PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

On the Comparative Efficiency as Condensation Nuclei of Positively and Negatively Charged Ions

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IX. *On the Comparative Efficiency as Condensation Nuclei of Positively and Negatively Charged Ions.*

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THE work, of which the results are given in this communication, forms part of an investigation on atmospheric electricity, on which I am engaged on behalf of the Meteorological Council.

The relation between rain and atmospheric electricity was one of the problems it was suggested I should study experimentally. The importance in connection with that question of the subject dealt with in this paper has already been noticed by Professor J. J. THOMSON, who points out* that "if the negative ions, say, were to differ in their power of condensing water around them from the positive, then we might get a cloud formed round one set of ions and not round the other. The ions in the cloud would fall under gravity, and thus we might have separation of positive and negative ions and the production of an electric field, the work required for the production of the field being done by gravity."

To make this process worthy of consideration as a source of atmospheric electricity, it would be necessary to show reason for believing (1) that atmospheric air in the regions in which rain is formed is likely to contain free ions, (2) that the positively and negatively charged ions differ in their efficiency as condensation nuclei.

With respect to the first of these questions, former experiments furnish considerable evidence in favour of an affirmative answer. When moist dust-free air is allowed to expand suddenly, a slight rain-like condensation always takes place if the maximum supersaturation attained exceeds a certain limit. This limit is identical with that which is necessary for the formation of fogs in air, in which a supply of ions has been produced by the action of Röntgen rays or other ionising agent. The nuclei, on which the drops are formed in air exposed to the rays, were shown experimentally to be identical with the ions to which the conductivity of the gas when exposed to the rays is due. The equality of the expansion required to give the comparatively few drops in the absence of the rays, with that required to cause water to condense on the ions, is so exact as to furnish what is at first sight almost convincing evidence

* 'Phil. Mag.,' December, 1898, p. 533

that ordinary moist air is always to a very slight extent ionised. The number of these nuclei is so small that the absence of any sensible conductivity in air under ordinary conditions is in no way inconsistent with the view that they are ions. In the latter part of this paper are described some attempts which I have made to decide experimentally whether these nuclei are charged or not.

It is mainly, however, with the second of the above questions that this paper deals. The experiments to be described prove that there is a great difference between positively and negatively charged ions, with respect to their power of serving as nuclei for the condensation of water vapour; a much smaller degree of supersaturation sufficing to cause water to condense on the negative ions than is required in the case of positively charged ions. They therefore furnish a possible explanation of the preponderance of negatively electrified rain,* which is required by theories which attribute the normal positive potential of the air to the action of precipitation.

I have shown, in a previous paper,† that the ions produced by various agents (X-rays, uranium-rays, negatively charged zinc exposed to ultra-violet light) are identical with respect to the minimum supersaturation required to make water condense on them. They are also identical in this respect, with the few nuclei apparently always present in moist air. In the present investigation I have therefore felt justified in using exclusively the Röntgen rays as being the most convenient ionising agent, and in assuming that the same results would be obtained with ions from other sources.

To compare the efficiency as condensation nuclei of the positive and negative ions respectively, expansion experiments were made with moist air containing ions all, or nearly all, charged with electricity of one sign, alternately positive and negative in successive experiments.

To enable a supply of ions nearly all positive or nearly all negative to be produced at will in the air under observation, this was enclosed between two parallel metal plates, and a narrow beam of Röntgen rays was made to pass between the plates parallel to and almost in contact with the surface of one of them. Under these conditions a supply of positive and negative ions is produced in the thin lamina of air exposed to the rays, and when a difference of potential is maintained between the plates, the two sets of ions move in opposite directions, the positive towards the negative plate and *vice versâ*. If we neglect the slight difference in the velocity of positive and negative ions, shown to exist by the experiments of ZELENY,‡ the number of ions in unit volume of the positive and negative streams will be the same, assuming (an assumption which later experiments justify) that equal numbers of positive and negative ions are produced, and that the ionisation does not, for example,

* The earlier observations of ELSTER and GEITEL appeared to show a preponderance of negatively electrified rain ('Sitzungsber. d. k. Akad. in Wien.,' 99, IIA, p. 421), but this is not shown in their later observations ('Terrestrial Magnetism,' vol. 4, p. 15).

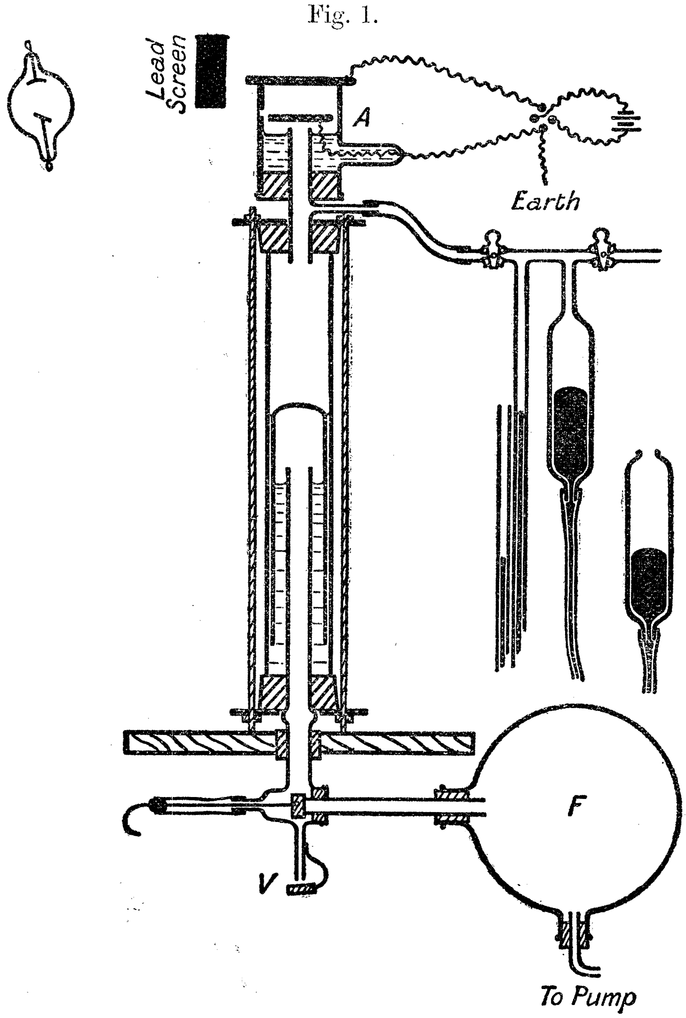
† 'Phil. Trans.,' A, vol. 192, pp. 403–453, 1899.

‡ 'Phil. Mag.,' vol. 46, p. 120, 1898.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

consist in the breaking up of the neutral molecules into a certain number of positive ions and half as many negative ions, each carrying twice as large a charge as the positive. It is plain, therefore, that there must at any moment be a great excess of the ions which have the greater distance to travel; in other words, of the ions charged with electricity of the same sign as that on the plate nearest the layer of air exposed to the rays. The expansion may either be made while this layer is exposed to the rays, or the rays may be cut off before the expansion. If the interval, between

Fig. 1.



cutting off the rays and making the expansion, lies within certain limits, it is plain that all the ions travelling to the plate next the ionised layer may have been removed, while only a small proportion of those travelling towards the more distant plate have reached it before the expansion is made. In this way we would therefore expect to get positive or negative ions with almost complete absence of ions of the other kind.

The method of producing sudden expansion of any desired amount was that which I have described in a previous paper.* Such differences as there were in the details of the apparatus are sufficiently indicated in fig. 1. The glass cylinder and piston of

* 'Camb. Phil. Soc. Proc.,' vol. 9, p. 333, 1897.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

the expansion apparatus were larger than before, the former being 3·7 centims. in internal diameter. The arrangements for connecting the air-space below the piston with the vacuum in F have been improved in form, and a self-acting indiarubber valve, V, has been substituted for the stop-cock, formerly used to cut off communication with the atmosphere immediately before making this connection. The addition of this valve was found to be a great convenience.

The method of arranging for an expansion of any desired amount is described in the paper to which reference has just been made. In the new apparatus, however, an error is introduced into the measurements of expansion by the yielding of the indiarubber stoppers closing the top of the expansion cylinder and the bottom of the vessel, A, in which the clouds are observed, as well as to some extent probably by the momentum acquired by the air in the connecting tube. Both sources of error tend to make the actual maximum expansion of the air in A greater than that obtained by calculation from its pressure before and after expansion.

Now the older experiments,* made with apparatus suitable for absolute measurements, showed that there are two well-defined critical values of the expansion, which we may use as fixed points to standardise an expansion apparatus unsuited for absolute measurements. At the first point the expansion (measured by v_2/v_1, the ratio of the final to the initial volume) is equal to 1·25; it is the minimum expansion required to make condensation in the form of drops begin in dust-free air initially saturated, whether the air be exposed to an ionising agent, such as Röntgen rays, or not. At the second point the transition from rain-like to cloud-like condensation (in the absence of ionising agents) takes place; v_2/v_1, is equal here to 1·38.

On testing the apparatus in this way the following results were obtained:—

(1.) The air being exposed to Röntgen rays, condensation was first observed when the apparent value of $v_2/v_1 = 1·22$ instead of 1·25. Error $= -$ ·03.

(2.) The change from rain-like to cloud-like condensation (in the absence of ionising agents) took place when the apparent value of $v_2/v_1 = 1·35$ instead of 1·38. Error $= -$ ·03.

Thus the correction to be added to the apparent values of v_2/v_1 is the same at both points and equal to $+$ ·03. I have, therefore, assumed that the same correction holds for intermediate values of v_2/v_1. Throughout the paper the corrected values of v_2/v_1 are given.

The vessel, A, in which the ions were produced and the clouds formed upon them observed, consisted of a wide glass tube, 4·2 centims. in diameter, closed above by a brass plate, cemented to the ground top of the tube with sealing wax; 2 centims. below this plate was a smaller circular brass plate, 3·7 centims. in diameter, fixed horizontally within the tube by means of three projecting tags cemented to the sides of the tube. In the side of the tube a horizontal slot was cut, 3 centims. long and 3·5 millims. in diameter, the lower edge of the slot being on a level with the upper

* 'Phil. Trans.,' A, vol. 189, p. 265, 1897.

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
THE ROYAL SOCIETY A
PHILOSOPHICAL TRANSACTIONS OF

surface of the lower plate. The slot was closed externally by a strip of thin aluminium, cemented to the glass with shellac. A focus bulb, giving out Röntgen rays, was fixed with the anticathode on a level with the upper surface of the lower plate, the anticathode being placed with its plane almost horizontal, so that the effective source of the rays which entered the slot was almost linear. A thick lead screen was fixed, as shown in the figure, to prevent any rays reaching the interior of the vessel above the level of the slot. There is thus only a thin layer of air, close to the surface of the lower plate, exposed to the direct action of the rays from the bulb. The lower plate was kept at zero potential, while the upper plate could be connected either to the positive or negative terminal of a battery, of which the other terminal was earthed. The vessel could thus be charged at will with an excess of either positive or negative ions.

All the metal surfaces within the tube were covered with wet filter paper, to keep the air saturated with water vapour, and to prevent nuclei being produced by the action of the metal itself.

A considerable advantage is gained by having the plates horizontal, and the ionised layer in contact with the lower plate, for any drops formed on the ions which are in a minority (these being confined to the lower part of the tube), have thus only a short distance to fall, and if condensation takes place on these ions only, the drops will be confined to the lower part of the vessel.

In the experiments first performed with this apparatus the expansions were made without previously cutting off the rays.

The apparatus being adjusted to give expansions somewhat exceeding the limit $v_2/v_1 = 1{\cdot}25$, comparatively dense fogs were obtained when the upper plate was maintained at a potential a few volts higher than the lower, so that negative ions were present in excess; whereas, when the field was reversed (the positive ions being now in excess) only a slight condensation could be observed, and this was mainly confined to the region immediately over the lower plate, where a considerable number of negative ions must have been present. With expansions as great as $v_2/v_1 = 1{\cdot}35$ the appearance of the fogs obtained was independent of the direction of the field, and this continued to be the case up to the limit 1·38, at which dense fogs appear even in the absence of ions. With the field in the direction which gives an excess of negative ions, the density of the fogs which result from expansion is practically the same for all values of v_2/v_1 between 1·28 and the above-mentioned limit 1·38. When, on the other hand, the upper plate is connected to the negative pole of the battery, so that the positive ions are in excess, the drops remain few till v_2/v_1 amounts to about 1·31, when the number of the drops begins to increase as the expansion is increased. With $v_2/v_1 = 1{\cdot}33$, we obtain, with the positive ions, comparatively dense fogs, still, however, considerably less dense than those obtained with negative ions. Finally, above 1·35 the positive and negative fogs are indistinguishable.

These results admit of only one interpretation; condensation takes place on some of the negative ions when v_2/v_1 amounts to 1·25, practically all the negative ions are caught when v_2/v_1 exceeds 1·28 ; while to make water condense on any of the positive ions v_2/v_1 must exceed about 1·31 ; all the ions positive and negative being caught when v_2/v_1 exceeds 1·35.

Experiments were now made in which the expansion did not take place till after the rays had been cut off.

The ions which are being attracted from the ionised layer to the lower plate, have at the most about $3\frac{1}{2}$ millims. to travel, while the upward moving ones have from 17 to 20 millims. to travel. One would expect, therefore, about six times as long a time to be taken for the removal of the latter as is required for the removal of the former. There is thus a considerable range of time available for making the expansion, so that the majority of the ions of one kind shall still be present, while all the ions of the other kind have reached the lower plate. Using one LECLANCHÉ cell to maintain the electric field between the plates, an interval of about 1 second between cutting off the rays and making the expansion was found to be suitable.

The results were in agreement with those previously obtained ; the drops, when the field was such as to give positive ions and v_2/v_1 was less than 1·31, were now no more numerous than if the expansion were made without exposure to the rays at all. The method, therefore, enables us to obtain ions entirely of one kind.

To test to what degree accidental variations in the time allowed to elapse between cutting off the rays and making the expansion could affect the result, some experiments were made in which this interval was varied. A metronome, giving 90 ticks per minute, was used ; the interval before the expansion was varied by switching off the current from the coil, as the metronome made a tick, and pulling the trigger of the expansion apparatus at the moment of the first, second, or any subsequent tick thereafter. The following results were obtained, one LECLANCHÉ cell being used to maintain the field. The expansion was such as to catch negative ions only.

(1) NEGATIVE Ions moving upward.

v_2/v_1.	Interval in seconds.	Result.
1·27	$\frac{2}{3}$	Dense fog
1·27	$1\frac{1}{3}$	Dense fog
1·27	2	Fog
1·27	$2\frac{2}{3}$	Slight fog
1·27	$3\frac{1}{3}$	Dense shower
1·27	4	Very few drops (no more than without rays)

The negative ions thus take between 3 and 4 seconds to travel from the ionised layer to the upper plate, and a large proportion of them are still present more than 2 seconds after turning off the rays. The field was now reversed.

(2) NEGATIVE Ions moving downwards.

$v_2 v_1$.	Interval in seconds.	Result.
1·27	$\frac{2}{3}$	Very few drops
1·30	$1\frac{1}{3}$	Very few drops (no more than without rays)

All the negative ions have now reached the lower plate in two-thirds of a second after turning off the rays. That the positive ions are still present was proved by increasing the expansion to 1·34 (which is sufficient to cause water to condense on them also); a fog was now obtained when the interval was $1\frac{1}{3}$ seconds. The actual time taken for the positive ions to disappear was not measured, but as ZELENY'S experiments show that they move more slowly than the negative, they would doubtless have been found to take at least as long as the negative to travel to the upper plate.

The above results show that any accidental differences in the length of the time between cutting off the rays and making the expansion are of little importance when the interval amounts to about 1 second.

The time taken for the ions to be removed, when they have to travel to the upper plate, is somewhat longer than the time we obtain by calculation, using RUTHERFORD'S* value for the velocity of the ions. The time calculated in this way amounts to about 2 seconds. The want of uniformity in the field is sufficient to account for the actual time being longer than the calculated.

The following tables contain the results of observations in which the expansion was effected about 1 second after cutting off the supply of Röntgen rays.

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

Rays turned off before expansion. Difference of potential between plates, 1 Leclanché cell.

v_2/v_1.	Result.	
	Upper plate negative (positive ions in excess).	Upper plate positive (negative ions in excess).
1·28	1 or 2 drops	Fog
1·29	1 or 2 drops	Fog
1·31	Very few drops	Fog
1·32	Drops few	Fog
1·33	Shower	Fog
1·34	Slight fog	Fog
1·36	Fog as dense as negative fogs	Fog

The effect of the positive ions begins to be detected when v_2/v_1 amounts to about 1·32 or 1·33; below that point no more drops are seen than in the absence of the rays.

The next series shows the point at which the positive ions first begin to be detected more sharply defined.

Rays turned off before expansion. Difference of potential between the plates, 1 Leclanché cell.

v_2/v_1	Result.	
	Upper plate negative (positive ions in excess).	Upper plate positive (negative ions in excess).
1·265	1 or 2 drops	Fog
1·31	1 or 2 drops	Fog
1·32	Slight fog	Fog
1·35	Fog as dense as negative	Fog

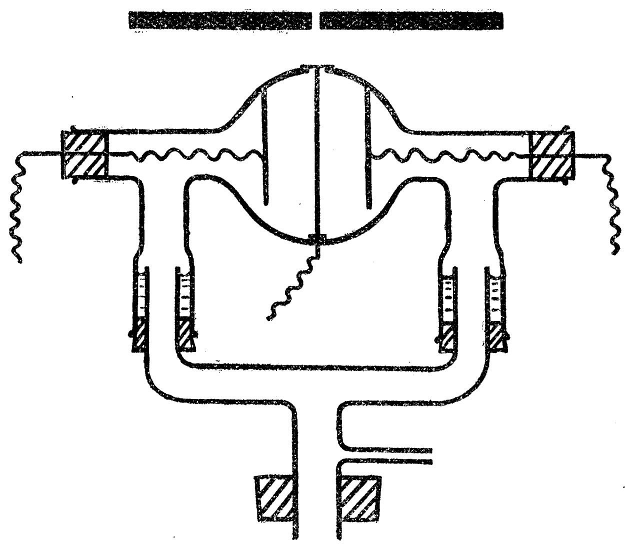
Positive ions begin to be caught when v_2/v_1 is between 1·31 and 1·32.

A double apparatus was now constructed, to allow of the comparison of fogs produced simultaneously in the presence of positive and negative ions respectively.

The arrangements for causing the sudden expansion were the same as before. The general form of the rest of the apparatus is indicated in the diagram (fig. 2) which is drawn approximately to scale.

The vessel in which the clouds were observed was nearly spherical, and about 5·8 centims. in diameter. It was divided into two equal chambers by a partition of brass (about 1 millim. thick) in the equatorial plane; the vessel was cut in two to allow of its insertion, the edges of the two halves being ground smooth, to allow them to be easily cemented against the faces of the partition. The latter was circular, its diameter being equal to the outside diameter of the vessel. A narrow strip of brass, $2\frac{1}{2}$ millims. in thickness, was soldered to each face, extending all round the circumference, except for a gap of 4·5 centims. at the top. When the ground edges of the two halves of the vessel were cemented against these strips there was left at the top a slit on each side of the brass plate, 4·5 centims. long and 2·5 millims. wide. The double slit was closed by covering it with a strip of thin aluminium cemented to the outer surface of the glass and to the edge of the brass partition. A thin layer of air in contact with each surface could thus be exposed to the Röntgen rays from a source placed vertically above the partition.

Fig 2.



Each half of the apparatus contained a second brass plate fixed parallel to the central plate at a distance of 1·8 centim. from it. These had the form of equilateral triangles, and were fixed to the glass with sealing wax at the corners. There was room between the sides of the triangle and the walls of the vessel for the air to escape from between the plates at the moment of expansion.

The metal plates were, as in the former apparatus, covered with wet filter paper.

The anticathode of the focus tube, which generated the rays, was fixed by eye vertically above the central plate of the apparatus. A lead screen connected to earth and provided with a slit, 4 millims. in width, was placed about 2 centims. above the aluminium window of the cloud vessel. The final adjustments were made by moving the screen until, when both side plates were kept at the same potential (higher than that of the central plate, which was always earthed), exactly equal fogs were obtained on the two sides, with expansions sufficient to catch the negative ions.

To make the fogs on the two sides readily visible simultaneously, a horizontal stratum of the air in both halves was illuminated by the light from a horizontally placed luminous gas flame brought to a focus within the apparatus, the source being behind the apparatus with its centre in the plane of the central plate. The fogs were best seen when the eye was placed sufficiently below the level of the illuminated stratum to receive none of the direct light, but only that scattered by the drops.

To compare the effects of positive and negative ions, expansions were made with the left-hand plate at a certain positive potential (generally about 1 volt), the right-hand plate being at an equal negative potential and the central plate earthed. The appearance of the fogs on the two sides was noted, the direction of the fields reversed, and the effect of an expansion of the same amount as before again noted. Any effect due to want of symmetry in the apparatus was thus eliminated.

To secure equality in the electric fields in the two halves of the apparatus, the following arrangement was used. The source of potential (generally two Leclanché cells in series) had its terminals connected by a resistance of 200 ohms. The middle point of this resistance was earthed, and the two extremities were connected through a commutator to the outer plates of the cloud apparatus, the central plate being earthed.

The correction to be applied to obtain the true values of v_2/v_1 was found to be the same as before; to the apparent values of v_2/v_1 ·03 must be added. The error was, as before, found to be the same at both the points, $v_2/v_1 = 1{\cdot}25$ and $v_2/v_1 = 1{\cdot}38$.

To obtain an approximation to quantitative comparison between the number of drops produced in the two halves of the apparatus, measurements were made on the time taken by the upper surface of the clouds on the two sides to sink below the level of the beam of light, which was used to make them visible. The expansion and consequent cooling on both sides being the same, the same quantity of water is condensed in each half; the quantity available for each drop is thus inversely proportional to the number of drops which are formed. Now the radii of the drops on the two sides can be compared by measuring the velocity with which they fall; a comparison of the rates of fall on the two sides will thus enable us to determine the ratio between the numbers of the drops produced in the two halves of the apparatus, or will at least serve as a test for equality between the numbers. Professor J. J. THOMSON* has in fact used the rate of fall of the drops, formed on the ions as the result of expansion, to determine the number of the ions present, from which he obtains an estimate of the charge carried by each.

The results of measurements with this double apparatus are given in the tables which follow. After what has already been said in connection with the other apparatus, it is hardly necessary to point out that, when the right-hand plate is connected to the positive terminal of the battery, and the left-hand plate to the negative terminal (the central plate being at zero potential), there will be a great excess of negative ions on the right, and of positive ions on the left. The terms "positive" and "negative" in the tables refer to the sign of the charge carried by the majority of the ions, not to the potentials of the plates; the corrected values of v_2/v_1 are given.

* 'Phil. Mag.,' *loc. cit.*

FIELDS produced by 4 Leclanché cells, terminals joined by resistance of 200 ohms, the middle point of which was earthed.

v_2/v_1.	Time taken by fogs to fall in seconds.		Ratio of times, negative / positive.
	Left side.	Right side.	
1·28	positive 5 negative 15	negative 16 positive 3	3·2 5·0 } 4·1
1·30	negative 15 positive 5 negative 10 positive 2	positive 2 negative 15 positive 2 negative 10	7·5 3·0 5·0 5·0 } 5·1
1·31	positive 7 negative 14	negative 12 positive 7	1·7 2·0 } 1·8
1·32	negative 8 positive 8 negative 14 positive 12	positive 5 negative 10 positive 8 negative 17	1·6 1·2 1·7 1·4 } 1·5
1·33	negative 12 positive 12	positive 10 negative 13	1·2 1·1 } 1·15
1·35	negative 10 positive 10	positive 10 negative 10	1·0 1·0 } 1·0

The results of another series, in which only two cells were used to produce the fields, are given in the next table.

v_2/v_1.	Time taken by fogs to fall in seconds.		Ratio of times, negative / positive.
	Left side.	Right side.	
1·28	positive 4 negative 14	negative 15 positive 4	3·7 3·5 } 3·6
1·30	negative 14 positive 3	positive 4 negative 17	3·5 5·7 } 4·6
1·32	positive 10 negative 20	negative 17 positive 12	1·7 1·7 } 1·7
1·34	negative 20 positive 12	positive 17 negative 17	1·2 1·4 } 1·3
1·36	negative 20 positive 20	positive 20 negative 20	1·0 1·0 } 1·0
1·37	positive 18 negative 20	negative 18 positive 20	1·0 1·0 } 1·0

The tables show plainly that with the smaller expansions the number of drops on the side which contains chiefly positive ions is very small compared with the number of drops on the side containing mainly negative ions. No difference can be detected between the fogs on the two sides when v_2/v_1 exceeds 1·35; the transition from the one kind of result to the other begins when v_2/v_1 is about 1·31. This is well shown by the ratio of the times taken by the fogs on the negative and positive sides to fall the same distance; increasing v_2/v_1 from 1·30 to 1·31 brings down the ratio from 5·1 to 1·8 in the first series, and in the second series the ratio diminishes from 4·6 to 1·7 as v_2/v_1 is increased from 1·30 to 1·32. The results are therefore in complete agreement with those previously obtained.

There can be no doubt that the drops which are formed when v_2/v_1 is less than 1·31 on the side containing mainly positive ions are deposited on negative ions, of which a considerable number must unavoidably be present, when the expansion is made while the rays are acting. The number of these was exceedingly small when the rays were turned off before the expansion was made.

There is no evidence of any increase in the number of the negative ions caught as v_2/v_1 passes through the region in which the positive ions begin to be caught. The following is an example of observations with expansions of different amount made in rapid succession (so that the radiation might not have time to change in intensity):—

v_2/v_1	Time taken by fogs to fall.	
	Left side.	Right side.
1·30	positive 2 seconds	negative 12 seconds
1·30	negative 12 ,,	positive 3 ,,
1·37	negative 12 ,,	positive 12 ,,
1·37	positive 12 ,,	negative 12 ,,

The rate of fall on the negative side is the same when $v_2/v_1 = 1·37$ as when it $= 1·30$. It is true that we would expect the drops if equally numerous to fall slightly quicker with the greater expansion, since a rather larger quantity of water would be condensed; against this is to be set the fact that the positive minority on the negative side are caught by means of the greater expansion, and not by the less.

It will be convenient to consider here what light the new knowledge now acquired throws upon phenomena previously observed in the course of experiments with expansion apparatus.

All the former measurements which I have published upon the least expansion required to make condensation take place in presence of ions, are now seen to have been concerned with negative ions only. One example of interest is the case of nuclei produced by a zinc plate exposed to ultra-violet light. When the plate was negatively charged, nuclei were found to be present, requiring an expansion, $v_2/v_1 = 1·25$, to make water condense on them; a fact in agreement with the results of the present investigation, since negative ions were, in this case, plainly in question. The absence of fog when the expansion was made with the field reversed was, however, as we now see, no proof that no ions escape from the positively charged plate, for the expansions used were insufficient to cause water to condense on positive ions had they been present. Another case of interest is that of the nuclei produced by the discharge from a point. Even when positive electricity was escaping from the point, fogs were obtained with expansions which are now seen to have been insufficient to catch positive ions. We are therefore driven to the conclusion that the positive discharge does not consist simply in the escape of positive ions from the point of the wire, but that negative ions (or nuclei of some other kind than ions) are present as well, possibly produced by the action upon the moist air of the radiation from the glowing point of the wire.

Indications had already been noticed of an increase in the number of drops, produced in ionised air as v_2/v_1 was increased beyond the point now shown to be that at which the positive ions first begin to act as condensation nuclei. Professor THOMSON was indeed led to make the suggestion contained in the words quoted at the beginning of this paper by noticing indications of such an increase in the neighbourhood of the point $v_2/v_1 = 1 \cdot 3$. My own observations had also previously led me to believe that there was an increase at the point $v_2/v_1 = 1 \cdot 31$; for example, my notes for March 4, 1898, contain the remark, "Many experiments with air, as well as H, seem to show that there are nuclei requiring expansion $= 1 \cdot 31$ to catch them in addition to those appearing at 1·25."

Positive and negative ions (at least those produced in air by Röntgen rays) have now been proved to differ in their efficiency as condensation nuclei; they also differ, as ZELENY has shown, in the velocity with which they move in an electric field of given strength. The negative ions move the faster and are the more efficient as nuclei for the condensation of water vapour.

A possible way of accounting for both differences is to suppose that the charge carried by the negative ions is greater than that carried by the positive, the number of the latter being, of course, correspondingly greater. We might, for example, take the view that the ionisation consists in the breaking-up of the neutral molecules into a certain number of positive ions and half as many negative ions, each carrying twice as large a charge as the positive, a process which we can readily imagine to take place in the case of water molecules.

The experiments already described make this view hardly tenable, for we have seen that when the expansion is sufficient to make water condense on all the ions ($v_2/v_1 = 1 \cdot 35$ or more) the fogs in the two halves of the apparatus are indistinguishable in appearance and in the rate of fall of the drops. We have still to consider to what extent this proves equality in the number of positive and negative ions produced.

The velocity with which the drops fall is proportional to the square of the radius, that is, to the two-thirds power of the volume of each drop, or for a given expansion to $1/n^{2/3}$ where n is the number per cubic centimetre. The time, t, taken to fall a given distance is thus proportional to $n^{2/3}$, or the number of drops is proportional to $t^{3/2}$. Now, when v_2/v_1 exceeds 1·35 the times taken by the drops on the two sides to fall a given distance certainly do not differ by as much as 1 part in 10. If $t_1/t_2 = 1{\cdot}1$ then $n_1/n_2 = 1{\cdot}1^{3/2} = 1{\cdot}15$. Thus the number of ions is the same on the two sides to within 15 per cent.

The equality of the fogs on the two sides is, in fact, rather more exact than we would expect; for the positive ions, according to ZELENY, take 1·25 times as long as the negative to travel a given distance. We would expect then (the strength of the field on each side being the same) that, if equal numbers of positive and negative ions were produced in a given time, the negative ions would be more quickly removed, and a somewhat larger number of drops should have been produced in the half containing mainly positive ions.

The absence of any indication of this slight excess of positive ions is of the less consequence for the present purpose, since it strengthens rather than weakens the evidence against the view that a larger number of positive than of negative ions is produced. As a test of the trustworthiness of the method for detecting a difference in the number of drops produced on the two sides, experiments were made in which the direction of the field on both sides of the central plate was such as to drive negative ions outwards towards the side plates; the strength of the field being, however, different on the two sides. The ratio of the fields was as 3 to 2, the stronger field being produced by two Leclanché cells. The following results were obtained :—

$v_2/v_1 = 1{\cdot}30$.		
	Left side.	Right side.
Relative strength of fields . . Time taken to fall	3 10 seconds	2 12 seconds
Relative strength of fields . . Time taken to fall	2 12 seconds	3 10 seconds

The excess in the number of drops on the side of the weaker field is plainly shown.

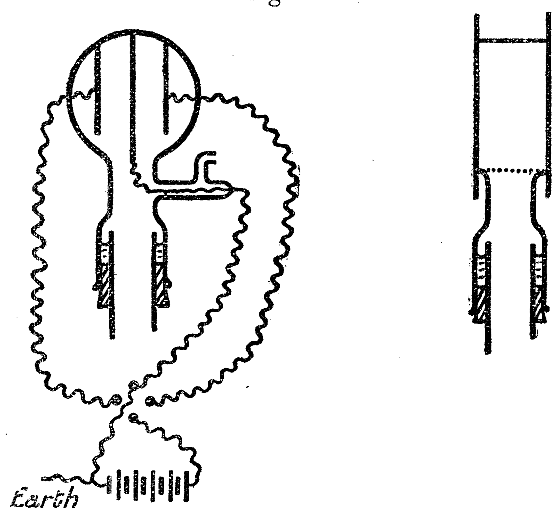
It appears, therefore, that the difference in the behaviour of the positive and negative ions is not to be explained by a difference in the quantity of electricity carried by positively and negatively charged ions respectively.

Some experiments were now tried with the object of determining whether the rain-like condensation, which takes place in dust-free air, even when not exposed to any ionising agents, is due to ions.

As already pointed out, the least expansion necessary to produce such showers in air initially saturated is identical with that required to cause condensation on ions —really on negative ions, as the experiments described in this paper show. This is a remarkable coincidence if we are really concerned with nuclei of entirely different kinds. Further, it was during experiments made in the absence of ionising agents that I first noticed indications of an increase in the number of the drops about the point $v_2/v_1 = 1{\cdot}31$, the expansion now proved to be that required to cause water to condense on positive ions.

These considerations seemed to furnish strong ground for believing that the very few nuclei always present actually are ions. In a recent paper,* it is true, I described some unsuccessful attempts which I had made to remove the nuclei by applying a strong electric field; I did not, however, consider these experiments to be conclusive evidence against the ionic nature of the nuclei. I have, therefore, recently subjected them to a much more severe test by means of a differential apparatus (fig. 3).

Fig. 3.



The mechanism for causing the sudden expansion was the same as in the other experiments, and is not shown in the figure. A front view of the apparatus is given on the left, a side view on the right. It consists of a short glass cylinder, 4 centims. in diameter and 2 centims. long, the ends being ground smooth and closed by plates, that forming the front face being of glass, the other of quartz. (The quartz was for experiments with ultra-violet light described below.) A thin brass plate, 2 centims. wide (reaching, therefore, from back to front of the apparatus), divided the vessel into two equal chambers. On each side of this, at a distance of 8 millims., was a parallel brass plate of the same width, 2 centims., but not reaching to the lower wall of the cylinder. The brass plates were covered with wet filter paper.

A difference of potential of 320 volts could be maintained, by means of a series of

* 'Phil. Trans.,' A, vol. 192, pp. 403–453, 1899.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

secondary cells, between the central plate and one of the side plates, the other being connected to the central plate, which was earthed. In one half, therefore, there was a strong electric field, in the other half, none. A lens was used to examine simultaneously the drops formed on the two sides of the central plate. Any difference in the number of the drops could thus readily be detected.

In the strong field the maximum length of life of an ion will be the time taken to travel from one plate to the other under the action of the field; in the present case, a distance of 8 millims., with a potential gradient of 320 volts in 8 millims., or 400 volts per centimetre. The velocity of the ions produced by X rays would in such a field be about $400 \times 1{\cdot}6$ centim. per second, if we take RUTHERFORD's value of the velocity for a potential gradient of 1 volt per centimetre. The 8 millims. would therefore be traversed in $\cdot 8/(400 \times 1{\cdot}6) = 1/800$ of a second. (The time would really be somewhat longer on account of the plates being too small to give a sufficiently uniform field.) Now the average length of life of the ions due to Röntgen rays when they are destroyed by recombination alone is of the order of 1 second.* The fewer the ions also the less rapid is the rate at which they recombine; we would, therefore, expect the average life of the very few nuclei with which we are now concerned, if they really are ions, to be at least as long as 1 second in the absence of any electric field. If then we have here simply a case of spontaneous ionisation due to molecular encounters, we ought to obtain something like 800 times as many drops without the field as with it. In similar experiments † made with the ions produced by Röntgen or uranium rays, much weaker fields were in fact found sufficient to prevent almost completely the production of fogs by expansion.

In the experiments now made without external ionising agents, not the slightest difference could be detected between the appearance of the showers on the two sides of the apparatus. All degrees of expansion from $v_2/v_1 = 1{\cdot}25$ to $v_2/v_1 = 1{\cdot}38$ were tried.

If then we have here to do with a case of ionisation, it differs completely from the ionisation produced by Röntgen rays.

Very similar nuclei, requiring practically the same supersaturation to make water condense on them as the ions, are produced by the action on moist air of sunlight and of weak ultra-violet light. Former experiments‡ showed that the nuclei produced by this volume effect of ultra-violet light (unlike those produced by its action on a negatively charged zinc plate) are unaffected by electric fields strong enough to remove the ions produced by Röntgen rays as fast as they are produced. More severe tests were now made with the double apparatus, to see whether they are altogether uninfluenced by the electric field.

The ultra-violet light was produced by the spark discharge between aluminium

* RUTHERFORD, *loc. cit.*

† 'Phil. Trans.,' A, vol. 192, pp. 403–453, 1899. Also J. J. THOMSON, 'Phil. Mag.,' *loc. cit.*

‡ 'Phil. Trans.,' *loc. cit.*

terminals, at a distance of 55 centims. from the quartz plate in one series of experiments, at 180 centims. in another. In neither case was the radiation strong enough to cause drops to be produced with expansions appreciably below $v_2/v_1 = 1{\cdot}25$. The spark-terminals were placed in the plane of the central plate, so that the air in both halves was equally exposed to the rays. The wet filter paper which covered the brass plates prevented any surface effect from the light which might reach the plates. As before, the air on one side was between plates at the same potential, that on the other side in a strong field. The central plate was earthed and one of the side plates kept at a positive potential of 320 volts, the other being earthed; the connections were interchanged after each observation, so that the air in each half alternately was subjected to the action of the field.

When the expansions were made while the air was exposed to the rays, no difference could be detected between the fogs in the two halves of the apparatus. Moreover, even when the rays were turned off 10 seconds before the expansion was made, a slight fog was obtained, equally dense on both sides of the central plate. Thus some of the nuclei appear to persist for 10 seconds, and even in that time the field has had no sensible effect in reducing the number of the nuclei.

A field, therefore, of 400 volts per centimetre causes the nuclei to move in 10 seconds, a distance small compared with 8 millims., the distance between the plates. This gives, for the velocity under a potential gradient of 1 volt per centimetre, less than 1/4000 centim. per second, whereas the ions produced by Röntgen rays travel under these conditions between 1 and 2 centims. per second.

The slight rain-like condensation which takes place, when v_2/v_1 lies between $1{\cdot}25$ and $1{\cdot}38$, in the absence of all radiation, as well as the much denser condensation produced by the same expansions when the air is exposed to weak ultra-violet light, are thus essentially different phenomena from the apparently similar condensation produced in air ionised by Röntgen rays.

We might perhaps most naturally conclude that we are in these cases not concerned with ions at all. There is, however, the difficulty of the unlikelihood of two entirely different classes of nuclei being so exactly identical in the degree of supersaturation necessary to cause water to condense on them. The apparent existence of a second coincidence (an increase of the number of drops when v_2/v_1 exceeds $1{\cdot}31$) is still harder to explain on this view.

It is possible that condensation in these cases really does take place on ions carrying the same charge as those produced by Röntgen rays. There are, in fact, several ways in which we may account for the fact that an electric field does not remove them.

We might suppose that the nuclei differ from those produced by Röntgen rays merely in being so much larger, that their velocity in a given field is diminished enormously, the charge in each nucleus remaining the same. It is difficult, however, to believe that the efficiency of the nucleus in helping condensation would remain unaltered by such an increase in size as would reduce the velocity to anything like such a small value as 1/4000 centim. per second for a potential gradient of 1 volt per centimetre. In fact, if we can trust to obtaining approximately correct results by applying to drops as small as 2×10^{-6} centim., the formulæ which hold for larger drops, we can see* that these nuclei must amount to at least 2×10^{-6} centim. in radius; the supersaturation required to cause condensation to take place on drops of this radius being that produced by an expansion, $v_2/v_1 =$ about 1·01, which is very far removed from that actually required, $v_2/v_1 = 1{\cdot}25$.

The ionisation may be a result of the expansion. This is the view I am inclined to take.

It is easy to understand, according to this view, how the number of drops produced is entirely uninfluenced by even a strong electric field, for the whole time for which the ions would be free to move under the action of the field, before the formation of drops upon them, would be exceedingly short.

Uncharged nuclei are probably present before the expansion. Some change is produced in the air by weak ultra-violet light independently of the expansion, for, as we have seen, the fogs may be obtained even when the expansion is made some seconds after the light has been cut off. The behaviour of moist air exposed to stronger ultra-violet light, and especially the extreme case where we get visible particles produced without expansion, almost compel us to conclude that even weak ultra-violet light produces nuclei before the expansion is made. I have already suggested† that these nuclei consist of what we may regard as minute water drops containing hydrogen peroxide in solution. The difference between the effects of the strongest and weakest ultra-violet light would consist in a difference in the size of these drops due to the larger quantity of hydrogen peroxide produced in each by the stronger radiation. We may suppose the very minute molecular aggregates due to weak ultra-violet light to be of themselves too small to act directly as condensation nuclei with the expansion $v_2/v_1 = 1{\cdot}25$; in other words, the growth which results from the supersaturation corresponding to this expansion may be insufficient to bring them up to the critical size beyond which the unstable condition is reached, where increase in size is accompanied by a diminution of the equilibrium vapour pressure. But if, as a consequence of the increase in size which results from the supersaturation, the nucleus becomes charged, an ion carrying electricity of opposite sign to that left on the original nucleus being thrown off, the result actually met with would be explained. Judging from the behaviour of hydrogen peroxide solutions, with respect to the electricity developed by splashing, we would expect the original nucleus to become negatively charged; for the splashing results in a negative electrification of the drops‡ indicating that the inner coat of the double layer originally covering the

* Using the value found by Professor THOMSON (*loc. cit.*) for the charge on one ion, and applying the formula for the steady motion of a sphere through a viscous fluid (LAMB, 'Hydrodynamics,' p. 532).

† 'Phil. Trans.,' *loc. cit.*

‡ J. J. THOMSON, 'Phil. Mag.,' vol. 37, p. 341, 1894.

drops is negative; in other words, that solutions of hydrogen peroxide in water, surrounded by air, attract negative electricity more than positive.

The view here suggested is, therefore, that the nuclei requiring the definite expansions 1·25 or 1·31 to make water condense on them are always really ions, the cases in which an electric field is without influence upon the result of expansion being explained by supposing that the ionisation does not in such cases take place until supersaturation is produced.

The separation of the positive and negative electricity by the formation of drops on the negative ions only, as soon as the supersaturated state reaches the necessary limit, will take place equally well whether the ions exist before the supersaturation is produced or are the result of the supersaturation. Moreover, if the initial growth of a drop, as above suggested, is able to cause it to acquire a charge equal to that of one ion, the further growth of the drop may result in an increase of the charge. The drops may thus acquire a charge considerably exceeding that of one ion, even if there be no coalescence of small drops to form large ones.

Further experiments on this point are evidently required.

I do not propose to discuss here the meteorological bearings of the results obtained. The questions with which the experiments are concerned are, I think, fundamental ones in connection with the electrical effects of precipitation. From this point of view the principal results of this investigation are :—

(1.) To cause water to condense on negatively charged ions, the supersaturation must reach the limit corresponding to the expansion $v_2/v_1 = 1{\cdot}25$ (approximately a fourfold supersaturation). To make water condense on positively charged ions, the supersaturation must reach the much higher limit corresponding to the expansion $v_2/v_1 = 1{\cdot}31$ (the supersaturation being then nearly sixfold).

(2.) The nuclei, of which a very small number can always be detected by expansion experiments with air in the absence of external ionising agents, and which require exactly the same supersaturation as ions to make water condense on them (as well as the similar nuclei produced in much greater numbers by the action of weak ultra-violet light on moist air) cannot be regarded as free ions, unless we suppose the ionisation to be developed by the process of producing the supersaturation.

We see, then, that if ions ever act as condensation nuclei in the atmosphere, it must be mainly or solely the negative ones which do so, and thus a preponderance of negative electricity will be carried down by precipitation to the earth's surface.

The experiments described in this paper were carried out at the Cavendish Laboratory.

NOTE ADDED SEPTEMBER 25, 1899.

In order that the results of these investigations should have a direct bearing on the subject of atmospheric electricity, it is necessary to assume that condensation in the atmosphere frequently takes place from the supersaturated condition. There is very little direct evidence of the existence of supersaturation in the atmosphere, but there is at least an equal lack of evidence against its existence above the lower cloud layers even as a normal accompaniment of precipitation. That supersaturation occurs in connection with thunderstorms is held by v. BEZOLD and others ('Sitzungsb. Akad. d. Wissenschaft. zu Berlin,' 1892).

In the lower dust-charged layers of the atmosphere supersaturation is not to be expected. When there is an ascending air current, however, the dust particles may be retained in the lower cloud layers, through each becoming loaded with water, and ceasing to rise as soon as a certain critical size, depending on the upward velocity of the air, is attained. Supersaturation will exist under these conditions in the air which has left its dust particles behind, and if the ascending current reaches a sufficient elevation a second condensation will take place at a higher level, as was pointed out in a former paper ('Phil. Trans.,' A, vol. 189, p. 286, 1897); the conditions will then be such that the experimental results obtained in the present investigation may be applied.

Whether the drops will from the first be too large to be supported by the upward current and therefore at once begin to fall as raindrops, growing rapidly as they fall through the supersaturated layers, or will still continue to be supported by the ascending current and form an upper cloud layer, depends on the upward velocity of the air, the number of nuclei (negative ions?) and other conditions. In either case we should expect the drops to be negatively charged, the air rising above them carrying a corresponding excess of positive ions.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES