side, and with a hole somewhat smaller than the diameter of the tube at each end, so that a beam of light from an arc lamp might pass along the axis of the tube.

The quartz lens through which the light entered had a focal length of about 10 centims., and the arc was generally placed at such a distance that the light was brought to a focus about the middle of the tube. A strong arc is necessary in these experiments.

Filtered air was passed through the apparatus until all dust particles were removed. The presence or absence of dust particles was easily ascertained by allowing expansion to take place as described above, while the light from the arc traversed the tube, a sheet of mica being interposed at this stage to cut off the ultra-violet rays. When drops ceased to appear on opening the stopcock T_2, a few minutes were generally allowed to elapse before exposing to the ultra-violet rays, to enable the air inside the tube to come to rest. To start the exposure to ultra-violet rays the mica was removed.

Under the conditions described above, a bluish fog is seen in the tube in about two minutes, making its appearance first near the apex of the beam of light, and then extending both ways in the form of a double cone. That the fog when it first appears is confined to the path of the light is easily proved by displacing the tube slightly to one side; or better, by inserting the mica screen and moving the box with the tube fixed inside it nearer the arc, so that the luminous rays converge to a focus much nearer the far end of the tube; or, without moving the tube, by inserting a glass lens just in front of the tube after the fog has appeared, so as to bring the luminous rays to a new focus. In each of these ways it is easy to prove that the fog does actually arise, not near the quartz nor the glass walls of the tube, but along the axis of the tube in the neighbourhood of the point where the light is most concentrated. It was found that the shape of the cloud was specially well defined when the water in the tube contained two or three per cent. of caustic potash. This prevented any deposit of fine drops on the inner surface of the quartz by keeping the inside of the tube not quite saturated.

We thus obtain a further confirmation of the conclusion already drawn from the expansion experiments, that ultra-violet light produces nuclei throughout the volume of the moist air which it traverses, and not only at the surface of the quartz or the glass walls of the tube.

On allowing the air to expand after the fog has appeared, condensation takes place throughout the tube, showing that outside the part traversed by the strongest radiation, nuclei have been formed, but not large enough or numerous enough to form a visible fog. These may arise partly through some of the nuclei produced in the strongest part of the beam travelling into other parts of the tube; they may also have been produced by the action of ultra-violet rays, scattered by the cloud particles produced in the direct path of the light. These will scatter ultra-violet light even before they have grown large enough to make themselves visible by scattering the luminous rays. The scattering of the ultra-violet rays by the cloud particles is probably also the cause of the fog (without expansion) spreading further and reaching a greater density on the side of the focus next the source.

If the exposure to the rays of the arc be continued after the fog has become visible, this often assumes very remarkable shapes, resembling those obtained by TYNDALL with air which had been passed through a solution of hydrobromic or hydroiodic acid.* The fog may, for example, develop dark striæ which may be straight and vertical, or may have quite complicated forms. They sometimes produce a regular cone-in-cone structure (*cf.* TYNDALL, *loc. cit.*), or the fog may become divided up into rounded clouds often connected by a thread of fog along the axis of the tube. These complicated forms were noticed most frequently in some of the earlier experiments, in which a longer tube (60 centims.) of the same cross-section was used, with a quartz lens whose focal length was 25 centims. The light was thus less concentrated and the fog took much longer to become visible, generally about ten minutes.

There can be no doubt that all these complicated cloud forms owe their origin to air currents in the tube. A dark stria may always be produced at will at any part of the fog by warming the lower edge of the tube at that point, by holding one's finger against it. A stream of air, free from fog, rises at this point in a narrow layer, and a dark vertical stria is produced,† the brightness of the fog immediately on each side of it being also increased. Such a dark band persists for a long time after the exciting cause has been removed.

No condensation could be produced in pure steam even with prolonged exposure. The air was expelled from the tube by allowing a rapid current of steam to pass through the apparatus for an hour at low pressure. The tube was allowed to cool to the temperature of the room (15° C.) before exposing to the ultra-violet rays. The failure to produce any visible condensation in the steam was not due to the quartz becoming dimmed through drops of water condensing on it, for on letting in a small quantity of air the effect was readily obtained. Fogs without expansion were obtained without difficulty with an air pressure of 5 centims. of mercury.

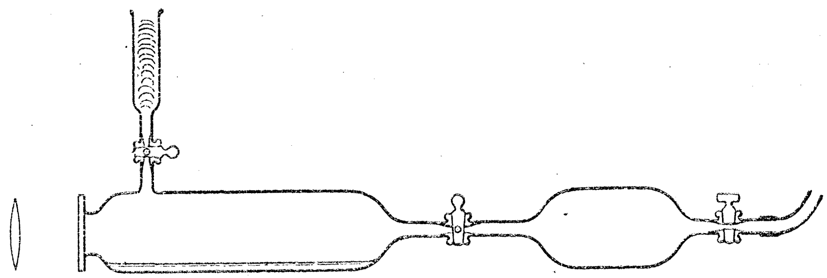
To determine to what extent water vapour was necessary for the production of these fogs, experiments were made with a much smaller apparatus than that just described. This is shown in fig. 6. The tube was 16 centims. long and 4 centims. in diameter. A solution of potash, or of sulphuric acid, was placed in the bottom of the tube. The stop-cocks were lubricated with H_2SO_4. A slow current of filtered air was drawn through the apparatus. This was then allowed to stand for some time to enable the equilibrium vapour pressure to be attained before the exposure to the ultra-violet rays was begun.

* TYNDALL, 'Roy. Soc. Proc.,' vol. 17, p. 92, 1869.

† The production of dark bands of this kind in fogs was observed by TYNDALL ('Roy. Inst. Proc.,' vol. 6, p. 1, 1870), and further studied by Lord RAYLEIGH ('Roy. Soc. Proc.,' vol. 34, p. 414, 1882), LODGE ('Nature,' vol. 28, p. 297, 1883), and AITKEN ('Trans. Roy. Soc.,' Edin., vol. 32 (1), p. 239).

No effect could be obtained with solid KOH or strong H_2SO_4 in the tube. With aqueous H_2SO_4 containing 45 per cent. of H_2SO_4, corresponding to a relative humidity of about 50 per cent., no fog was obtained. Over 10 per cent. sulphuric acid, which had been all night in the tube, so that there can be no doubt that the equilibrium vapour pressure was reached, a fog very quickly appeared under the action of the ultra-violet light. Over aqueous caustic potash, containing about 17 per cent. of KOH, a fog was readily obtained. The relative humidity over such a

Fig. 6.



solution is less than 90 per cent. Experiments have not been tried with humidity between 50 and 90 per cent. These experiments then show that both air and water vapour are necessary for the production of the ultra-violet light fogs; it is not necessary that the air should be saturated.

The cloud particles produced by the action of ultra-violet light persist, for some hours at least, after the rays have been cut off. This is so, even when the air is unsaturated; for example, the fog produced over a 17 per cent. potash solution was found to be still visible three hours after the arc was stopped. The drops are therefore small enough to settle with extreme slowness; yet in spite of their small size there is no indication of any tendency for them to evaporate again. It is probable, therefore, that the drops do not consist of pure water. We might, it is true, account for their persistence by supposing each to have become charged with electricity under the influence of the ultra-violet rays. In the light of later experiments, however, the former view appears to be the more probable.

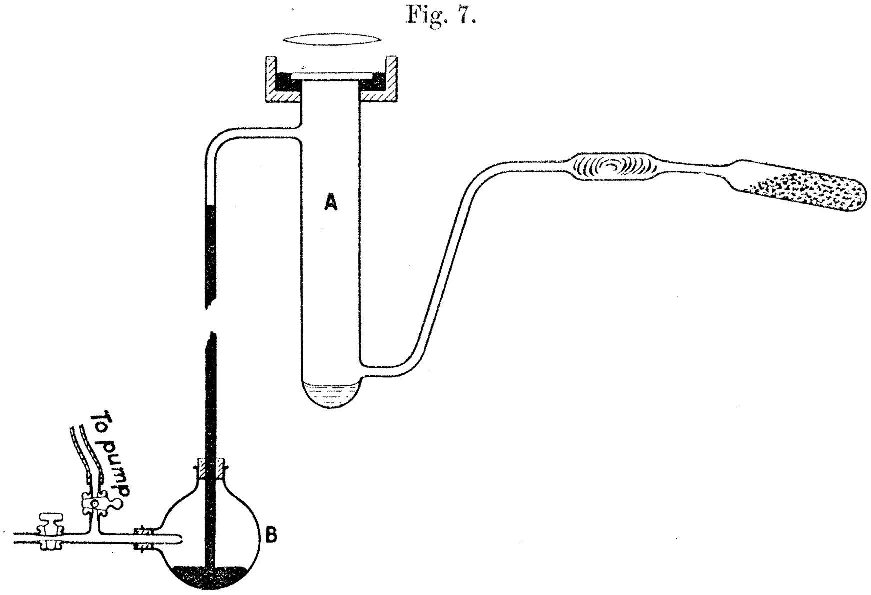
Any discussion of the nature of these fogs is, however, postponed till the experiments made with other gases than air have been described.

Before going on to describe the experiments made with oxygen, mention should be made of experiments in which no indiarubber or cement of any kind came in contact with the air exposed to the ultra-violet rays. For this purpose a test-tube with the open end ground smooth was closed by a plano-convex quartz lens, simply held in position by an indiarubber band, no indiarubber washer being inserted. The inside of the tube was moistened with distilled water; the air inside was at atmospheric pressure. The tube was fixed in a horizontal position and left for two days to allow the dust particles to settle. On exposing to the light of an arc lamp, placed so that its light was brought to a focus near the middle of the tube, a fog developed in less than two minutes.

Expansion experiments were made with oxygen with the same apparatus as was used in the experiments on air. The results obtained were identical with those obtained in the former experiments. The oxygen was obtained by heating potassium permanganate. With weak radiation nuclei were produced requiring, however long an exposure might be made, a pressure fall of 15 centims. or more; while, when the radiation was stronger, fogs were produced with comparatively slight expansions, the expansion required depending on the time of exposure. Finally, with sufficiently strong ultra-violet rays, visible fogs were obtained without expansion.

For the purpose of making experiments with oxygen as pure as could be obtained; and without any danger of contamination by vapours, which might be present if any indiarubber or cements were used in attaching the quartz plate, the apparatus shown in fig. 7 was used.

Fig. 7.



The vertical tube A, in which the gas was exposed to the action of the rays, was 16 centims. long and 3 centims. in diameter. Its open end was carefully ground flat and closed by a quartz plate, which was simply placed upon it, mercury being then poured into the wooden collar surrounding it to make a tight joint. The tube was exhausted before filling the collar with mercury.

A small quantity (less than 1 cub. centim.) of well boiled distilled water was placed in the tube immediately before closing it with the quartz plate. The water was drawn up into a pipette while still boiling and run into the apparatus after cooling slightly. The apparatus was then pumped out by connecting to a water pump.

The oxygen was prepared by heating potassium permanganate, which had been twice recrystallised, and then heated in an open dish till the greater part of it fell to powder. Between the tube which contained the permanganate and the rest of the apparatus a tube of glass wool was inserted, to prevent any of the small particles passing over with the oxygen.

The apparatus was kept at a low pressure by the pump, and a stream of oxygen made to pass through it by heating the permanganate tube. The gas passed through the mercury in B on its way to the pump. The connection to the pump could be closed at any time and the space above the mercury in B connected with the atmosphere. The mercury then rose in the long vertical tube, which dipped into it to a depth of about 1 centim., and now served to indicate the pressure. The pressure could now be raised to any desired amount, less than that of the atmosphere, by further heating of the permanganate. By closing the connection between B and the atmosphere and opening that leading to the pump, the apparatus could be again exhausted and a stream of oxygen allowed to pass through it at a pressure of a few centimetres of mercury.

A quartz lens, fixed above the quartz plate, served to bring the light from an arc to a focus a little below the middle of the tube. The arc was formed between two horizontally placed carbons contained in a box with an aperture below somewhat smaller than the diameter of the tube.

A current of oxygen was passed through the apparatus, while this was connected to the pump for 15 minutes, the apparatus was then left for one night and oxygen again allowed to stream through it for 30 minutes. After the pressure had been raised to 70 centims. the contents of the tube were exposed to the ultra-violet light of the arc. A fog appeared in a very few minutes. The apparatus was again left for a day and then pumped out, and a stream of oxygen allowed to pass for 10 minutes. Again, less than two minutes' exposure to the ultra-violet rays was sufficient to produce a fog. Again, after standing for three days, while repeatedly exposed to the ultra-violet rays till a fog appeared, the oxygen was pumped out and a vigorous stream passed for 30 minutes. The pressure was then brought up to 50 centims., and the gas exposed to the ultra-violet rays. A fog appeared after an exposure of about one minute.

The presence of nitrogen thus appears to be unnecessary for the production of cloud by the ultra-violet rays. There is no indication of any diminution in the density of the clouds or in the ease with which they are produced as the gas becomes purer.

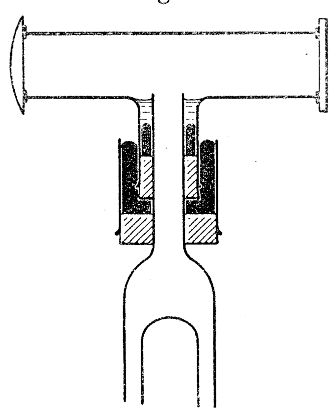
The quantity of matter in the clouds which develop under the action of ultra-violet light is very small: as is seen from the fact that even isolated patches of the fog remain suspended in the tube. Since the mass of each drop, even if its diameter be as great as one mean wave-length of light, does not amount to 10^{-12} gram, a very large number of drops may be present although the total weight of the fog is very small.

The small quantity of matter in these clouds makes it very difficult to exclude the possibility of their formation being due to the presence of traces of some vapour, which might become oxidised under the influence of the ultra-violet rays. That it is not due to mercury vapour was proved by making the exposure immediately after the stream of oxygen had stopped before the mercury vapour in the gauge could have had time to diffuse into the rest of the apparatus. Before the final experiment, also, the tubes leading to the gauge and the permanganate tube were sealed off. After the cloud appeared the exposure was continued for three-quarters of an hour and the apparatus left till the next day. The fog was found to have disappeared by that time, as was seen on exposing to the light of the arc with a plate of mica interposed; in less than two minutes after the removal of the mica, however, a new fog was produced. The last experiment was performed with the object of determining whether the formation of the cloud depended on the presence of minute traces of some substance, which might all be used up to form fog if the exposure was sufficiently prolonged. After the fog had settled to the bottom of the vessel, it was thought that the complete or partial removal of the active substance would be made manifest in an increased difficulty in producing a second fog. No such effect was found; the exposure was perhaps, however, not sufficiently prolonged for any very great weight to be attached to the result.

The experiments described leave little room for doubt that pure oxygen and water vapour alone are sufficient to enable a cloud to be produced under the influence of ultra-violet light.

In hydrogen, fogs could not be obtained under the influence of ultra-violet light without expansion. Experiments were made with an expansion apparatus to see if nuclei of any kind were produced in this gas when exposed to ultra-violet light.

Fig. 8.



A T-shaped cloud-chamber (fig. 8) was used, the rest of the apparatus being that shown in fig. 1. The horizontal tube (fig. 8) was 9 centims. long and 1·8 centims. in diameter. The ends were closed by quartz plates, fixed like those in the large apparatus which was used for experiments on the clouds produced in moist air by ultra-violet light without expansion.

The arc was used as the source of ultra-violet rays. These were made to converge by means of a quartz lens to a point slightly beyond the middle of the tube. The hydrogen was obtained, as in previous experiments, by heating a tube containing palladium saturated with the gas.

In hydrogen prepared in this way nuclei were produced under the influence of the ultra-violet rays, but never in very large numbers, and always requiring great supersaturation to make water condense upon them, however long the exposure. On replacing the hydrogen by air, without making any other alteration in the apparatus, and again exposing to the rays, a fog was obtained without expansion in less than 1 minute.

HYDROGEN exposed to Ultra-violet Rays of Arc.

Gauge reading (in millims.) (approx. = pressure fall).	Result of expansion.
137	0
147	Slight shower
167	Dense shower
167 (mica interposed)	0

In all the above observations the time of exposure was thirty seconds.

FRESH hydrogen prepared.

Gauge reading (in millims.) (approx. = pressure fall).	Result of expansion.
147	Very few drops
142 (exposed for 60 seconds)	0
150	Dense shower

The expansion required to make condensation take place upon these nuclei is, it will be seen, approximately the same as is required in the case of the nuclei produced by X-rays or Uranium rays.

With CO_2 exposed to ultra-violet rays fogs were obtained with slight expansion and even without expansion, but stronger radiation was found to be necessary than in the case of air or oxygen. For these experiments an apparatus like that used for hydrogen was used. The CO_2 was prepared by heating potassium bicarbonate.

The nuclei produced by the action of ultra-violet light on moist air, oxygen or carbonic acid, are thus seen to be capable of growing under the action of the rays till they actually become large enough to scatter ordinary light. At least in the case of air these visible fogs may persist for hours, although the air be not saturated with water vapour. Later experiments make it very improbable that the growth of these nuclei is due to each one becoming charged with electricity under the action of the ultra-violet light. The most obvious way of accounting for the growth of the nuclei into visible particles, and their persistence even in unsaturated air, is to suppose that by the action of the ultra-violet light some compound is formed in solution in each drop. Were it not for the fact that the fogs are produced in pure oxygen as well as in air, one would naturally consider the combination of oxygen and nitrogen with the water of the incipient drop to form nitric acid as the most likely reaction which could account for the phenomena. Possibly when the clouds are produced in moist air this may be, in fact, the reaction which takes place. When the clouds are produced in oxygen, however, the only possible combination which can account for the phenomena is that of oxygen and water to form hydrogen peroxide. The formation of ozone would not enable us to explain the production of the clouds, and indeed although clouds are very easily produced in ozonised oxygen it is, as the experiments of MEISSNER and others show, only as a consequence of reactions, by which some of the ozone is destroyed.

The view here taken is then, that under the action of the ultra-violet light small drops of water combine with the oxygen in contact with them, and in consequence of the lowering of the equilibrium vapour pressure by the dissolved H_2O_2 they are able to grow, when similar drops of pure water would evaporate.

The time taken by the nuclei to grow to any given size depends simply on the time required for the quantity of dissolved substance produced in each drop by the action of the ultra-violet light to become sufficient to enable a drop of that size to be in equilibrium. That, for a drop containing a definite quantity of dissolved substance, there is a definite size necessary for equilibrium, is obvious from the fact that the lowering of vapour pressure due to the dissolved substance is proportional to the concentration, that is, inversely proportional to the volume, while the increase of vapour pressure due to the curvature of the surface is inversely proportional to the radius. By the growth of the drop, if initially the solution is too strong for equilibrium, the lowering of vapour pressure due to the dissolved substance will very quickly diminish till it ceases to exceed the rise of vapour pressure due to the curvature.

If it is only, as is in itself quite likely, at the surface of separation of the gas and liquid that the ultra-violet rays cause combination to take place, the maximum effect will be produced where, as in this case, the water is in the form of a cloud of minute particles; for it is only in very small drops that any considerable proportion of the molecules are situated in the surface layer.

The absence of any effect of this kind in moist hydrogen is in agreement with the view that the growth of the drops in air or oxygen is due to the formation of hydrogen peroxide.

§ 6. NUCLEI PRODUCED BY SUNLIGHT.

AITKEN* has shown that many vapours when exposed to sunlight in glass vessels

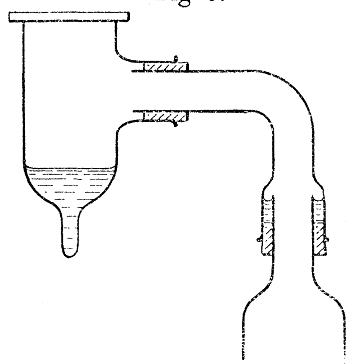
* AITKEN, 'Trans. Roy. Soc.,' Edin., vol. 39 (1), p. 15, 1897.

become charged with nuclei, on which condensation takes place when supersaturation is brought about by expansion. He was unable to detect any such effect when moist air was exposed in this way to the action of the sun's rays.

In experiments such as AITKEN'S, in which the sunlight has to traverse glass, any ultra-violet rays which may be present are cut off before reaching the gas under investigation. Now the light from an arc lamp, when deprived of its ultra-violet rays by passing through glass, was found to have no cloud-producing effect. An apparatus provided with a quartz window was therefore used.

This had the form shown in fig. 9. The quartz plate was fixed, as in the other

Fig 9.



expansion experiments in which a quartz window was required, with the help of an indiarubber washer. There was a joint on the horizontal part of the tube, made by means of an indiarubber stopper, as shown in the figure; the connection between the expansion apparatus and the gauge also was made by means of an indiarubber tube, instead of glass tubing with the joints made by the blow-pipe, as in other experiments. The cloud-vessel could thus be placed so that the quartz plate was directly facing the sun.

The presence of indiarubber vapour is doubtless a disadvantage, but the experiments with ultra-violet light from other sources make it highly improbable that any complications are thereby introduced.

On account of the heating effect of the sunlight, accurate measurements of the expansion were not possible.

The experiments were made during the month of August, between the hours of 10 A.M. and noon. The apparatus was placed at an open window, which was closed when it was desired to make an experiment with the ultra-violet rays intercepted by glass. Even when a quartz lens was used to concentrate the sunlight no nuclei were produced which could be caught with slight expansions. Even with a pressure fall of 137 millims. no drops were seen under these conditions.

With pressure falls exceeding 15 centims., showers or fogs were obtained in which the drops were plainly more numerous when no glass was interposed than when a glass screen was used to cut off the ultra-violet rays.

Observations were now made without any glass screen, the quartz lens being still used to concentrate the light. The expansions were made alternately with the apparatus unscreened, and with a screen of black paper in front of the quartz plate. The black paper was removed immediately after the expansion, to enable the drops to be seen.

The pressure fall being 174 millims., the drops were very few when the black paper was interposed, while a fog resulted when the expansion was made without the screen.

Similar experiments, made with a glass screen interposed, the expansion being the same as before, showed again a very marked difference between the results of expansions made with and without the black paper screen.

The difference is, in fact, more marked than that between the showers or fogs obtained with and without the glass screen.

It is plain, therefore, that sunlight, unlike the light from the other sources tried, contains nucleus-producing rays which can penetrate glass.

The black paper and the window-glass screen were now removed, and expansions of the same amount as before made with a red glass screen interposed. Only a few drops were produced. On substituting a screen of blue glass, a fog was obtained under the same conditions. These active rays can thus penetrate blue glass, but not red glass.

In connection with the above results it is of interest to notice that ELSTER and GEITEL ('Wied. Ann.,' vol. 38, p. 497, 1889) found that the actino-electric effect of sunlight was not stopped by window-glass or blue glass (red glass being almost opaque to it), while glass is quite opaque to the active rays from a zinc-spark or arc.

To determine to what extent the unconcentrated light of the sun was effective in producing nuclei, the quartz lens was removed, and expansions again made with and without a black paper screen, which was removed immediately after the expansion. A glass lens was interposed immediately after the expansion to make the drops readily visible.

With expansions sufficient to give a few drops in the absence of sunlight, comparatively dense showers were obtained when the air had been exposed to the rays immediately before expansion.

In AITKEN's experiments on the effect of sunlight the expansion was probably not sufficiently great to make condensation take place on the nuclei produced by it in moist air. Moreover, nuclei, which require such a large degree of supersaturation of water vapour before it can condense upon them, have never been found to persist for more than a few seconds; while in AITKEN's experiments the exposure to the sunlight was made at an open window and the apparatus then removed to a dark room before the expansion was made.

Although in these sunlight experiments no nuclei, requiring only slight supersaturation to make condensation take place on them, have been produced, they do not absolutely prove that such nuclei may not be formed by sunlight even in the lower layers of the atmosphere. For it is quite possible that the disappearance of the nuclei produced by weak ultra-violet light, when they are left to themselves, is entirely due to the fact that they very quickly reach the walls of the vessel by diffusion on account of their small size. The time for which they persist would then entirely depend on the size of the vessel containing them. Now the explanation of the fact, that with weak radiation they never grow sufficiently to be caught by slight expansions, may simply be that they reach the walls before any considerable growth has time to take place. In the atmosphere, according to this view they would persist for an almost indefinite time, and might finally become large enough to act like "dust" particles in helping condensation.

In the preliminary note already published* it was pointed out that in the upper regions of the atmosphere sunlight was likely to be rich in ultra-violet rays, and it was suggested that from their action on air and water vapour alone the small particles, to which the blue colour of the sky is due, might arise. TYNDALL† recognised the resemblance between the light of the sky and that scattered by the fogs which he obtained by the action of light on various vapours, pointing out that the light scattered by the fogs is polarised like that of the sky. He concluded that the blue colour of the sky was due to the presence of small particles like those produced in his tubes. The connection between the blue colour of the sky and that of the fogs produced from air and water vapour by the action of ultra-violet light is possibly a still closer one, the small particles to which the colour is due having a similar origin in both cases.

The cloud or nucleus-producing effect of ultra-violet rays has obviously bearings on other meteorological phenomena. The nuclei which enable clouds to form may in many cases arise from this source. The upper clouds especially may owe their formation in this way to the action of sunlight. It is possible, too, that owing to the action of the ultra-violet rays, sunlight may sometimes cause clouds to persist in unsaturated air.

§ 7. NUCLEI PRODUCED BY METALS.

The presence of certain metals in the expansion apparatus was found to give rise to condensation nuclei.

The apparatus used in most of the experiments was of the form shown in fig. 10A. (Only the cloud-vessel is shown, the rest of the expansion apparatus was the same as shown in fig. 1.) The cloud-vessel consisted of a portion of a wide test-tube. This was held in position by means of an indiarubber band. The cloud-vessel was divided into two equal parts by a vertical partition, consisting in most cases of mica on one

* 'Camb. Phil. Soc. Proc.,' vol. 9, p. 392, 1898.

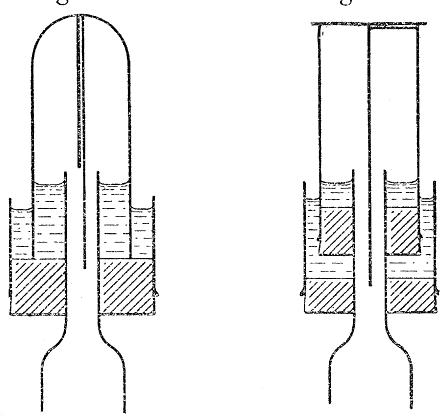
† TYNDALL, 'Roy. Soc. Proc.,' vol. 17, p. 223.

side and the metal under investigation on the other, or simply of metal polished on one side only, or of two metals, such as zinc and copper, in contact.

Another and better form of apparatus which was used in some of the later experiments is that shown in fig. 10B. The top of the tube (2·8 centims. in diameter) was closed by a metal plate, bolted down, with an indiarubber band interposed as a washer. Half of the lower surface of the metal plate was covered with a semicircular sheet of mica, attached to the metal by a little shellac; a vertical mica partition divided the apparatus into two equal parts; the roof of the one compartment being of mica, that of the other of the metal whose effect was to be investigated.

The apparatus first described had this defect—that when a fog had been produced

Fig. 10A. Fig. 10B.



by expansion, the metal caused the re-evaporation of the drops in the air near it, before they had time to settle to the bottom of the vessel. This made the process of removing dust particles, by repeatedly forming a cloud by expansion and allowing it to settle, a very slow one in an apparatus of this kind. With the metal at the top there is no difficulty of this kind, for any drops formed near it very quickly fall out of reach of the metal.

In no case were the metals found to produce nuclei requiring only slight expansion to catch them.

This simplified the method of working, making it possible to remove all ordinary dust particles originally present, or any drops remaining in suspension after a cloud had been produced, by the expansion method just referred to, without any arrangement for shielding the air from the action of the metal while this was being done. When this process had been completed, so that with expansions of moderate amount drops were no longer produced, the expansion might be increased without any visible condensation generally to the point ($v_2/v_1 = 1·25$) where a few drops are produced even in the absence of any metal.

When, however, the expansion was such that a rain-like condensation would have resulted in the absence of any metal (v_2/v_1 being between 1·25 and 1·38), the number of drops in the compartment next the metal was generally greater than on the other side of the partition.

With amalgamated zinc comparatively dense fogs are obtained with such expansions; polished zinc and lead also show the effect well; polished copper and tin produce no appreciable effect. A plate of zinc amalgamated on one side and merely polished on the other shows a great difference in the density of the fog on the two sides, the fog next the amalgamated metal being much the denser. If the partition consists of lead with an old surface on one side and a freshly scraped surface on the other, many more drops appear in the half of the tube next the fresh surface. With a zinc copper partition also, the drops are much more numerous on the zinc side.

With amalgamated zinc a few drops may be produced even when v_2/v_1 is rather less than 1·25; they have been observed with a pressure fall of only 13 centims. The effect of the metals is much more marked when the expansion is considerably greater ($v_2/v_1 = 1·30$ or more); in many cases, indeed, the effect of the metal was inappreciable with smaller expansions. When v_2/v_1 exceeds 1·38 no difference can be detected between the comparatively dense fogs which then occupy both sides of the tube.

There can be little doubt that the effect here described is due to the same cause as the influence which these metals have on a photographic plate, studied by RUSSELL* and others. As far as these experiments go they tend to show that the order in which the metals must be arranged to indicate their relative activity in producing nuclei is the same as their order when arranged according to their photographic activity; amalgamated zinc giving the most effect; tin and copper little effect, if any; polished zinc and lead being intermediate in activity.

The experiments described above were all performed with air in the expansion apparatus. In experiments with hydrogen in the apparatus the metals (zinc, amalgamated zinc, and lead) showed only a very slight effect. This, however, does not prove conclusively that more nuclei are produced when the metal is in contact with air than with hydrogen; the difference may be due to the more rapid removal of the nuclei in hydrogen by diffusion to the walls of the vessel.

I have not been able to obtain any effect from metals outside the apparatus, even through celluloid, which RUSSELL found to be penetrated by the photographic action.

§ 8. NUCLEI PRODUCED BY THE ACTION OF ULTRA-VIOLET LIGHT ON A NEGATIVELY ELECTRIFIED ZINC PLATE.

LENARD and WOLFF (*loc. cit.*) were able to show that the condensation of a steam jet becomes dense in the neighbourhood of a negatively electrified zinc plate when this is exposed to the action of ultra-violet light.

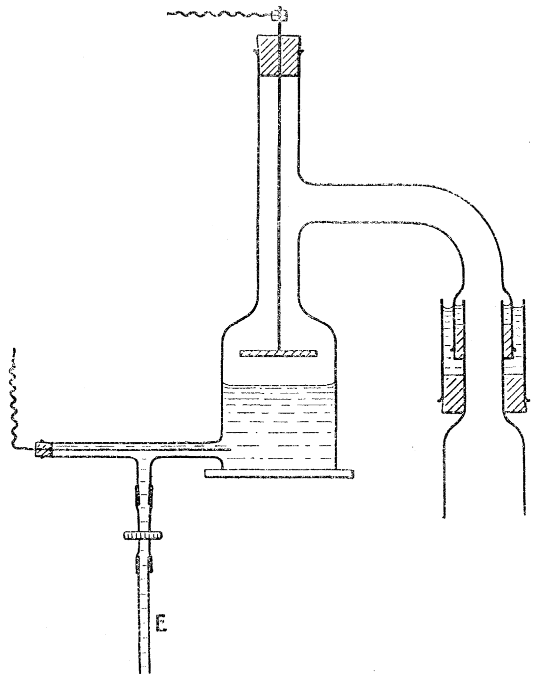
The delicacy of the expansion method makes it a matter of some difficulty to

* RUSSELL, 'Roy. Soc. Proc.,' vol. 61, p. 424, 1897; vol. 63, p. 102, 1898. COLSON, 'C. R.,' vol. 123, p. 49, 1896.

investigate by its means this effect in air. For, as has already been shown, not only does ultra-violet light produce nuclei in moist air in the absence of any zinc plate, negatively charged or otherwise, but a zinc plate introduces nuclei into the surrounding air in the absence of both electrification and ultra-violet light. These two effects are apt to disguise the one looked for.

By using very weak ultra-violet light, however, it was found possible to demonstrate the production of condensation nuclei by the action of the light on a negatively charged zinc plate.

Fig. 11.



The ultra-violet light (from a zinc spark) entered the apparatus (shown in fig. 11) through a quartz plate covered with 2 or 3 centims. of water, the surface of which served as one plate of a condenser, a zinc plate placed about 1 centim. above the water serving as the other. The condensation from the action of the ultra-violet light alone, or of the zinc alone, was too slight to be detected with a pressure fall below about 18 centims.; the short distance which the few drops that are doubtless produced had to fall, causing them to be overlooked.

On allowing the ultra-violet light to strike the zinc plate, and using a pressure fall of between 15 and 18 centims., a fog was obtained if the zinc plate was made negative (a difference of potential of a few volts being applied between the plates of the condenser); while no condensation could be detected if the zinc was positive or uncharged. The experimental details are given below.

The general construction of the cloud-vessel will be understood by reference to the figure (fig. 11). The zinc plate was soldered to a brass rod, which passed through the small indiarubber stopper closing the upright tube at the top of the apparatus. The lower surface of the zinc was freshly polished, and the upper surface was covered with wet filter paper, to diminish as far as possible the production of cloud nuclei by the zinc. The thickness of the layer of air could be increased or diminished by running water out, or drawing water in, through the tube pointing downwards on the left. Any desired difference of potential could be maintained between the zinc and the water by means of a battery of small secondary cells.

The actual experimental numbers are given in the tables which follow.

Polished Zinc Plate in Air.

Ultra-violet light from zinc-spark 30 centims. below the quartz plate. Depth of water over the quartz = 2·8 centims. Thickness of air-layer = 0·8 centim.

Gauge reading (in millims.) = p.	E.M.F., in volts.	Result of expansion.	
		Zinc positive.	Zinc negative.
151	9	0	0
159	9	0	Slight fog
167	9	0	Fog
173	9	0	Fog
181	9	Slight fog	Dense fog
161	32	0	Fog
157	32	0	Fog
177	40	0	Fog
177	80	0	Fog
177	240	0	Fog
153	240	0	0
153	80	0	0
183	240	Fog	Fog

No difference could be observed between the results without any E.M.F., and those obtained with the same expansion when the zinc was positive.

Zinc plate freshly polished; zinc-spark 54 centims. below the quartz; depth of water over quartz = 2·3 centims.; thickness of air layer = 1·6 centims.; barometer = 766; temperature = 15° C., π = 13 millims.

Gauge reading (in millims.) = p.	E.M.F. in volts.	Result of expansion.		
		Zinc uncharged.	Zinc positive.	Zinc negative.
163	240	Shower	Shower	Fog
153	240	Very few drops	Very few drops	Very dense shower
151	80	Very few drops	Very few drops	Distinct shower
149	80	Very few drops	Very few drops	Very few drops
149	120	Very few drops	Very few drops	Very few drops
139	120	Very few drops	Very few drops	Very few drops

Gauge reading when the effect of the negative charge is first detected = 151 millims.

Corresponding value of $v_2/v_1 = \frac{B - \pi + m}{B - \pi - p} = 1 \cdot 252$.

In the second series, partly owing to the greater thickness of the air layer, and the consequent greater chance of drops being seen, partly also on account of greater activity of the zinc surface, or greater intensity of the ultra-violet rays, drops were seen, with the expansions used, even when the zinc was positively charged or neutral. The change produced when the charge is negative is however well marked. It will be seen that, although drops are formed even when the expansion is below the limit $v_2/v_1 = 1 \cdot 25$, the effect of the negative electrification first becomes manifest at that point. It will be remembered that the nuclei produced by metals or by ultra-violet light do not show any very definite limit in the least expansion required to catch them.

Experiments were also made in which all conditions were the same as in the experiments just described with this exception, that the zinc plate was covered on the side exposed to the ultra-violet light with wet filter paper. Under these conditions, as is well known,* it ceases to be capable of allowing negative electricity to escape under the influence of ultra-violet light.

The result of a given expansion was now found not to depend on the sign of the charge on the zinc plate, the appearance of the showers or fogs being the same whether the zinc was positive, negative, or uncharged.

Hydrogen.

The phenomena are more easily studied in hydrogen than in air, the effect of ultra-violet light throughout the volume of the gas being so very slight that quite strong radiation may be used.

The hydrogen was obtained by heating palladium which had been charged with the gas. The gas was first allowed to pass through the apparatus at a pressure of a few centimetres of mercury. The tube E was prolonged downwards and passed through the cork of a small wash-bottle containing distilled water, through which the gas had to bubble on its way to the pump. A convenient quantity of this water was finally admitted into the apparatus by closing the tube leading to the pump, and allowing a little air to enter the wash-bottle. The clip between the wash-bottle and the expansion apparatus was then closed and the hydrogen brought to atmospheric pressure by heating the palladium. A parallel beam of ultra-violet light was used, the zinc-spark being placed at the focus of a quartz lens (focal length = 6 centims.) The beam of light was just wide enough to illuminate the whole of the zinc plate.

* STOLETOW, 'Comptes Rendus,' vol. 106, p. 1593, 1888.

ZINC Plate freshly polished. Depth of water over the quartz 1·5 centim. Thickness of hydrogen layer = 2·3 centims.; barometer = 749, temperature = 15° C. π = 13 millims.; m = 1 millim.

Gauge reading (in millims.) = p.	E.M.F.	Result of Expansion.		
		Zinc positive.	Zinc negative.	Short circuit.
171	6 Leclanché cells	1 or 2 drops	Fog	
152	6 ,, ,,	0	Shower	
161	6 ,, ,,	1 or 2 drops	Fog	1 or 2 drops
161	1 ,, ,,	1 or 2 drops	Slight fog	
161	3 ,, ,,	...	Dense fog	
161	6 ,, ,,	...	Fog no denser	
161	20 secondaries	...	Much less dense	
161	120 ,,	1 or 2 drops	1 or 2 drops	1 or 2 drops
151	6 Leclanché cells	0	Very few drops	
145	6 ,, ,,	0	1 or 2 drops	
143	6 ,, ,,	0	0	

Gauge reading, when expansion is just sufficient to make condensation take place on the nuclei due to the negative electrification = 145 millims.

Corresponding value of $v_2/v_1 = \dfrac{B - \pi + m}{B - \pi - p} = 1{\cdot}247$.

It will be noticed that the expansion required to make condensation take place on the nuclei, produced by the action of ultra-violet light on a negatively electrified zinc plate, in air or in hydrogen, is identical with that required in the case of the nuclei produced by X-rays and Uranium rays.

It is only when the zinc plate is negatively electrified that there is any action of this kind.

With the zinc at the given height above the surface of the water the density of the fog produced in hydrogen by a given expansion is a maximum with a comparatively small difference of potential between the zinc and water. The maximum number of drops is obtained with a difference of potential produced by 6 Leclanché cells or less. With the much stronger field, produced by 120 secondary cells (= 240 volts) only a few scattered drops were seen, no more numerous than were obtained with the same expansion when the zinc plate was positively charged, or when the terminals leading to the zinc and water respectively were connected together by a wire.

The diminution of the number of the drops as the electromotive force is increased is easily understood, for when the electric intensity is more than sufficient to remove all the carriers from the zinc as fast as they are produced by the ultra-violet light, then the total number of the carriers which cross from one plate to the other in a given time must remain constant, being equal to the number produced in that time by the ultra-violet light. The velocity of each carrier, however, is proportional to the electric intensity; the number of drops produced on expansion, indicating as it does the number of carriers which at that instant are on their way across between the plates, will therefore be inversely proportional to the difference of potential. The phenomenon is, in fact, closely related to the fact first noticed by STOLETOW,* that the currents produced by the action of ultra-violet light on negatively electrified surfaces approach a saturation value as the electromotive force is increased.

The fact that the source of the rays is discontinuous must also not be forgotten, for with strong fields all the ions produced by the action of one spark may have time to travel across to the other plate, under the influence of the electric field, before the next spark takes place.

The fact that the carriers in hydrogen, as RUTHERFORD† has shown, travel several times as fast as in air, explains why the phenomenon under consideration was only observed in the former gas. With greater differences of potential, or a smaller distance between the plates, it would no doubt be observed in air also.

The fact that the nuclei produced by the action of ultra-violet light on a negatively electrified zinc plate whether in air or hydrogen, require just the same degree of supersaturation in order that they may act as centres of condensation as those produced by Röntgen rays or Uranium rays, is strong evidence that the carriers of the electricity in all these cases are of the same nature. RUTHERFORD‡ has already proved this in quite a different way by his measurements of the velocity with which the carriers move in an electric field.

The very considerable degree of supersaturation necessary to make condensation take place on these nuclei is of itself sufficient to prove that the particles which carry off the negative charge from the zinc-plate are not of the nature of dust particles, but on the contrary must be of almost molecular dimensions (*vide* 'Phil. Trans.,' *loc. cit.*, p. 305).

The conclusion arrived at is therefore opposed to that which LENARD and WOLFF drew from the results of their steam-jet experiments (*loc. cit.*), that the escape of negative electricity from a zinc plate exposed to ultra-violet light is due to the escape of particles arising from the disintegration of the metal. As was pointed out by R. v. HELMHOLTZ and RICHARZ,§ the steam jet is incompetent to distinguish between dust particles and the "ions," to which the latter observers attribute most of the condensation phenomena studied by them.

* STOLETOW, 'Comptes Rendus,' 106, p. 1149, 1888.

† RUTHERFORD, 'Camb. Phil. Soc. Proc.,' vol. 9, p. 401, 1898.

‡ RUTHERFORD, 'Camb. Phil. Soc. Proc.,' *loc. cit.*

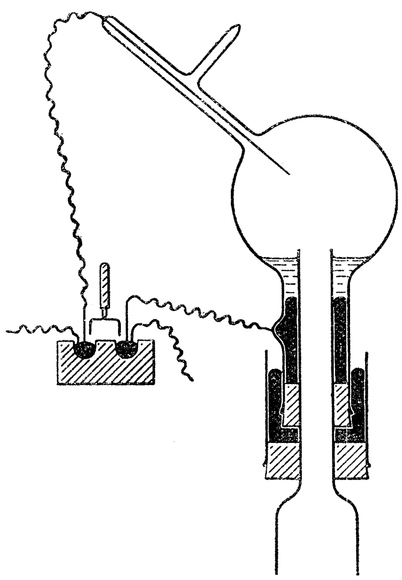
§ R. v. HELMHOLTZ und RICHARZ, 'Wied. Ann.,' 40, p. 161, 1890.

§ 9. Nuclei Produced by the Discharge of Electricity from a Pointed Platinum Wire.

The effect of the electric discharge from a pointed wire in altering the appearance of a steam-jet has been studied by many observers.

In expansion experiments, however, no effect appears to have been noticed other than the immediate removal of all dust particles or fog from the air inside the apparatus.* To study the properties of the condensation nuclei arising from this source an expansion apparatus allowing of rapid expansions of large amount is, in fact, necessary.

Fig. 12.



The apparatus which I have used for experiments on this subject is shown in fig. 12. The cloud-vessel consisted of a glass bulb with a side tube through which was sealed a platinum wire, reaching well into the interior of the bulb and ending in a sharp point. This was connected to one terminal of a Wimshurst machine. The other terminal of the machine was connected to earth and to another platinum wire fused through the neck of the bulb, the lower part of which was filled with mercury, covered with distilled water. The side tube was kept dry by warming when necessary with a small flame.

No condensation nuclei were produced, except when the point of the wire was luminous when viewed in the dark.

* First observed by Lodge, 'Nature,' vol. 31, p. 265, 1885.

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Discharge from a Pointed Platinum Wire in Air. Expansion made while the Discharge is taking place.

Gauge reading (in millims.) = p.	Result of expansion.	
	Pointed wire positive.	Pointed wire negative.
141	0	0
147	0	Fog
155	Fog	Fog
167	Very dense fog	Dense fog
177	Very dense fog	Very dense fog

The phenomena are simplest when, as in the observations given in the above table, the expansion is brought about while the discharge is taking place. No drops whatever are seen, so long as the pressure fall is below a limit amounting to about 15 centims., corresponding approximately to an expansion, $v_2/v_1 = 1{\cdot}25$. The fogs, when the pointed wire was the negative terminal, were always obtained with a slightly lower expansion than was required when this was positive. With expansions only slightly exceeding this limit the fogs obtained were very dense. The fogs have only a momentary existence, on account of the dust- or fog-removing property of the point discharge already referred to. This was especially the case when the point was positive. The fogs, during the few seconds or less for which they lasted, made manifest the violent eddying motion of the air which accompanies the discharge.

It was found that, when the discharge was stopped before the expansion was made, the results were not so simple. These were reduced to some degree of regularity when the stopping of the discharge was brought about by suddenly connecting together by a wire the two terminals of the apparatus. For this purpose each was connected to one of two mercury cups made near together in a block of paraffin. A short wire was dropped into these cups while the discharge was taking place. This must very quickly have brought the pointed wire and the wet walls of the apparatus to the same potential. Any electrified particles produced by the discharge had, therefore, a greater chance of remaining in suspension on the air than would have been the case if the difference of potential were allowed to exist for any considerable time after it ceased to be sufficient to produce a supply of the particles which act as carriers of the electricity.

DISCHARGE from Pointed Platinum Wire in Air. Terminals joined by a wire before expansion.

Gauge reading (in millims.) = p.	Interval before expansion.	Sign of charge on wire.	Result of expansion.
75	40 secs.	Negative	Fog
75	10 ,,	,,	Slight shower
75	5 mins.	,,	Slight fog
26	90 secs.	Negative	0
55	30 secs.	Negative	Fog
55	20 ,,	,,	Slight fog
55	60 ,,	,,	Shower
45	30 secs.	Negative	Very few drops
45	10 ,,	,,	0
45	60 ,,	,,	Very few drops
87	10 secs.	Negative	Very few drops
87	30 ,,	,,	Fog
87	10 ,,	Positive	Slight fog
87	2 ,,	,,	0
87	30 ,,	,,	Slight fog
104	2 secs.	Negative	0
104	30 ,,	,,	Fog
104	60 ,,	,,	Fog
104	2 mins.	,,	Slight fog
104	6 ,,	,,	1 or two drops
170	15 secs.	Negative	Very dense fog
170	2 mins.	,,	Slight fog
170	15 secs.	Positive	Dense fog
170	70 ,,	,,	Slight fog

In the second column of the above table is given the time which elapsed from the moment when the discharge was stopped till the expansion was made to take place.

It will be observed that, as this interval is increased, the expansion required to produce a fog diminishes; in other words, the nuclei appear to grow when left to themselves. In no case was fog obtained with a pressure fall of less than 4 or 5 centims.

The nuclei produced by the discharge last for one or two minutes (whether the wire is positive or negative); during this time the number has diminished considerably, and practically none last so long as six minutes.

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Hydrogen.

The results obtained with hydrogen when the expansion was made while the discharge was taking place are given in the table which follows :—

Gauge reading (in millims.) = p.	Result of expansion.	
	Pointed wire positive.	Pointed wire negative.
144	0	0
150	0	Shower
156	0	Fog
157	Slight fog	Fog
158	Slight fog	Dense fog

The expansion required is, it will be seen, practically the same as in air. The fogs were again observed with slightly less expansion when the wire was negative than when it was positive.

The results of a second series of experiments made some weeks later are contained in the next table.

Gauge reading (in millims.) = p.	Result of expansion.	
	Pointed wire positive.	Pointed wire negative.
145	0	0
153	Slight shower	Fog
159	Fog	Fog

In a third independent series obtained some months later, the following numbers were obtained :—

Gauge reading (in millims.) = p.	Result of expansion.	
	Pointed wire positive.	Pointed wire negative.
132	0	0
146	0	Few drops
157	Dense fog	Dense fog

The positive fogs thus obtained are much more evanescent than the negative, appearing generally as a momentary flash of brightness in the apparatus, while the negative fogs last for two or three seconds. This is due to the "electric wind" accompanying the positive discharge being the stronger. Possibly the greater expansion required to give visible condensation when the wire is positive may be due to this rapid motion of the contents of the cloud-vessel causing very thin fogs to be overlooked.

Except under certain conditions, to be mentioned immediately, the expansion required to catch the nuclei in hydrogen shows very little diminution (none in the case of the positive discharge) when the discharge is stopped by short-circuiting the terminals before the expansion is made. A slight effect of this kind can be detected when the wire is negative, but the least expansion required to give even a slight shower, whatever interval might be allowed to elapse before making the expansion, was not less than that corresponding to a gauge-reading of 13 centims. The difference between air and hydrogen in this respect is not entirely due to the more rapid diffusion of the nuclei in the latter causing them to reach the sides of the vessel before they have time to grow to any considerable extent, for nuclei, requiring a pressure fall of more than 15 centims., can be detected even 30 seconds after the discharge has been stopped, and when this interval only amounts to 15 seconds they are sufficiently numerous to give quite a dense fog on expansion. Possibly even this slight tendency to become larger exhibited by the nuclei produced in hydrogen when the discharge from the pointed wire is negative, is really a remnant of the effect now to be described.

When the apparatus was first charged with hydrogen, fogs could be obtained under the conditions just described (after the discharge was stopped), even with comparatively slight expansions. The effect was much more marked with the negative than with the positive discharge, and was often absent in the latter case. If, however, the experiments were continued for a day or two the fogs obtained under these conditions became gradually less dense, and finally only a few drops could be obtained with expansions less than that corresponding to a pressure fall of 15 centims.

There can be little doubt that the effect just described is due to some impurity, probably air or oxygen remaining in the apparatus, either mixed with the hydrogen, or absorbed by the platinum wire. This is gradually removed by combination with the hydrogen, the combination being doubtless hastened by the luminous discharge from the point of the wire.

We may conclude from the condensation phenomena attending the discharge of electricity from a pointed platinum wire, that in a discharge of this kind, whether in air or hydrogen, the electricity is carried by "ions" identical with those which are produced in air exposed to Röntgen rays.

The after-effect of the discharge, noticed in air and under certain conditions in hydrogen, is probably a consequence of the chemical combination which can scarcely fail to take place at the glowing point of the wire; where also the ions are, doubtless, liberated. So long as the difference of potential is maintained high enough to produce the discharge, the carriers are driven across to the walls of the vessel, before they have time to grow appreciably. If, however, the electric field be removed suddenly, by short-circuiting the terminals, many of the carriers which have left the point of the wire may not have reached the walls before this process is completed, and their comparatively slow motion when the wire and walls are at the same potential enables them to persist for some time. The growth which then takes place is probably the result of the condensation, upon the nuclei, of some substance produced by the discharge. The substance may be nitric acid or H_2O_2.

§ 10. Behaviour of the various kinds of Nuclei in an Electric Field.

It has already been suggested ('Camb. Phil. Soc. Proc.,' *loc. cit.*) that the nuclei requiring expansions between 1·25 and 1·37 to make condensation take place on them are to be identified with the ions, to which the conductivity of gases exposed to X-rays or Uranium-rays is due. The only evidence there furnished for this view was the fact that in ordinary moist air or other gases such nuclei were found to be present in exceedingly small numbers, while when the gas was made a conductor by being exposed to X-rays or Uranium-rays, immense numbers of these nuclei could be detected.

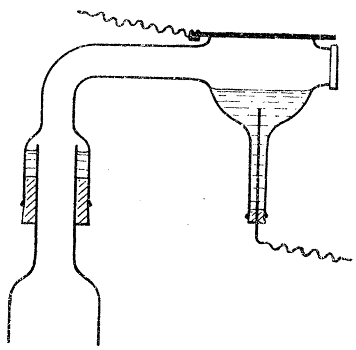
The experiments with the nuclei produced by the discharge from a pointed platinum wire, as well as with those which are produced by the exposure of a negatively charged zinc plate to ultra-violet light, support this view, at the same time pointing to the conclusion that in all these cases the carriers of the electricity are of the same kind.

A difficulty, however, is introduced by the results obtained with air exposed to weak ultra-violet light or to the action of certain metals, for in both cases nuclei are produced, requiring, in order that water may condense on them, a degree of super-saturation approximately the same as is required in the case of nuclei associated with conducting power in the gas. Now there is no evidence that either the presence of metals or exposure to ultra-violet light causes air to act as a conductor of electricity.

It might be thought that the great delicacy of the condensation method of detecting free ions (each individual carrier being represented by a visible drop on expansion) was the cause of this apparent discrepancy, and that air under the conditions in question really has conducting power, too small to be detected by ordinary methods. The experiments to be described, however, show that the nuclei produced by the presence of metals, as well as those produced by the action of ultra-violet light on moist air, differ from those present in air exposed to X-rays or Uranium-rays in not carrying a charge of electricity, or, to be more exact, in not being affected by an electric field.

To compare the behaviour of the nuclei produced by the action of ultra-violet light on moist air with that of the nuclei produced by Röntgen rays, the apparatus shown in fig. 13 was used. The air is contained between two plates of a condenser, the upper plate consisting of a sheet of aluminium, forming the roof of the cloud-vessel, the lower plate being formed by the upper surface of the water which fills the lower part of this. The aluminium plate was fixed by means of sealing wax. The thickness of the layer of air between the plates was 1·6 centim. By means of a battery of secondary cells, any difference of potential up to 240 volts could be maintained between the plates. The positive terminal of the battery was connected to the aluminium. An aperture at the side, closed by a quartz plate, fixed with sealing-wax, enabled a horizontal beam of ultra-violet light from a zinc spark to enter the apparatus. The light did not impinge on the aluminium plate. The air could be exposed either to the ultra-violet light or to the Röntgen rays from a focus-tube placed above the aluminium plate.

Fig. 13.



The first experiments were made with ultra-violet light weak enough to give no condensation with pressure fall less than about 15 centims. When a somewhat greater expansion was used ($p = 172$ millims.), an equally dense fog was obtained, whether the difference of potential between the plates was 240 volts or zero. The ultra-violet light in both cases was applied for 30 seconds, and the expansion was made before cutting off the light. In other experiments the expansion was not made till 3 seconds after cutting off the ultra-violet rays; in these experiments the expansion was somewhat greater than before, p being equal to 183 millims. The fogs obtained, when a difference of potential of 240 volts was maintained between the aluminium and the water during the exposure and till after the expansion had been made, were again indistinguishable in appearance from those obtained in the absence of any difference of potential.

On exposing the air to Röntgen rays, instead of ultra-violet light, the expansion being the same as before (gauge reading = 183), very dense fogs were obtained in the absence of electromotive force, while, when a difference of potential of 240 volts was maintained between the metal and water surfaces, only a very slight fog appeared on expansion. An expansion of the same amount, made 3 seconds after the rays were cut off, gave a fog in the absence of any difference of potential, whereas, when the potential difference amounted to 240 volts, no drops at all were produced, even when the expansion was brought about 2 seconds after cutting off the rays. In fact, with the difference of potential just mentioned, no nuclei could be detected if the rays were cut off before the expansion, even if this were effected as quickly as possible after the rays were stopped. On the other hand, when no electromotive force was applied, some of the nuclei lasted for at least 10 seconds after the rays were cut off, a shower being even then obtained on expansion.

There is thus a very marked difference in the behaviour of the nuclei according as they are produced by Röntgen rays or ultra-violet rays, the nuclei produced by the latter being uninfluenced even by a comparatively strong field. The phenomena observed with air exposed to Röntgen rays are easily understood in the light of RUTHERFORD'S experiments* on the velocity of the ions in air which has acquired conducting power under the influence of these rays. He finds the velocity, with a potential gradient of 1 volt per centim., to amount to about 1·6 centim. per second in air.

In the present case,

$$\text{Potential gradient} = \frac{240}{1{\cdot}6} = 150 \text{ volts per centim.}$$

$$\text{Velocity of carriers} = 150 \times 1{\cdot}6 \text{ centim. per second.}$$

$$\text{Time taken to travel across the air space} = \frac{1{\cdot}6}{150 \times 1{\cdot}6} \text{ seconds} = \frac{1}{150} \text{ second.}$$

Thus even the carriers which have the greatest possible distance to travel reach one of the plates in less than $\frac{1}{100}$th of a second. This explains how no fogs were obtained when the expansion was made even a very short time after cutting off the Röntgen rays.

Now, when the air was exposed to weak ultra-violet light in place of the Röntgen rays, the difference of potential being, as before, 240 volts, no diminution in the number of the nuclei by the action of the electric field could be detected even 3 seconds after the radiation was cut off. Even in three seconds the distance they have travelled under the influence of the electromotive force is therefore small compared with the thickness of the air layer. These nuclei therefore travel at least 300 times as slowly as those produced by Röntgen rays under the same potential gradient. It is unlikely that this difference is due mainly to a difference in the size of the nuclei, the charge being the same; for with ultra-violet light of the intensity used the two classes of nuclei are indistinguishable from one another, with respect to their power of enabling condensation to take place upon them. There can be little hesitation in concluding that the nuclei produced throughout the volume of the moist air by the action of ultra-violet light differ from those produced by Röntgen rays in being uncharged. If any ions are present in air exposed to ultra-violet light they are exceedingly few in comparison with the uncharged nuclei which are at the same time produced.

* RUTHERFORD, 'Phil. Mag.,' vol. 44, p. 422, 1897.

It still remains possible that the comparatively few nuclei, all requiring large expansions, which can be detected in hydrogen exposed to strong ultra-violet light, may consist of ions produced throughout the volume of the gas. This point could easily be tested by experiments like those just described.

Further experiments were made with air exposed to the much more intense rays which were obtained when a quartz lens was interposed between the zinc points and the quartz plate. The intensity of the ultra-violet rays was then sufficiently great to give fogs with comparatively slight expansion. The apparatus being arranged to give expansion corresponding to a gauge reading $p = 64$ millims., no condensation (in the absence of electromotive force) was obtained with an exposure of 10 seconds, while an exposure of 15 seconds with an expansion of the same amount gave a fog. The nuclei thus took between 10 and 15 seconds to grow large enough to be caught with the degree of expansion used. Yet the application of a difference of potential of 240 volts between the plates did not prevent very dense fogs being obtained with the same expansion with an exposure of 3 minutes. Thus, in spite of the electric field, the nuclei were able to exist for more than 10 seconds; in other words, they took more than 10 seconds to travel across the space between the plates, which were again 1·6 centims. apart. They thus took more than 1000 times as long as the nuclei produced by Röntgen rays to travel the same distance. It is, therefore, very improbable that the growth of the nuclei under the action of strong ultra-violet rays, or the diminution of the expansion required to catch them, is the result of any electrification of the nuclei by the action of the rays. Another explanation, therefore, than the possession of a charge of electricity by the drops, must also be sought for the persistence of the visible fogs, which are the final result of prolonged exposure to strong ultra-violet rays.

The great diminution of the number of drops which are produced on expansion when an electromotive force is applied during the exposure of the air to Röntgen rays is easily understood. For the number of nuclei present at any instant is proportional to the rate at which these are being produced by the rays and to the average length of time for which they persist. Now before the application of the electric field the average life of the nuclei, depending on the rate at which they combine with one another or reach the walls by diffusion, is seen to be something of the order of 1 second, for a large proportion of the nuclei persist for 2 or 3 seconds. Now, when the electric field of the intensity used in the experiments is applied the time for which they persist must, as has been seen, be reduced to something like $\frac{1}{100}$th part of this. The number of drops in the fog will be diminished in the same ratio. The immense difference in the appearance of the fogs with and without the action of the electric field is in complete agreement with this. The complete absence of any such difference in the case of the fogs produced under the action of the ultra-violet light is again a proof that the nuclei on which their production depends do not move under the action of an electromotive force.

Uranium Rays.

For experiments on the influence of an electric field on the nuclei produced by Uranium-rays the apparatus constructed for the experiments on the nuclei arising from a zinc plate exposed to ultra-violet rays was used (fig. 11). A piece of thin sheet tin was substituted for the zinc. A thin float, consisting of a sheet of cork wrapped in tinfoil, formed the lower plate of the condenser. On the upper surface of this was placed a layer of moist uranium oxide. The thickness of the air layer was regulated by allowing some water to escape or drawing a little more into the cloud-vessel, according as an increase or diminution of the thickness was required.

The following results were obtained.

DIFFERENCE of potential used = 240 volts; thickness of air layer = 1 centim.

Gauge reading (in millims.) = p.	Result of expansion.		
	Upper plate positive.	Upper plate negative.	No E.M.F.
162	0	0	Fog
184	0	0	Fog

These experiments were many times repeated with the same results. The effect of the electric field was equally marked when the distance between the plates was increased to 1·3 centims. The drops produced while the electric field was maintained were too few to be detected. All the nuclei produced by the action of the uranium appear therefore to be charged.

Metals.

The same apparatus was used, but the float was omitted and a polished zinc plate was substituted for the tin. The arrangements were in fact exactly the same as in the experiments on the nuclei produced by the action of ultra-violet light on zinc, with the omission of the apparatus necessary for producing these rays. The results obtained were entirely negative.

Difference of potential = 240 volts; thickness of air layer = 1·4 centims.

Gauge reading (in millims.) = p.	Result of expansion.		No E.M.F.
	Zinc positive.	Zinc negative.	
165 188	Slight shower Dense shower	Slight shower Dense shower	Slight shower Dense shower
Thickness of air layer = ·8 centims.			
189 217	Dense shower Dense fog	Dense shower Dense fog	Dense shower Dense fog

Exactly similar results were obtained when the zinc was amalgamated, so that a larger number of nuclei might be produced.

The action of zinc in producing nuclei is thus proved to be of quite a different nature to that of uranium oxide. It does not consist in the production of free ions throughout the volume of the air near it by the action of radiation like that from uranium and its compounds.

It might be supposed, however, that the nuclei consisted of ions, not produced throughout the volume of the air, but having their origin at the surface of the zinc. They might in fact be a direct product of the oxidation of the zinc, the oxygen or water molecules being split up, half of the molecule combining with the zinc, the other part escaping into the surrounding gas as a free ion. One would expect the ions, according to this view, to be all charged with electricity of the same sign. There ought therefore to have been a difference in the number of cloud particles produced according as the zinc was made positive or negative. In fact one would expect, as was found to be the case when the zinc was exposed to ultra-violet light, an increase in the number of nuclei when the electromotive force was in one direction, that namely tending to move the ions from the zinc, and a diminution when the field was reversed. The absence of any difference whatever in the appearance of the fogs whether the zinc was the positive or negative terminal or was uncharged, shows that the nuclei do not consist of ions, produced either at the surface of the metal or throughout the volume of the air and in its neighbourhood. They are, like the nuclei produced by the action of ultra-violet light on moist air, uncharged.

Ions are thus not the only nuclei requiring expansions between the limits $v_2/v_1 = 1·25$ and $v_2/v_1 = 1·37$, in order that condensation may take place upon them; both weak ultra-violet light and certain metals produce such nuclei, which experiment shows to be unaffected by an electric field, that is, not to be ions. They have less definite properties as nuclei of condensation than the ions; the minimum expansion required to make condensation take place on them may be less or more than is required for the ions according as their number is great or small, and those produced by ultra-violet light grow, if the rays are strong enough, till they become visible without expansion. To account for the growth of the nuclei under the influence of ultra-violet light, I have already suggested that some compound such as H_2O_2 may be produced by the action of these rays on the nuclei. We may, perhaps, extend this idea somewhat, and regard also the nuclei produced in air by weak ultra-violet light or by metals, as consisting of molecules of H_2O_2 or of aggregates of molecules of H_2O and H_2O_2. SCHÖNBEIN, so long ago as 1866, found that hydrogen peroxide was produced by shaking together amalgamated zinc, oxygen and water ('Journ. für Pr. Chem.,' vol. 98, p. 65). There can be little doubt that the nuclei produced in the neighbourhood of metals have some relation to the active substance, hydrogen peroxide, "active oxygen," or whatever it may be, which is produced in many cases of slow oxidation, and about which there has been so much controversy.

The question now arises in which class of nuclei, the charged or the uncharged, must we place those which always appear to be present in small numbers in moist air, giving rise to the rain-like condensation which takes place with expansions between the limits $v_2/v_1 = 1{\cdot}25$ and $v_2/v_1 = 1{\cdot}38$.

To decide this question the same apparatus as that used for the experiments last described was used, but the zinc plate was replaced by one of sheet tin, because this metal appears to be inactive, that is, it produces no increase as far as can be detected in the number of nuclei present. The plate was, moreover, covered on both surfaces with wet filter paper to prevent direct contact of the metal with the air. The thickness of the air layer was equal to 1·7 centims.; an electromotive force of 225 volts was used.

The expansion used was that corresponding to a gauge reading of 187 millims. This gave a slight shower, and no difference could be detected in its appearance whether the electromotive force was applied or not. This appears to indicate that these nuclei are not charged. It is, however, doubtful whether the tin, even when covered with wet filter paper, is absolutely inactive, and on that account, perhaps, not a great deal of weight can be attached to this experiment. If we assume that the effect of the tin is negligible, there still remains the possibility that although the nuclei requiring expansions considerably exceeding the limit $v_2/v_1 = 1{\cdot}25$ are uncharged, the very few which require an expansion only very slightly exceeding this may be charged and identical with those produced by Röntgen rays. Otherwise we have the somewhat astonishing result that two quite different kinds of nuclei require absolutely the same degree of supersaturation, that, namely, corresponding to the expansion $v_2/v_1 = 1{\cdot}25$, in order that condensation should take place on them. To make experiments of the same kind with expansions only slightly exceeding the limit $v_2/v_1 = 1{\cdot}25$ is difficult on account of the exceedingly small number of the drops. Apparatus on a much larger scale would be better for experiments on this point.

One way of accounting for the fact that an electric field has no effect on the rain-like condensation under consideration would be to suppose that the nuclei are produced at the moment of expansion. They might, for example, be caused by the motion of the piston or plunger through the water. The fact, however, that the condensation is just as easily observed when the cloud-vessel is connected with the rest of the apparatus by a bent tube of considerable length, as for example in the apparatus shown in fig. 2, shows that this is not the source of the nuclei.

The question whether the nuclei which exist in small numbers in moist air are charged or not must, I think, be left an open one for the present. It is manifestly a matter of considerable meteorological interest.

The view which was taken in previous papers concerning the dense fogs which are obtained with expansions exceeding the second limit $v_2/v_1 = 1{\cdot}38$, was that the degree of supersaturation is then great enough to cause condensation to take place independently of all nuclei other than the molecules of gas or vapour themselves. According to this view no effect is to be expected on applying an electric field when expansions so great as this are used. In fact, the same apparatus being used as before, no difference could be detected in the appearance of these fogs, whether they were produced in the absence of any electric field, or with a difference of potential of 225 volts, between the tin and water surfaces, these being 1 centim. apart.

§ 11. On Ions and Condensation.

The experiments described in this paper furnish strong evidence that the passage of electricity through gases is effected by carriers of the same nature, whether the conduction is the result of exposure of the gas to Röntgen rays or Uranium rays, or the action of ultra-violet light on a negatively electrified zinc plate, or consists in the escape of electricity from a pointed platinum wire. It is not only in their efficiency as condensation nuclei that the carriers from the first three of the above-mentioned sources agree, for Rutherford has shown that their velocity in an electric field of the same strength is almost identical.

Further, these carriers are by no means of the nature of dust particles, for unlike the latter, which require only an exceedingly slight supersaturation in order that condensation may take place on them, they do not act as centres of condensation unless the vapour is about 4·2 times as dense as that in equilibrium over a flat surface of water at the same temperature (*vide* 'Phil. Trans.,' *loc. cit.*). In the paper just referred to the number $8{\cdot}6 \times 10^{-8}$ was given as an approximate value of the radius in centims. of water-drops equivalent in their action to these nuclei. The nuclei are therefore not much larger than molecules; the fact that dense condensation takes place with a supersaturation only twice as great when, as far as can be judged, no nuclei are present other than the molecules of vapour and gas, is further evidence that the nuclei with which we are here concerned are not very large compared with molecular dimensions. This again is an agreement with experiments on the velocity of the ions.*

It is, perhaps, of some interest to calculate what charge would be required to keep a drop of the above-mentioned size (radius = $8 \cdot 6 \times 10^{-8}$ centim.) from evaporating. Making use of the results given by Professor THOMSON ('Applications of Dynamics,' pp. 163, 165), we have, when the charge on the drop just balances the effect of surface tension so that there is no longer any tendency to evaporate in vapour saturated with respect to a flat surface,

$$e^2 = 16\pi T a^3,$$

where e is the charge on the drop, T is the surface tension, and a is the radius.

This gives us in the present case

$$e = 1 \cdot 5 \times 10^{-9} \text{ electrostatic unit},$$

which agrees sufficiently nearly with what we have reason to suppose the order of magnitude of ionic charges to be. We must not forget, however, the assumptions made in obtaining the above-mentioned estimate of the size of the nuclei (*vide* 'Phil. Trans.,' *loc. cit.*, p. 305).

TOWNSEND has shown† that freshly prepared gases are often electrified, and that the charge is carried by nuclei on which, even if the gas be not saturated with aqueous vapour, water condenses to form visible drops. He has shown, moreover, that the charge carried by each of these nuclei (in oxygen) amounts to about 3×10^{-10} electrostatic unit, and is presumably the charge carried by one ion. The experiments of H. A. WILSON‡ furnish strong evidence that the growth of the drops in the fogs studied by TOWNSEND is not, however, a direct consequence of the charge which they carry, but is due to the presence of some substance in solution in the drops.

Many of the cases of condensation (apparently with only slight or without any super-saturation) produced by chemical action, which were studied by R. v. HELMHOLTZ and RICHARZ,§ and which were attributed by them to the influence of free ions, are probably also mainly the result of the formation of some substance in solution in incipient drops (of which the original nuclei may be free ions). Professor J. J. THOMSON‖ has suggested that the great influence which the presence of moisture has in facilitating chemical reactions between gases may be due to the presence of minute drops, at the surface of which (or throughout the volume) the combination is able to take place. For example, dry NH_3 and HCl do not combine, but if water vapour be present,

* RUTHERFORD, 'Camb. Phil. Soc. Proc.,' vol. 9, p. 415, 1898.

† TOWNSEND, 'Camb. Phil. Soc. Proc.,' 9, pp. 244 and 345, 1897.

‡ H. A. WILSON, 'Phil. Mag.,' vol. 45, p. 454, 1898.

§ HELMHOLTZ and RICHARZ, 'Wied. Ann.,' vol. 40, p. 161, 1890.

‖ J. J. THOMSON, 'Phil. Mag.,' vol. 36, p. 313, 1893.

combination at once takes place with the formation of a cloud. If the moist gases contain minute water drops, it is evident that combination must take place within the drops, for HCl and NH_3 at once combine when in solution. It appears to me natural to suppose that the fogs produced by this and similar reactions are to be explained by the products of the reaction being formed in solution in incipient drops, in quantities sufficient to counterbalance the effect of the curvature of the surface on the vapour pressure. The drops then grow so long as the products of the reaction continue to accumulate within them. The original droplets may be formed by the action of the ions; but it is quite possible that even in the absence of any ions, minute drops are continually being formed, and on account of surface tension at once evaporating again, unless made permanent by the formation within them of some other substance than water.

AITKEN* found that when proper precautions were taken, no condensation nuclei were produced by the combustion of hydrogen. In this case (if we assume the product of combustion to be pure water only) any growth of the droplets through the lowering of the vapour pressure by a dissolved substance is out of the question. Although these experiments of AITKEN show that in this case there is no production of comparatively large nuclei, such as would be capable of promoting condensation with slight supersaturation, or of travelling a considerable distance along a narrow tube without being removed, they do not prove that no free ions are produced by the combustion, or that these would not act as centres of condensation if the degree of supersaturation were reached, which the experiments described in this paper show to be in general required to cause condensation on the ions.

There is, I think, no evidence that the ions alone, in the absence of other influences, ever act as centres of condensation unless the above-mentioned comparatively great degree of supersaturation (approximately fourfold) be exceeded.

In conclusion, I wish to acknowledge how greatly I am indebted to Professor THOMSON for his suggestions and encouragement during the course of this work.

* AITKEN, 'Trans. Roy. Soc., Edin.,' vol. 39 (1), p. 15, 1897.