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THE CAPTURE OF IONS BY ICE PARTICLES

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Summary

The application of Wilson's process of ion capture by falling drops is extended to the case of ice particles, and it is shown how the results differ from those with water drops. Although ice particles in clouds can operate in Wilson's process, arguments are given against this being the agency by which the separation of charge occurs in clouds.

1. Introduction

Wilson (1929) first put forward the idea that drops of water, falling in an electric field, would become polarised and, under suitable conditions, could capture preferentially ions of one sign, thus acquiring a charge. Wilson suggested two applications of this idea in discussing the phenomena of atmospheric electricity; in the first place, he suggested that such a process might be important in the separation of charges within thunder clouds, for an existing field would be increased in certain circumstances; also, the process could account for the acquisition of charge by raindrops falling below a cloud. The detailed theory has been worked out by Whipple and Chalmers (1944) (referred to as "*W* and *C*"); the theory is applicable only to a spherical conductor.

The question as to whether ice particles can replace water drops in Wilson's process, and therefore whether Wilson's process can operate in clouds where the falling particles are ice, not water, has been discussed by Simpson and Scrase (1937) and by Wormell (1939). Simpson and Scrase rejected the possibility on the ground that the ice crystals are nearly perfect non-conductors and so do not become electrically polarised as would conductors, but Wormell pointed out that the crystals would become polarised as dielectrics.

It is the purpose of the present paper to develop the idea of the dielectric polarisation of ice crystals, and to work out the detailed consequences, thereby extending the results of *W* and *C* to ice, and making it possible to discuss in detail the role of Wilson's process in clouds where the falling particles are composed of ice, and also in the charges on snow, and on rain which has recently melted.

2. Polarisation of ice particles

When a dielectric is situated in an electric field, it becomes polarised, though rather differently from the polarisation of a conductor. Ice has a dielectric constant greater than unity, so that the polarisation charges are of the same sign as the charges which would be induced on a conductor of the same shape, though smaller in magnitude.

If an ice particle is situated in a vertical electric field, positive in sign (with the usual convention of atmospheric electricity that a positive field is one in which positive ions move downwards), it will carry a negative charge at the top and a positive charge at the bottom, the magnitude and distribution of the charge depending on the shape of the ice particle, the strength of the field and the dielectric constant of the ice.

In calculations, the dielectric constant of ice is required; most of the measurements quoted in International Critical Tables have been made with alternating potentials of various frequencies, and show variations with frequency and with temperature; the values given at low frequencies and for temperatures not far below the freezing point range from 60 to 90. The differences between the polarisation charges on conductors and dielectrics depend upon factors such as $\frac{k-1}{k+2}$ and $\frac{k-1}{k}$ and these can be taken as unity for values of k about 75. Thus the distribution of charge on an uncharged ice particle placed in an electric field is practically the same as that on a conductor of the same shape in the same field.

3. The capture of ions

The complete analysis of the trajectories of ions, as carried out in *W* and *C*, is not feasible for other shapes than the spherical, nor is it possible to deal with non-conductors, even spherical, by this method. There is, however, a simpler type of argument which yields the same results as *W* and *C* for the spherical conductor and which can be used in other cases.

As in *W* and *C*, we can consider negative ions, which move upwards relative to the body and are attracted to the positively charged lower part of the body; the positive ions, moving downwards in the field, may be moving faster or slower than the body. The terms "fast" and "slow" refer to the distinction between positive ions moving faster or slower than the body, and the same ions may be "fast" and "slow" in different fields. Fast positive ions move downwards relative to the body and are attracted to the negatively charged upper part of the body, but slow positive ions move upwards relative to the body and are repelled from the lower part; they can reach the negative upper part only if they get round the "dead space" see *W* and *C*, Figs. 2(c) and 4(c)).

The results in *W* and *C* can be obtained by making the following assumptions:

(*a*) Negative and positive ions are present in their normal numbers per unit volume when close to the oppositely charged parts of the body.

(*b*) The "dead space" for slow positive ions "protects" an area of the body carrying a negative charge equal to the positive charge on the lower part of the body.

(*c*) As in *W* and *C*, that the motion is streamline not turbulent.

From assumption (*b*) it follows that slow positive ions can only reach the body when it has a resultant negative charge, and in such cases assumption (*a*) applies and they are present in their normal number per unit volume.

A small positive charge δQ_1 on a small area δs gives a surface density of charge $\sigma = \frac{\delta Q_1}{\delta s}$ and near this a field $4\pi\sigma$. The rate at which negative charge reaches this area is $4\pi\sigma n_2 e w_2 \delta s$ per unit time, if there are n_2 negative ions per unit volume, each of charge $-e$ and mobility w_2. Thus the charge reaches the area at a rate

$$-4\pi n_2 e w_2 \delta Q_1$$

Integrating for all areas with positive charge:

$$\frac{dQ}{dt} = -4\pi n_2 e w_2 Q_1 = -4\pi\lambda_2 Q_1 \quad . \quad . \quad . \quad . \quad (1)$$

where λ_2 is the negative polar conductivity.

Similarly, for fast positive ions:

$$\frac{dQ}{dt} = -4\pi\lambda_1 Q_2 \quad . \quad . \quad . \quad . \quad (2)$$

But, for slow positive ions, there is the arrival of charge only when the resultant charge is negative and then:

$$\frac{dQ}{dt} = -4\pi\lambda_1(Q_1+Q_2) = -4\pi\lambda_1 Q \quad . \quad . \quad . \quad (3)$$

4. Application to a spherical conductor

Before it is possible to apply the assumptions of the last section to other cases, it is necessary to show that they yield the results of *W* and *C*.

A spherical conductor in a field X has a surface density of charge $\frac{3X\cos\theta}{4\pi}$ due to polarisation. If it also carries a charge Q, there is an additional surface density of charge $\frac{Q}{4\pi a^2}$, where a is the radius. Provided that Q lies between $\pm 3Xa^2$, the portion of the sphere between $\theta = 0$ and $\cos\theta = -\frac{Q}{3Xa^2}$ is positively charged, the rest being negative.

The total positive charge on the sphere is thus:

$$Q_1 = \int_{\theta=0}^{\cos\theta = -\frac{Q}{3Xa^2}} \frac{1}{4\pi}\left[\frac{Q}{a^2} + 3X\cos\theta\right] 2\pi a \sin\theta a d\theta = \frac{(Q+3Xa^2)^2}{4 \cdot 3Xa^2}$$

Using (1), $\dfrac{dQ}{dt} = -\dfrac{\pi\lambda_2 (Q+3Xa^2)^2}{3Xa^2}$

when negative ions alone are present. This is identical with *W* and *C* (11).

Similarly for fast positive ions, the result is *W* and *C* (18).

For slow positive ions, it is only the resultant charge Q, when negative, which can receive ions and thus, from (3):

$$\frac{dQ}{dt} = -4\pi\lambda_1 Q \text{ which is } W \text{ and } C \text{ (23).}$$

In the same way, when the whole sphere is positive, *i.e* when $Q > 3Xa^2$:

$$\frac{dQ}{dt} = -4\pi\lambda_2 Q \text{ which is } W \text{ and } C \text{ (16) and (26).}$$

Other results, such as *W* and *C* (25) and (27) can be obtained by combination of the results just deduced.

Thus the assumptions made can give the results of *W* and *C* in a very much simpler way than in *W* and *C*. This can be taken as justification for using the same assumptions in other cases, when the complete analysis of *W* and *C* is not applicable.

5. Distinction between conductors and non-conductors

Although the polarisation charges on a conductor and a non-conductor of high dielectric constant are practically the same when both are uncharged, a difference appears as soon as ions of one sign are captured by the body.

In the case of the conductor, the charge arriving is spread over the whole body and alters the position of the boundary between positive and negative charges; thus when negative ions arrive at the positive portion of the conductor, the area of surface carrying positive charge becomes less and so there is a decreasing area at which the negative ions can arrive.

But, in the case of the non-conductor, a charge arriving at the body cannot spread, but remains at the point where it arrives. Thus the area of surface carrying positive charge remains constant, while the positive charge itself diminishes.

When ions of both signs are arriving at a conductor, there can be a condition of "equilibrium" when equal numbers of ions of both signs are arriving and the conductor has a constant net charge; an example is that of *W* and *C* (30). But, for a non-conductor, the ions of each sign move to the oppositely charged parts of the body and tend to neutralise the charges present there, without spreading. The final result in the presence of ions of both signs is that all charges are neutralised and the body becomes uncharged.

6. Spherical non-conductors

The distinction between conductors and non-conductors is most clearly seen in the case of a spherical body, for which the results for a conductor are those of *W* and *C*.

An uncharged spherical non-conductor of high dielectric constant in a field X has a surface density of charge $\dfrac{3X\cos\theta}{4\pi}$ and the total positive charge on the lower hemisphere is $\dfrac{3Xa^2}{4}$.

If negative ions alone are arriving at the body, the rate of charging is given by (1) and so the initial rate of charging is $-3\pi\lambda_2 Xa^2$, agreeing with *W* and *C*, as would be expected since the conditions for conductor and non-conductor are the same when uncharged. The positive charge on the lower part of the body decreases exponentially according to:

$$Q_1 = Q_0 e^{-4\pi\lambda_2 t} \qquad (4)$$

finally reaching zero. When no positive ions are present, the upper hemisphere retains its negative charge of $-\dfrac{3Xa^2}{4}$, and this is the final charge on the sphere, one quarter of the resultant charge for the conducting sphere. When $Q_1 = \frac{1}{2}Q_0$ the sphere has half its final charge and the time taken for this is $t = \dfrac{\log_e 2}{4\pi\lambda_2}$ whereas *W* and *C* found the time taken for the conducting sphere to reach half its final charge to be $t = \dfrac{1}{\pi\lambda_2}$.

For fast positive ions, the results are exactly similar and need not be considered farther.

For slow positive ions, assumption (*b*) shows that the body can attract the ions only when it has a resultant negative charge. The total charge of a body in the presence of both negative and slow positive ions will be affected by: (*a*) the arrival of negative ions at the lower part, according to (1), and (*b*) the arrival of positive ions at the upper part according to (3).

Thus: $$\frac{dQ}{dt} = -4\pi\lambda_2 Q_1 - 4\pi\lambda_1 Q$$

Using (4): $$\frac{dQ}{dt} = -4\pi[\lambda_2 Q_0 e^{-4\pi\lambda_2 t} + \lambda_1 Q] \qquad (5)$$

This is of the same form as the equation for the rise and decay of a radioactive substance produced by a decaying parent (see Rutherford, Chadwick and Ellis (1930), p. 11).

The general solution is:

$$Q = -Q_0 \frac{\lambda_2}{(\lambda_1 - \lambda_2)}[e^{-4\pi\lambda_2 t} - e^{-4\pi\lambda_1 t}] \qquad (6)$$

In the particular case when $\lambda_1 = \lambda_2$, which corresponds to the assumptions made by *W* and *C*, this solution is not applicable and the solution is:

$$Q = -Q_0 \cdot 4\pi\lambda t e^{-4\pi\lambda t} \qquad (7)$$

and it can be seen that the total charge on the body rises to a maximum negative value of $-\frac{Q_0}{e} = -\frac{3Xa^2}{4e}$ at a time $t = \frac{1}{4\pi\lambda}$, and then decreases to zero. This is in striking contrast to the results for a conductor, given by *W* and *C* (28), (29) and (30), showing an approach to a final value of $-0{\cdot}515Xa^2$.

7. Non-conductors of other shapes

Ice particles which exist in nature are not spherical in shape except approximately in the case of hailstones, and so the preceding theory cannot hold as it stands.

As in the case of a spherical non-conductor, there will be a polarisation charge on either side of the body, negative on the upper and positive on the lower side in a positive field, the magnitude of the charges depending on the shape of the body and the strength of the field. If we consider an ice particle as a flat plate of area *A* lying horizontally then, neglecting edge effects, its polarisation charges are $\pm \frac{AX}{4\pi}$.

When negative ions only are present, the positive charge on the lower part diminishes according to equation (1) and the initial rate at which the ice particle acquires charge is $-\lambda_2 AX = -Ai_2$, where i_2 is the ionic current density carried by the negative ions. Edge effects would increase the effective area above the value *A*, but if the plate is inclined the effective area is diminished.

When ions of both signs are present, and the positive ions are "fast," then both polarisation charges diminish according to (1) and (2), and if the polar conductivities are equal, the body has no resultant charge at any time.

When the positive ions are "slow," we have the results (5), (6) and (7) as for the spherical body, but Q_0 is no longer $-\frac{3}{4}Xa^2$, but is $-\frac{XA}{4\pi}$ in the case of a flat plate. There is, however, still the rise to a maximum negative charge at a time $t=\frac{1}{4\pi\lambda}$.

When a flat plate of effective area A falls with a velocity V for a distance x, so that the charge is always small compared with $-\frac{XA}{4\pi}$ and when any positive ions present are "slow," the charge acquired is $-\frac{i_2Ax}{V}$, where i_2 is the negative ionic current.

8. Effect of overturning

An ice particle in the form of a flat plate is likely to overturn while falling, and the electrical effects of this must be considered.

As a flat plate overturns, it loses its polarisation charges and regains them with signs changed when the plate is upside down. But the charges that have been acquired from ions remain attached.

If negative ions alone are present, then the lower side of the plate will be acquiring negative charge according to (1), and if there is continual overturning, each side of the plate is the lower side in turn, and the final result is that each side of the plate finally acquires a charge of $-\frac{XA}{4\pi}$ and the resultant charge is twice that without overturning.

If there are negative and fast positive ions present in equal numbers, then there is never any resultant acquisition of charge and the overturning has no effect.

When there are negative and slow positive ions present, the matter is more complex. We now have to deal with the positive and negative charges separately instead of together, as in obtaining (6) and (7) from (5).

From (1) $\frac{dQ_1}{dt}=-4\pi\lambda Q_1$

so $Q_1=Be^{-4\pi\lambda t}$ . . . . (8)

where B is the value of Q_1 at $t=0$.

From (3) $\frac{dQ_2}{dt}=-4\pi\lambda(Q_1+Q_2)$.

The solution of this is:

$$Q_2=(C-4\pi\lambda tB)e^{-4\pi\lambda t} \quad \text{. . . . . (9)}$$

where C is the value of Q_2 when $t=0$.

If an ice particle overturns at intervals T, we can use (8) and (9) to calculate the charges before each overturning, and then we can bring in the change of sign of the polarisation charges to give the initial charges for the next period T.

If the value of $4\pi\lambda T$ is small compared with unity, the calculation can be made approximately. Let $4\pi\lambda t=y$.

Then (8) becomes $Q_1=B\left(1-y+\frac{y^2}{2}\right)$ . . . . . (10)

and (9) becomes $Q_2=(C-yB)\left(1-y+\frac{y^2}{2}\right)$ . . . . (11)

Suppose the polarisation charges are $\pm Q_0$, then for the first period, $B = Q_0$, $C = -Q_0$ and we get:

$$Q_1 = Q_0\left(1 - y + \frac{y^2}{2}\right)$$

$$Q_2 = -Q_0\left(1 - \frac{y^2}{2}\right)$$

giving a resultant charge of $Q_0(-y + y^2)$.

On overturning, each charge alters by $2Q_0$ and:

$$B = Q_0\left(1 + \frac{y^2}{2}\right)$$

$$C = -Q_0\left(1 + y - \frac{y^2}{2}\right)$$

After the next time T:

$$Q_1 = Q_0(1 - y + y^2)$$
$$Q_2 = -Q_0(1 + y - 2y^2)$$

giving a resultant charge of $Q_0(-2y + 3y^2)$.

On overturning we get:

$$B = Q_0(1 - y + 2y^2)$$
$$C = -Q_0(1 + y - y^2)$$

and after a time T:

$$Q_1 = Q_0\left(1 - 2y + \frac{7}{2}y^2\right)$$

$$Q_2 = -Q_0\left(1 - y - \frac{7}{2}y^2\right)$$

with a resultant charge of $Q_0(-3y + 7y^2)$.

Using the same methods, we get, for n overturnings, if n is even

$$Q = Q_0\left(-ny + \frac{3}{4}n^2y^2\right) \quad . \quad . \quad . \quad (12)$$

If n is odd

$$Q = Q_0\left(-ny + \frac{1}{4}(3n^2 + 1)y^2\right) \quad . \quad . \quad (13)$$

If we now put $y = 4\pi\lambda T$ and $nT = t$, the total time of fall, we get:

$$\left.\begin{aligned} Q &= Q_0\left[-4\pi\lambda t + \frac{3}{4}(4\pi\lambda t)^2\right] \text{for } n \text{ even} \\ \text{and } Q &= Q_0\left[-4\pi\lambda t + \frac{3}{4}(4\pi\lambda t)^2 + \left(\frac{1}{4}\frac{4\pi\lambda t}{n}\right)^2\right] \text{for } n \text{ odd} \end{aligned}\right\} \quad (14)$$

If we now expand (7) when $(4\pi\lambda t)$ is small, we get:

$$Q = Q_0[-4\pi\lambda t + (4\pi\lambda t)^2]$$

Thus if the overturning is fairly rapid and we are concerned with times small compared with the time $\frac{1}{4\pi\lambda}$ in which the charge reaches its maximum, we see that the charge on the particle is not far different from that which would occur in the absence of overturning. The condition that $4\pi\lambda t$ is small is the same as that the charge acquired is small compared with Q_0.

For a fall through a distance x, the charge acquired is $-\frac{Q_0 \cdot 4\lambda\pi x}{V} = -\frac{i_2 A x}{V}$ for a flat plate just as without overturning.

9. Application to conditions below clouds

The conditions below clouds differ according to whether there is or is not point discharge; when point discharge occurs, the ionic current is unidirectional and, in a positive field, consists of negative ions moving upwards; but when there is no point discharge, there are, in addition, positive ions moving downwards and these may be "fast" or "slow."

When there is point discharge, the ice particles receive charge according to (1), the initial rate being $-Ai_2$ for a flat plate; as discussed above, the charge obtained in falling through a distance x is $-\dfrac{i_2Ax}{V}$ if this is small compared with $-\dfrac{XA}{4\pi}$. As we have seen, overturning does not affect this approximate result. This result can be compared with the charge obtained by a spherical water-drop, namely $-\dfrac{3\pi i_2a^2x}{V}$ (W and C (15)) and it will be noticed that, for a drop of the same mass as a flat ice particle, the charge acquired is less for the water drop than for the ice particle because $3\pi a^2$ is less than A and V is greater for the drop. Thus we should expect snow flakes to acquire greater charges than rain drops, and when we enquire into the origin of the charges on rain drops it is necessary to consider what part, if any, of their fall below the cloud has been in the form of snow.

If there is no point discharge, and there are fast positive ions as well as negative ions present, then the discussion above shows that no resultant charge is acquired if the ionic currents of both signs are equal; but if the field is sufficiently large to cause the positive ions to be fast, then it is probably also sufficiently large to produce point discharge.

When there are slow positive ions as well as negative ions, the ice particles acquire negative charges, which they then lose if the time of fall is sufficiently large. For small times of fall, the negative charge gained by the particle is greater than that obtained by a water drop of the same mass.

Simpson (1942) has rejected Wilson's process as the origin of the positive charge on rain in a negative field (a change of sign all through as compared with the above discussion) on the ground that the distance through which the particles fall as rain is insufficient. It is possible that this difficulty can be overcome when it is realised that snow flakes can acquire charges by Wilson's process, and that the rate of charging is greater than for rain drops. Any test of this possibility must await the publication of actual rain charges and the simultaneous fields.

10. Application to conditions within clouds

The above discussion has shown that ice crystals can acquire charges by Wilson's process, under suitable conditions. But it remains to discuss whether these conditions hold within clouds, and whether the process can then give rise to a separation of charge.

Within clouds, it is probable that ions of both signs exist. Ice crystals can acquire charges from the negative ions (in a positive field), but may also acquire charges from positive ions. If the number of ions are equal, the crystals can acquire charges only if the positive ions are slow, and even then the above results show that there is a rise to a maximum charge, followed by a decrease to zero charge.

The theory that Wilson's process is responsible for the building up of a field in the cloud requires that the process shall still be operative when the field has been built up to values which approach the sparking potential. Macky (1931) has shown that, in the presence of water drops, sparking occurs when the field reaches 10,000 volts/cm. It is possible that sparking would occur at a lower field when sharp-pointed ice crystals are present. The field is certainly sufficiently large before sparking occurs for the small ions, of mobilities 1 to 2 units, to be "fast" as compared with the rate of fall of the ice particles, for this is achieved by a field of the order of 100 volts/cm. Thus, if small ions are present in clouds, the positive ions would be fast, and Wilson's process could not be effective.

There are reasons for belief that small ions may exist in clouds for a long enough time to affect the capture by Wilson's process. In the first place, a lightning flash must produce intense ionisation and some, at least, of these ions must be small ions; Nolan and O'Keefe (1930), supported by Macky (1931), have shown that small ions are certainly produced in discharges from water drops, such as might be taking place in clouds; if the discharges are from ice crystals, the same is likely to be taking place.

This discussion would suggest the rejection of Wilson's process as a factor in clouds solely on the ground of the probable presence of small ions. But it is desirable to investigate further the possibilities of Wilson's process in the case in which small ions may not be present.

Large ions have a mobility of the order of 1/500 unit, so that, in a field of 10,000 volts/cm., their velocity is only 20 cm./sec. and they will be slow compared with the falling ice particles. If we do not take vertical air currents into account, the ions will move upwards and downwards in the field, thereby tending to destroy the field. The most that Wilson's process can achieve in such circumstances is to bring down again the negative charges on some of the upward moving ions and thus to decrease the tendency to destroy the field. If, however, there is an upward air current of sufficient velocity to overcome the downward motion of the positive ions, but not to overcome the downward motion of the negatively charged ice particles, then there can be a separation of charge. The condition is thus that the upward velocity of the air shall be intermediate between the velocities of the positive ions and the ice particles; this condition must continue to hold as the field increases if the building process is to go on. As the field increases, the velocity of the positive ions increases, but if they are large ions this cannot rise beyond about 20 cm./sec.; also, as the field increases, there is an upward force on the negatively charged ice particles, opposing the gravitational force and thus decreasing their rate of fall.

The most favourable condition for the operation of Wilson's process in the building up of the field would be when a large proportion of the negative ions present are carried down by the ice particles and when there are few positive ions captured. The limiting case, which is never attained, would be that in which all the negative ions are brought down and all the positive ions are carried up in the stream; in such a case the current of separation of charge would be equal to the rate of production of ions within the volume affected.

Schonland (1932) has discussed the curves of recovery of field after a lightning flash and has pointed out that they lead to an initial current, after the flash, of about 4 amperes. Gish (1944) has suggested an area of active cloud of about 10 km.^{2}, and the height cannot be more than 10 km., so that the volume in which charge is produced is at most 10^{17} cm.^{2}. If charge is produced in this volume of sufficient amount to give 4 amperes by complete separation, the rate at which ions are produced must be about 250 per c.c. per second; this is very much greater than the normal production of ions by cosmic rays etc. at the same height, and the figure of 250 would be increased if not all the ions produced are separated, *i.e.* if some negative ions escape capture by the ice particles, or if some positive ions are captured. It must be realised that this current of 4 amperes is to exist during the whole building up of the field, from immediately after the preceding flash until the next flash. The curves of recovery show an exponential form which is interpreted similarly to the exponential recovery of a radioactive substance after chemical separation, as due to a constant rate of production of field and a dissipation proportional to the field. Immediately after a lightning flash, one might expect an increase of ionisation, owing to the ions produced by the flash, and when the field approaches the sparking potential again extra ions might occur from local brush discharges. But the recovery curves show a constant rate of production of field, and if this is due to Wilson's process, the above limiting condition of complete capture suggests that there must be a very considerable extra ionisation throughout the whole time of building up. It is difficult to suggest an origin for such ionisation, and so it is difficult to see how Wilson's process could operate to build up the field.

If the positive ions carry a current of 2 amperes and if the field is as high as the sparking potential of 10,000 volts/cm., the positive ion conductivity is 18×10^{-4} E.S.U.; assuming that negative ions are present in equal numbers with the positive ions, the ice particles would reach their maximum negative charge in a time of about 1 minute, and the time would be very much less for smaller fields. Now an ice particle falls inside the cloud for a time which is very much greater than 1 minute and is more likely to be of the order of 100 minutes if the cloud is 10 km. thick. The charge on the ice particle would then have had time to fall to a small value, according to (7) and so could give no appreciable separation of charge.

Even supposing that the previous objections can be overcome, there is yet another difficulty in the way of accepting Wilson's process as the agent of separation of charge. Immediately after a lightning flash, there must be only a very small field and so, even though there may be a great number of ions, the polarisation of the ice particles will be small, and they cannot attain greater negative charges than $-\frac{XA}{4\pi e}$, proportional to X. Thus the maximum current which can be carried by the ice particles is proportional to the field, and so the rate at which the field is built up would be, at first, proportional to the field, giving initially a parabolic law of field against time, instead of the exponential law which is initially linear as actually found.

Thus, although Wilson's process can operate with ice crystals there are many arguments against it being the agency by which the field is built up in clouds; these can be summarised as the probable existence of small ions in clouds, the difficulty of an origin of the necessary number of large ions, the long time of fall of ice particles which would thus lose any charge they had acquired and the fact that the recovery of field would give a law different from that found by observation.

It may be pointed out that the above difficulties do not arise if the process of separation of charge is one which gives the ice particles their negative charge directly, for example the process of ice friction suggested by Simpson and Scrase (1937). It may be considered that the process is going on through a considerable thickness of the cloud, and so a single ice particle may acquire negative charges a number of times at different heights. Since there will be positive charges present, which rise in the vertical air current, we shall have the condition of slow positive ions, which will be captured by the negative charges of the ice particles, thus reducing these charges. For the same reasons as have been discussed for conditions below clouds, the ice crystals are more effective in Wilson's process, weight for weight, than are water drops, and this conclusion agrees with the calculations of Chalmers and Little (1940) who pointed out that the loss of charge of falling particles within the cloud would have to be greater than could be produced by Wilson's process with water drops.

A complete theory of the generation and movement of the electric charges in clouds would have to take into account the effect of Wilson's process on the charges carried by ice crystals but it is unlikely that this is a major factor in the process of separation of charge.

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A micro-climatological investigation of Bath: continuation of reply to discussion by Messrs. Balchin and Pye (*communicated*), from p. 323.

reading. It is clear from the text that it is not the operation of any of the factors that go to make up the general temperature lapse rate but the effect of the lapse rate *itself* that is claimed can affect the temperature in the locality with available height differences of some 650 feet.

The interest stimulated by the paper is very encouraging and it is hoped to consider many of the other suggestions made this evening in future contributions.