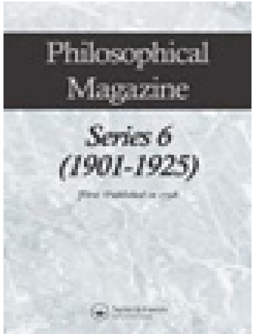

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LXXV. The condensation method of demonstrating the ionisation of air under normal conditions

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pressures and corresponding dimensions of vessels for different gases $\left(\text{according to } h=1;\ n=\alpha;\ b=\frac{\beta}{\sqrt{\alpha}}\right)$.

Also the thermic variability of conductivity—not yet known with desirable precision—may be investigated in an analogous manner, by application of similar motions. If we make use, for the higher temperatures, of vessels with dimensions increased in proportion of the first, and of pressure increased in proportion of the $(\epsilon-\frac{1}{2})$th power of temperature, the quantity of heat transferred must be proportional to θ^{ϵ}, whence ϵ may be determined. The method of heating wires by electric currents may be easily adapted to this way of experimenting.

We confine ourselves to these few examples on this sort of similarity, since its range of applications is less extensive and since there is little experimental work hitherto done which could serve as a basis for further speculations.

LXXV. *The Condensation Method of Demonstrating the Ionisation of Air under Normal Conditions.* *By* C. T. R. Wilson, *M.A.*, *F.R.S.*, *Fellow of Sidney Sussex College, Cambridge*[*].

SOME years ago I described experiments[†] which proved that when air saturated with water-vapour has been freed from dust particles, it will still give condensation in the form of drops on sudden expansion provided the expansion exceeds a definite limit. If v_1 v_2 be the volume of the air before and after the sudden expansion, then if v_2/v_1 be less than 1·25 no drops are produced on expansion, but if this critical expansion be exceeded a rainlike condensation results. The drops remain comparatively few if v_2/v_1 does not exceed a second limit about 1·38. It was found that exposure of the air to Röntgen or other ionising rays increased enormously the number of drops produced by expansions between these limits, the least expansion required to cause the formation of drops remaining, however, the same. It was concluded that the nuclei giving the clouds in air exposed to Röntgen rays are to be identified with the ions to which its conducting power under the action of the rays is attributed, and that the few drops always produced with expansions exceeding the critical value are due to ions of the same nature continually being produced even in the absence of the rays.

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[*] Communicated by the Author.

[†] Phil. Trans. vol. clxxxix. p. 265 (1897).

Further experiments showed[*] that the number of drops produced by expansions between the above-mentioned limits in air exposed to Röntgen rays, is reduced in a very striking manner when a sufficiently strong electric field is maintained across the air before expansion, thus proving that the nuclei move in an electric field and are therefore electrically charged, and presumably identical with the ions to which the conducting power is due. On the other hand, similar experiments made in the absence of ionising agents failed to show any diminution of the number of drops by the action of even very strong fields. The absolute identity of the degree of supersaturation required to cause condensation upon ions and upon the nuclei to which the rainlike condensation is due, made it difficult to believe that the latter are not ions also, and to explain their non-removal by an electric field it was suggested that they might be ions produced in some way as a result of the expansion. When, however, subsequent experiments[†] on the leakage of electricity from conductors suspended within closed vessels, showed that a continual slight ionisation of the air is always going on in such vessels, it appeared more likely that the rainlike condensation really is due to this ionisation, and that the failure to detect any diminution in the number of drops under the action of an electric field is due to some defect in the conditions of the experiments. In the experiments thus far made the vessels used had been small, and to permit of a strong electric field being applied the air was enclosed between conducting surfaces generally only a centimetre or less apart; in many cases one of the conductors was a layer of water at the bottom of the vessel, the other being a horizontal metal plate coated with wet filter-paper. The drops were under these conditions very few whether an electric field was applied or not; it was thought that if a much larger volume of air were used there would be more chance of detecting the diminution in number when an electric field was applied. This expectation has been realized. With the large apparatus described below the effect of an electric field in removing the nuclei which gave rise to the rainlike condensation is very striking.

The construction of the apparatus[‡] (shown in the figure) is the same in principle as in the experiments on condensation nuclei which I have described in previous papers. On

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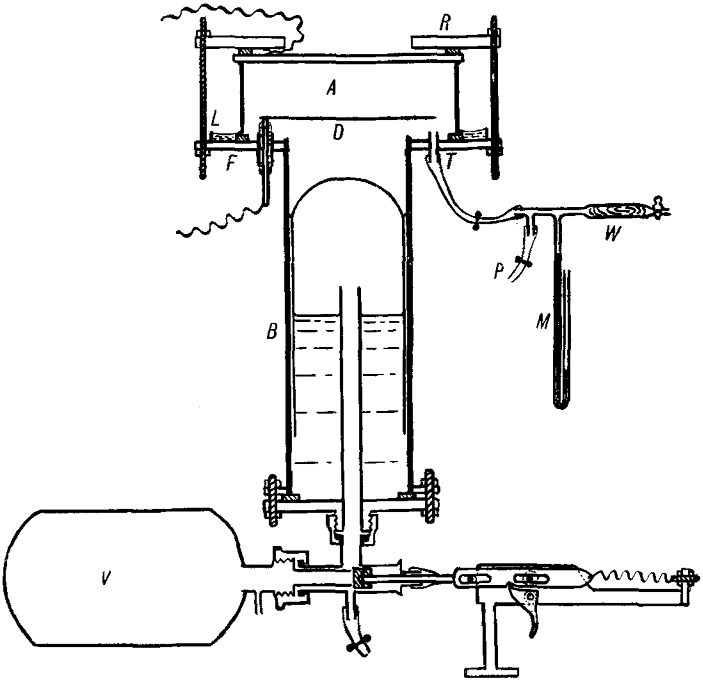
[*] Phil. Trans. vol. cxcii. p. 403 (1899).

[†] Geitel, *Physikalische Zeitschrift*, vol. ii. p. 116; C. T. R. Wilson, Roy. Soc. Proc. vol. lxviii. p. 151.

[‡] The apparatus was made by Messrs. W. G. Pye & Co., Cambridge. To Mr. Pye I am indebted for many suggestions as to the mechanical details.

account of the much larger size of the new apparatus, the mechanism by which the sudden expansion is produced was



constructed, however, of brass, not, as in the older experiments, of glass. The cloud chamber A, in which the drops formed by expansion are viewed, is a glass cylinder 18·5 cms. in internal diameter and 5·9 cms. high. Its roof consists of a thick brass disk cemented to it by means of sealing-wax. The cylinder rests on an indiarubber ring lying on an annular brass plate F, which forms a flange at the top of the expansion cylinder B. The glass cylinder is squeezed down on the indiarubber by means of an upper annular brass plate R resting on the roof of the cloud chamber, from which it is separated by a second indiarubber ring; the upper and lower annular plates are connected by six bolts, by means of which the necessary pressure can be applied. The external diameter of the annular plates is 26 cms.; about one cm. from the edge of the lower one on its upper surface a thin ring L of brass 1·2 cm. high is soldered. This serves to contain water, all risk of air leaking in below the edge of the glass cylinder being thus removed. Through three symmetrically placed tubes penetrating the lower plate of the cloud chamber are sealed three insulated brass rods supporting a horizontal brass disk D, 15·3 cms. in diameter. Between this disk and the roof of the cloud chamber, 4·7 cms. above it, any desired difference of potential could be maintained by means of a battery of storage-cells. Both this disk and that forming the roof were covered on the surfaces facing one another with wet filter-paper. In addition to the three tubes through which pass the supports of the brass disk, the floor of the vessel is pierced by a fourth smaller tube T, by means of which air can be removed from or admitted into the apparatus.

Below the cloud chamber and supporting it is a vertical brass expansion cylinder B, 10 cms. in internal diameter and 30 cms. long. Sliding freely in this and serving as a piston is a thin-walled brass cylinder open below and with a hemispherical top, the length of the cylindrical part being 18·75 cms., the thickness of the walls being less than one millimetre. The expansion cylinder is bolted by means of a flange at its lower end against a thick brass disk, an indiarubber ring, of which the internal diameter is considerably less and the external diameter greater than that of the cylinder, being inserted between them. Rising up from the centre of the disk is a brass tube 18 cms. long and 1·3 cms. in internal diameter. The cylinder is filled with water to within a few cms. from the top of this tube. By means of the mechanism to be presently described, the central tube can be put into sudden communication with a vacuum chamber V, thus causing the piston to fly sharply down against the indiarubber at the bottom of the cylinder, and to remain pressed tightly against this so that no air or water can escape. It is in this way that the sudden expansion is produced: on putting the central tube in communication with the atmosphere instead of the vacuum chamber, the piston rises to its original position.

The thick brass disk to which the expansion cylinder is attached rests upon an iron tripod (not shown in the figure) to the top of which it is firmly fixed by three screws. The feet of the tripod are screwed down to a board. The tubes for making connexion with the vacuum chamber are shown below the expansion cylinder. For convenience the connexions are made with screw-joints, indiarubber washers being inserted to prevent leakage. The vacuum chamber was a brass cylinder 22 cms. long and 14 cms. in diameter, with rounded ends; it was maintained at low pressure by a water-jet pump. A gauge was connected to avoid the risk of making an expansion while the vacuum was not sufficiently good. The construction of the mechanism for making sudden communication with the vacuum chamber is the same as in the smaller apparatus described in previous papers, but of brass instead of glass; its mode of working will be understood from the figure. An indiarubber stopper held tightly by the pressure of the atmosphere against the end of the tube leading to the vacuum-chamber V can be suddenly pulled away by a spring released by the trigger arrangement shown. In this way the sudden motion of the piston, and the consequent expansion of the air in the cloud chamber, are effected.

The final volume of the air after expansion is always the same, for the piston is then held against the indiarubber at the bottom, owing to the low pressure below. To vary the expansion the initial volume has to be varied. The air before expansion is always at very nearly atmospheric pressure—really at a pressure less than that of the atmosphere by the pressure required to balance the weight of the partially immersed piston, the air below the piston being always before expansion at atmospheric pressure. The amount of any expansion is determined by adjusting the pressure after opening communication with the gauge M, before allowing the piston to rise after the previous expansion, a sufficiently long interval being allowed to elapse for the temperature to return to that of the surroundings; the constancy of the pressure serves as a test of this condition being fulfilled. The pressure thus determined will be the same as the pressure after the next expansion has taken place and the temperature has again become steady. The ratio of the air-pressure before expansion (*i. e.*, of the whole pressure in the cloud chamber less the saturation pressure of the aqueous vapour) to that after expansion will then be equal to v_2/v_1, the ratio of the final to the initial volume. To adjust the final pressure to any desired value, air can be admitted from the atmosphere through the cotton-wool filter W, or removed by opening communication with the water-pump through the tube P.

The drops resulting from expansion are illuminated by a narrow beam of light converging to a focus at the centre of the cloud chamber; the source was in most cases an arc or lime-light; the effects were, however, quite easily observed with the light from an ordinary luminous flame. It was found convenient to coat the outside of the glass with black enamel over half the circumference, leaving, however, a vertical strip about one cm. wide in the middle for the light to enter; the glass immediately opposite this slit was also blackened over a width of a few cms. Any drops produced were then well seen on looking towards the centre of the cylinder through the unblackened portions of the glass*.

The apparatus gave a value for the least expansion required in order that rainlike condensation might result, which agreed well with that obtained in previous experiments with much smaller apparatus.

The results of one series of measurements, those of May 15th, 1903, are given below.

p = gauge-reading when piston is at bottom.
w = pressure required to support weight of piston.
B = barometer-reading.
π = maximum vapour-pressure of water at temperature of experiment.

Then
$$v_2/v_1 = \frac{B-w-\pi}{B-p-\pi}.$$

In the experiment temperature = 15° C. Barometer = 766 mm. $\pi = 13$ mm. $w = 5$ mm.

In the Table which follows the result of the expansion corresponding to various values of the gauge-reading is given (*a*) when the upper and lower plates were metallically connected; (*b*) when a difference of potential of 160 volts was maintained between them.

Gauge-reading in millimetres.	P.D. = 0.	P.D. = 160 volts.
159 …………	Shower.	
153 …………	Very few drops.	
151 …………	No drops.	
152 …………	No drops.	
153 …………	Very few drops.	No drops.
155 …………	Shower.	No drops.
160·5 ………	Shower.	No drops.
171 …………	Shower.	Very few drops.
177 …………	Dense shower.	Very few drops.

Value of v_2/v_1 when rainlike condensation begins (in the absence of an electrical field)
$$v_2/v_1 = \frac{766-5-13}{766-153-13} = 1{\cdot}247.$$

In the early experiments† the value found for the least expansion required for rainlike condensation was $v_2/v_1 = 1{\cdot}252$.

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[*] The apparatus was exhibited at the British Association meeting at Southport last September, and the removal of the ions by an electric field demonstrated.

[†] Phil. Trans. vol. clxxxix. p. 265.

The above observations show also the very marked effect of an electric field. It will be observed that when v_2/v_1 only slightly exceeds the critical value, a difference of potential of 160 volts entirely prevents the formation of drops. When the expansion is made larger a few drops are seen even in presence of the field ; the drops were found to increase in number as the expansion was increased. That some drops should be formed when the expansion considerably exceeds the critical value, even in presence of a strong field, is not surprising ; for the supersaturation when nuclei are few or absent will exceed the critical value for a finite time, the longer the greater the expansion. Any ions, set free while the supersaturation exceeds the critical value, will come into action as condensation nuclei and give rise to drops before the electric field has had time to remove them.

A difference of potential of 40 volts between the plates was found to reduce the number of drops formed on expansion to sensibly the same degree as 1000 volts. Even a potential-difference of two volts produced a noticeable diminution. In the older small-scale experiments, in which the distance between the plates was often considerably less than one cm., the strength of the field for a given difference of potential would be about five times as great as in the present experiments, and the maximum distance the ions had to travel only one-fifth as great; the effect of a given difference of potential in removing ions would then be much greater. It is possible that accidental differences of potential may in some cases have already largely reduced the number of ions present, so that the additional reduction following the application of much stronger fields was not noticeable. In the small apparatus also the number of ions present per c.c. in the absence of an electric field would be less on account of the much greater rate of loss of ions by diffusion to the walls of the vessel. The number of drops being small a larger share of water would fall to each, and they would fall too rapidly for variations in their number to be readily detected.

The total number of ions present when a steady state is reached, in the absence of an electric field, is such that the number of ions removed per second by recombination and by diffusions to the sides is equal to the number produced per second. On account of the small rate of production of ions, diffusion rather than recombination is in these experiments the more important factor in limiting the number of ions even with the large apparatus ; with the small apparatus the loss of ions by recombination is negligible in comparison with that due to diffusion to the walls. Let us assume, for example, that 40 ions of either sign are produced per second in each c.c. This is the rate of ionization deduced from leakage experiments in a small vessel of silvered glass*. (The number 20, given in the original paper, was deduced from the experiments by using J. J. Thomson's first value for the ionic charge, since shown by him and by H. A. Wilson to be about twice too large†.) If q be the rate of production of ions per c.c. per second, then the number of ions of either sign in each c.c., if loss by diffusion be ignored, will be given by

$$N = \sqrt{q/\alpha},$$

where α is the coefficient of recombination. Putting $q=40$, $\alpha=3{\cdot}3\times10^3\,e$ (where e is the ionic charge) and $e=3\times10^{-10}$ we have $N=6\times10^3$. If, on the other hand, we neglect the loss by recombination and consider only the loss by diffusion, then in a column of one sq. cm. in cross section extending from plate to plate and perpendicular to the plates, the number of ions when a steady state is reached is equal to $\frac{2}{3}\frac{q}{D}l^3$, where $2l$ is the distance between the plates and D is the coefficient of diffusion of the ions through the gas (J. J. Thomson, 'Electrical Properties of Gases,' p. 21). The average number for every c.c. of air between the plates will be

$$N=\frac{1}{3}\frac{q}{D}l^2.$$

For negative ions in moist air D is equal to 0·035‡. Thus when q is 40, $N=4\times10^2\,l^2$. In an apparatus with plates less than a centimetre apart, as in many of the older experiments, so that l is less than $\frac{1}{2}$, N is less than 100 per c.c. instead of the 6×10^3 obtained when only loss by recombination is considered: thus in this case the final number of ions is determined by diffusion, the loss by recombination being negligible. With the larger apparatus of the present paper $2l=5$cms., $N=4\times10^2\times2{\cdot}5^2=2{\cdot}5\times10^3$ when we consider only the loss of ions by diffusion. The loss by recombination is now no longer negligible, but the loss by diffusion is the more important factor; the total number of ions when a steady condition is reached will be less than the value obtained when either recombination or diffusion is ignored, it must be somewhat less than $2{\cdot}5\times10^3$ per c.c.

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* C. T. R. Wilson, Roy. Soc. Proc. vol. lxviii. p. 151.

† J. J. Thomson, Phil. Mag. vol. v. p. 346; H. A. Wilson, Phil. Mag. vol. v. p. 429 (1903).

‡ Townsend, Phil. Trans. A. cxcv. p. 259 (1900).

The value of q, the rate of production of ions, used above was deduced from measurements of the leakage of electricity through air contained in a small vessel of silvered glass. As a part of the effect is almost certainly due to a somewhat easily absorbable radiation from the walls, a smaller value of q is to be expected in a larger vessel such as that used in the experiment now described; q has, moreover, been shown by several observers to depend on the material of which the walls are composed. The experiments of H. L. Cooke*, who used a brass vessel of 1100 c.c. capacity, are more nearly comparable with those of the present investigation. The value of q found by him (without special shielding of the apparatus) was about one-third of the value used in the above calculations. If we use this value the effect of recombination becomes still less important in comparison with that of diffusion; and if we ignore recombination, the maximum number of negative ions in the absence of an electrical field, being proportional to q, is reduced to less than 900 per c.c.

I have not yet succeeded in making any direct determination of the number of drops actually produced on expansion. A superior limit to the number was, however, obtained indirectly by observing the rate of fall of the drops—the method adopted by J. J. Thomson in his determination of the charge carried by an ion. In this method of finding the number of the drops, the total quantity of water which separates out from each c.c. as a result of a given adiabatic expansion is calculated and assumed to be equally distributed among the drops; while the radius of the drops is obtained from the rate of fall by the use of Stokes' formula. When the drops are so few and the fall so rapid as in the present experiments, one cannot assume that they attain their maximum size; in other words, that sensibly all the available water is condensed upon the drops. The value found for the number of drops by dividing the total available water by the volume of each drop (as obtained from the rate of fall) will therefore be too high, but may be considered as a superior limit below which the actual number of drops really lies.

A series of observations, in which comparatively rough measurements of the time taken by the drops to fall were attempted, gave the following results. Expansions capable of catching all the negative ions produced drops all of which had fallen to the lower plate in less than three seconds; the temperature being 14° C. The distance between the

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* H. L. Cooke, Phil. Mag. vol. vi. p. 403 (1903).

plates, *i. e.* the maximum distance fallen, was 4·7 cms.; the rate of fall when negative ions alone came into action thus did not exceed 1·6 cm. per second. Treating these data in the manner described by Professor Thomson*, we find that the number of negative ions present, in the absence of an electric field, is less than 1000 per c.c.: this is in agreement with the value calculated above from the data afforded by leakage experiments.

LXXVI. *Escape of Gases from Atmospheres.*

To the Editors of the Philosophical Magazine.

GENTLEMEN,—

A LETTER under the above heading, by Mr. S. R. Cook in 'Nature' of the 24th of March, puts forward views which ought not to remain on record without reply; and as between 30 and 40 years ago I carried on the investigation into the rate at which gases can escape from atmospheres in the same way as Mr. Cook has done, and arrived from the premisses employed by him at substantially the same conclusions, perhaps the best answer will be to state the considerations which led me to distrust that line of argument, and finally to abandon it. To do this, however, requires more to be said than can be brought within the compass of a letter to a weekly journal; and on this account, and because the discussion is a physical discussion and concerns one of nature's greater operations, I venture to request for the following pages the hospitality of the Philosophical Magazine.

A study of the phenomena attending the escape of gases from atmospheres has been approached in two ways—*inductively*†, by arguing upwards from events which are found to have occurred or to be in process of occurring in nature; and *deductively*‡, by drawing inferences from the supposition that it is legitimate to attribute to the real gases of nature, behaviour which it has been ascertained would prevail in certain models of gas, so much simpler in their

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* 'Electrical Properties of Gases,' p. 121.

† "Of Atmospheres upon Planets and Satellites." By G. Johnstone Stoney, F.R.S. See Scientific Transactions of the Royal Dublin Society, vol. vi. p. 305 (October 1897); or Astrophysical Journal, vol. vii. p. 25 (January 1898).

‡ "On the Escape of Gases from Planetary Atmospheres according to the Kinetic Theory." By S. R. Cook. See Astrophysical Journal, vol. xi. No. 1 (January 1900).

"The Kinetic Theory of Planetary Atmospheres." By Professor G. H. Bryan, F.R.S. See Philosophical Transactions, A. vol. cxcvi. p. 1 (March 1900).