A laboratory study of the inductive theory of thunderstorm electrification

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Summary

The individual charges transferred when supercooled water droplets or ice spheres collided with an artificial hailstone in the presence of an electric field have been measured in order to check the theoretical predictions of the inductive theory of thunderstorm electrification. The inductive theory equation was found to be obeyed for 100 μm supercooled water droplets, but droplet transit time measurements suggested that separation only occurred following equatorial collisions with the smooth hailstone. This greatly limits the maximum charge that the hailstone can carry, and so, if rougher natural hailstones behave in a similar manner, this process is not thought to be significant in thunderstorm electrification.

The charge transfer measured when 100 μm diameter ice spheres collided at 8 m s⁻¹ with a hailstone was affected by the presence of radial fields, but the change was less than that predicted by the inductive theory. The charge transfer was independent of temperature between −5°C and −25°C although the conductivity of ice varies greatly over this range. The effect of the field was to broaden the histograms of charge transfer rather than shift them as a whole to greater or lesser values and the charge transfer was not symmetrical under the influence of positive and negative fields of the order of 100 kV m⁻¹. These facts make the field-dependent charging results difficult to explain purely in terms of the inductive effect.

1. Introduction

There is no general agreement on the mechanism responsible for the electrification of thunderstorms, but the inductive theory has recently been favoured by many workers in the field (Mason 1972; Ziv and Levin 1974). This theory was originally suggested as a method of charge separation in thunderclouds by Elster and Geitel (1913) for water drops, and was developed by Müller-Hillebrand (1954) and Latham and Mason (1962) for ice particles. The essence of the theory lies in the suggestion that a cloud particle (radius, \(r_c\)) colliding with the underside of an uncharged precipitation particle (radius \(r_p\)) polarized in an electric field \(E\) should separate charge of magnitude proportional to the field strength, and of such a sign that separation of the particles under gravity will serve to reinforce the field (Fig. 1).

The inductive theory is an attractive one because of this inherent positive feedback between charge separation and field strength. It is shown in section 2 that the charge transfer \(q\) per interaction if the larger particle has charge \(Q_B\) is,

\[
q = \left(\frac{\pi^3}{6}\right)(r_o^2/r_p^2)(12\pi\varepsilon_0 r_p^2 E \cos \phi + Q_B)[1 - \exp(-T/\tau)]
\]

where \(T\) is the contact time, \(\phi\) the angle of contact between the direction of field and the radius to the point of contact, \(\tau\) the electrical relaxation time, and \(r_b \gg r_o\).

Because it is likely that water droplet–raindrop collisions result in permanent coalescence when the field exceeds 25 kV m⁻¹ (Jennings 1975), interactions involving the ice phase seem to be the most likely candidates. Aufermaur and Johnson (1972) showed that a fraction (typically 1 in 1000) of supercooled droplets, colliding with a hailstone in the presence of an electric field, separate after a collision and transfer charge in accordance with Eq. (1). However, they suggested that separation events probably occur after glancing collisions close to the equator (\(\phi\) about 90°, \(\cos \phi\) about 0) although higher angle separations could not be ruled out.

Moore (1976) has pointed out that in subsequent collisions with hailstones the drop-

* Following Dr Gaskell's death in March 1980 this paper has been adapted from his Ph.D. thesis by A. J. Illingworth.
Figure 1. Inductive charging for spheres. A small sphere of radius $r_s$ collides with a larger sphere of radius $r_n$ in the presence of an electric field $E$. Positive charge is carried away by the small sphere causing the neutral zone to migrate downwards. Small spheres colliding above the neutral zone will carry away negative charge.

Icets are likely to coalesce thus short-circuiting the process. This difficulty does not arise for interactions between ice crystals and hailstones because separation nearly always occurs. If the rebounding probability is constant over the whole of the underside of the hailstone, then assuming geometrical sweep-out the average value of $\cos \phi$ in Eq. (1) will be $2/3$. However, because the conductivity of ice is low, it is not obvious that the electrical relaxation time, $\tau$, is less than the contact time, $T$. The theoretical aspects will be discussed in section 2; we now review the experimental evidence.

Latham and Mason (1962) drew crystals of $50 \mu m$ diameter past an ice-coated cylinder at velocities in the range 1-30 m s$^{-1}$ and found that an electric field of 70 kV m$^{-1}$ had no effect on the charging. Aufermaur and Johnson (1972) allowed 100 $\mu m$ diameter ice spheres to collide with an ice cylinder at impact velocities of 10 m s$^{-1}$ and found charging of the order of 50 fC per collision; the charging was independent of the applied field. In a similar experiment Buser and Aufermaur (1977) allowed ice spheres, with an average diameter of 20 $\mu m$, to collide with ice and metal cylinders in the presence of radial fields in excess of 1 MV m$^{-1}$. The ice–metal collisions showed field dependent charging, while the ice–ice collisions showed a similar trend but with a magnitude much smaller than that predicted by Eq. (1). However, because of the large spread in their results, with ice–ice collisions, the experiment must be considered as inconclusive.

Marshall (1976) drew 10 $\mu m$ diameter particles past an ice cylinder, in the presence of a
linear potential gradient, and found field-dependent charging the magnitude of which was comparable with that predicted by theory but of an opposite sign. This effect could be explained if the ice crystals slid round the ice cylinder before separating, rather than making a bouncing contact. The ice crystals in the experiment would be charged, due to collisions with the walls of the wind tunnel, and increased collection efficiency for one sign of charged crystal, under the influence of the electric field, is a possibility. The experiments of Scott and Levin (1970) show that inductive ice–ice charting does occur for large 1 mm diameter natural ice crystals colliding with 2.5 cm diameter ice-coated spheres at low velocities of about 1 ms\(^{-1}\), but these very long contact times are unlikely to occur widely in clouds.

Because of this inconclusive evidence a series of laboratory experiments was undertaken to measure the field-dependent charge transfer when cloud particles collided with simulated hailstones. It was felt that by looking at individual collisions some of the difficulties, identified above, of uncertain collection efficiencies, concentrations and size distributions could be avoided, and also that any charges on the small cloud particles before collision could be monitored. The work forms an extension of the study by Gaskell and Illingworth (1980), who concluded that in the absence of an external electric field the ice–ice charge transfer was proportional to the area of contact during the collision, with the charge carriers probably resident on the surface of the ice at the contact interface. The results were consistent with the two ice surfaces having different surface potentials or ion densities, with thermal effects not playing a direct role.

In a natural cloud the ice–ice collisions of interest will be those between hailstones and vapour-grown crystals. Because of the difficulty of making and manipulating individual large vapour-grown crystals, ice spheres formed by freezing liquid droplets were used in this study. In the earlier work of Buser and Aufdermaur (1977) and Gaskell and Illingworth (1980) frozen droplets were also used.

2. Theory

Previous theoretical treatments of the inductive mechanism (Latham and Mason 1962) have treated the problem electrostatically. Because of the critical time constants involved in the ice–ice interactions we now derive the solution as a function of time.

To estimate the amount of charge separated in a precipitation-cloud particle interaction, first consider the case of two conducting spheres, radii \(r_a\) and \(r_b\), carrying charges \(Q_a\) and \(Q_b\) respectively, with no impressed field. The potentials of the spheres with these charges \((V_a\) and \(V_b\)) can be calculated using the coefficients of potential of the spheres, \(P_{aa}, P_{ab}, P_{ba}\), and \(P_{bb}\), defined as follows:

\[
V_a = P_{aa}Q_a + P_{ab}Q_b
\]
\[
V_b = P_{ba}Q_a + P_{bb}Q_b
\]

If the spheres are brought into contact, then the charge will redistribute itself so as to equalize the potentials. The instantaneous current will be given by the potential difference divided by \(R\), the resistance between the two spheres:

\[
dQ/dt = \{(P_{aa} - P_{ab})Q_a + (P_{ab} - P_{bb})(Q - Q_a)\}/R
\]

where \(Q\) (that is, \(Q_a + Q_b\)) is the total charge.

The equation may be solved for the case where \(Q_a\) is initially zero to give:

\[
Q_a(t) = KQ\{1 - \exp(-t/\tau)\}
\]
where $K = (C_{aa} + C_{ab})(C_{aa} + 2C_{ab} + C_{bb})$, and $\tau = R(C_{bb}C_{cc} - C_{bb})/(C_{aa} + 2C_{ab} + C_{bb})$ and the coefficients of capacitance $C_{aa}$, $C_{ab}$, $C_{ba}$ and $C_{bb}$ are defined by

$$Q_a = C_{aa}V_a + C_{ab}V_b$$
$$Q_b = C_{ba}V_a + C_{bb}V_b.$$  \hspace{1cm} (5)

If $r_a \ll r_b$ then, from the properties of the coefficients of capacity (Russell 1909), $K$ becomes equal to $(\pi^2/6)(r_a^2/r_b^2)$ and the solution can be considered as that of a sphere placed on a plane carrying a surface charge density, $\sigma$, given by $Q_b/4\pi r_b^2$.

If the spheres are in a potential gradient then the charge density at any point $p$ on the surface of the large sphere, the radius to $p$ being at an angle $\phi$ with respect to the direction of field, is equal to:

$$\sigma(\phi) = 3\varepsilon_0E\cos\phi + Q_b/4\pi r_b^2.$$ \hspace{1cm} (6)

where $E$ is the field strength and $\varepsilon_0$ is the permittivity of free space.

Finally, the charge transferred when a small sphere collides at the point $p$, with a much larger sphere, carrying a charge $Q_b$ in the presence of an electric field $E$ is,

$$q = (\pi^2/6)(r_a^2/r_b^2)(12\pi\varepsilon_0r_b^3E\cos\phi + Q_b\{1 - \exp(-T/\tau)}$$ \hspace{1cm} (7)

where $T$ is the contact time.

The Hertzian theory of collisions between elastic spheres (Tabor 1951) predicts that a small sphere of radius $r_a$ will remain in contact with a much larger sphere for a time given by:

$$T = 5.1r_a\{V^{-4}\rho(1 + \alpha)(1 - \gamma^2)E^{-1}\}^{2/5}.$$ \hspace{1cm} (8)

where $V$ is the impact velocity, $\alpha$ is the ratio of impact to rebound velocities, and $\rho$, $\gamma$, $E$ are the density, Poisson’s ratio and Young’s modulus of the spheres respectively.

Substitution of the appropriate values for ice predicts that a 100 $\mu$m diameter sphere will remain in contact with the large sphere for approximately 0.3 $\mu$s. No measurements for $\alpha$ exist, but even a value as high as 10 instead of 1 will only increase $T$ by a factor of 2. It should be noted that the above calculation takes no account of aerodynamic forces on the spheres, or adhesive forces known to exist between them. Thus in practice the contact time will be longer than 0.3 $\mu$s.

The conductivity of pure ice at $-10^\circ$C is of the order of $10^{-7}\Omega^{-1}\text{m}^{-1}$ for the bulk and $10^{-10}\Omega^{-1}$ for the surface (Jaccard 1967). If the static relative permittivity is taken to be 100 this results in a relaxation time for redistribution of charge in bulk ice of about 10 ms. The corresponding relaxation time, $\tau_\sigma$, for the surface depends on the thickness of the anomalous conducting layer. This thickness is not known, but Fletcher (1968) has estimated the thickness of a liquid-like layer on the ice surface to be the order of 2 nm. If this layer is identical with the anomalous conducting layer then $\tau_\sigma$ is found to be of the order of 20 ns. This value gives the relaxation time for the redistribution of charge in the conducting layer. We still need to estimate the value of $\tau$ in Eq. (7) to arrive at the relaxation time for charge transfer between the spheres.

The capacitance between the spheres when the gap $z$ between them is small can be calculated from the equation given by (Russell 1909),

$$C = C_{ab} = 4\pi\varepsilon_0r_a\{\gamma + \ln(2r_a/z)\}.$$ \hspace{1cm} (9)

where $\gamma$ is Euler’s constant, 0.5572. To calculate the capacitance between two ‘touching’ spheres we follow the method used by Harper (1967) who took $z$ as the thickness of the
charge layer, which is difficult to calculate, but is not critical because of the logarithmic
dependence. The constriction resistance between the spheres can be estimated by consider-
ing the resistance of an annulus, of inner radius equal to the radius of contact, and outer
radius equal to the distance from the centre of contact to the point to which the charge
carriers flow. This value again turns out to be non-critical and can be taken, reasonably, as
the radius of the smaller spheres,

\[ R = (1/2\pi\lambda_s)\ln(r_a/r_c), \]  

(10)

where \( r_c \) is the radius of contact and \( \lambda_s \) the surface conductivity. If we take the value of \( z \) as
2 nm, \( \lambda_s \) as \( 10^{-10}\Omega^{-1} \), \( r_a \) as 50 \( \mu \)m and \( r_c \) as 10 \( \mu \)m then, the resulting time constant is
100 \( \mu \)s. This time constant is much longer than the theoretical contact time, suggesting that
the inductive mechanism would not operate for ice-ice interactions under atmospheric
conditions. In view of the idealized nature of the theory the experimental evidence is

3.1. THE EXPERIMENTAL APPARATUS

The experimental apparatus comprising a droplet generator, a freezing section and a
wind tunnel containing a cylindrical hailstone is described in detail by Gaskell and Illing-
worth (1980). For this series of experiments the rimming tube was removed and, as in Aufder-
marm and Johnson (1972), an additional series of rings placed just above and below the
target so that an electric field could be impressed on the hailstone surface as shown in
Fig. 2. A radial field could be formed at the target by applying equal voltages, \( V \), to the
field rings. The uniformity and calibration of this arrangement was checked using conduct-
ing paper. The surface field was estimated to be \( (\sim -0.2 V) kV m^{-1} \) (similar to Buser and
Aufdermaur 1977) with a variation of \( \pm 10\% \) over the surface. In an attempt to create a
linear field at the target the field rings were raised to equal but opposite voltages but the
results from this arrangement were not felt to be reliable (see section 3.2). As in the earlier
study the induction rings and the hailstone target were connected to a sensitive charge
amplifier with a rapid rise time but having a 12 ms decay time constant, thus a charged
particle passing through the ring gave a 2 ms symmetric pulse, but when charge was gained or
lost by the target a step followed by a 12 ms decay was observed. If, after colliding with the
target, the charged particle passed through the lower ring then a second independent check
of the charge transfer was available. This check was not possible for ice crystals which,
after collision with the target, bounced onto the wind tunnel wall and received spurious
charge. Some of the charge waveforms when ice spheres collided with the target were
complex, probably due to multiple collisions after spheres rebounded into the airstream. As
in the earlier paper only unambiguous simple waveforms were included in the analysis.

Unless mentioned otherwise, all experiments were carried out using cloud particles of
100 \( \mu \)m diameter, impacting at 8 m s\(^{-1}\) on the hailstone at a temperature of \(-10^\circ\)C.

3.2. FIELD DEPENDENT DROPLET-HAILSTONE INTERACTIONS

Water droplets of 100 \( \mu \)m diameter were produced from freshly de-ionized water of
100 \( \mu \)m\(^{-1}\)1 m\(^{-1}\) conductivity, at a rate of one per second and allowed to collide with the
hailstone, manufactured from the same water sample, at a velocity of 8 m s\(^{-1}\).

As the droplets carried a small charge of approximately 5 fC it was possible to monitor
them as they passed through the measurement section. It was found that all droplets
generated passed cleanly through the wind-tunnel, in the absence of a hailstone, without
interaction with the tunnel wall. When a smooth 4 mm diameter hailstone was introduced into the wind-tunnel, the majority of droplets collided with the hailstone causing 12 ms duration output pulses from the amplifier. After a collision event in the absence of an electric field no charge was measured at the lower induction ring. These results are consistent with those of Aufdermaur and Johnson (1972).

When equal voltages were applied to both field rings, producing a radial field, approximately 10% of the droplets separated charge, which was measured at the hailstone and correlated with the charge measured at the lower induction ring. A small fraction of the separation events at the hailstone had no counterpart at the lower induction ring. This may have been caused by the droplet colliding with the wind-tunnel wall, because of turbulence in the wake of the hailstone, before reaching the lower induction ring. No anomalous charging of the target was observed for these cases.

Figure 3 shows the average charge separated at the hailstone, after correction for the small initial charge on the droplets (5 fC), for different values of electric field. The straight line is derived from Eq. (1) for spheres of 100 μm diameter colliding with a plane which has a field $E$ at its surface. It can be seen that there is excellent agreement between the average measured values and the theoretical values. Figure 4 shows a histogram of the charges.
Figure 3. Graph of the average charge transferred to the hailstone against applied field when 100 \( \mu \text{m} \) diameter droplets collided with the hailstone, at a velocity of 8 m s\(^{-1}\) and at a temperature of \(-10^\circ\text{C}\).

Figure 4. Histogram of the charges transferred to the hailstone when 100 \( \mu \text{m} \) diameter droplets collided with the hailstone, at a velocity of 8 m s\(^{-1}\) and at a temperature of 10°C, in the presence of an applied radial field of \(-10 \text{kV m}^{-1}\).
separated in one of the experiments with a surface electric field of $-10 \text{kV m}^{-1}$. There is a considerable spread of values, with the maximum charges being in excess of the theoretical predictions. However, the theoretical equation is derived for a perfect sphere while the actual charge separated will depend on the shape of the droplet just before the contact breaks.

As the droplets carried a small charge it was possible to measure the time of transit between the hailstone and lower induction ring, by use of the storage oscilloscope, for both separation events and for droplets which passed close to the hailstone without contact. It was found that the transit time varied between 13 and 14 ms, with no discernible difference between collisional and non-collisional events. Thus it appears that the charging events occurred when a droplet made a grazing collision with the hailstone, with very little retardation of the droplet occurring in the interaction. Experiments with ice spheres, to be described later, showed considerable delays after interaction. These findings are different from those of Aufdermaur and Johnson (1972) who found, in their experimental arrangement, that the transit time for collisional events were delayed by several milliseconds. The reason for the above discrepancy between the two sets of experiments may be found in the fact that Aufdermaur and Johnson used a hailstone which was formed by riming as the experiment progressed, thus producing a rough hailstone with many fine protrusions, while in the above experiments a smooth hailstone was used. This fact may also explain the greater fraction of separation events found in the present experiment.

Measurements of charge separation, when equal but opposite voltages were applied to the field rings, indicated that the droplets separated, after a collision, from the far side of the hailstone at a point well below the equator. These results appeared to be suspect as the transit time measurements showed that negligible delay occurred during the collision separation process. The results could be explained if the zero equipotential did not lie along the hailstone equator. This conclusion was verified by increasing the time constant of the hailstone charge amplifier to several seconds and observing the D.C. level output when the field voltages were applied simultaneously. In this manner it was found that a net charge was induced on the hailstone. This non-linearity of the field was probably caused by the resistance of the Tufnal measuring section varying along its length between the field rings. Thus it was felt that information about the contact points from which separation events occurred could be deduced more reliably from the transit time measurements.

The above experiments confirm the results of Aufdermaur and Johnson (1972) in that a fraction of water droplets colliding with a hailstone separate charge, in an electric field, of a magnitude consistent with that predicted by the inductive theory. Both sets of experiments indicate, from transit time measurements, that the separation events occur after glancing collisions close to the equator of the hailstone ($\phi$ about 90\(^\circ\) in Eq. (1)) which would predict only a small charge separation in a linear vertical field. Thus it seems unlikely that water droplet/hailstone interactions will play a prominent role in the electrification of thunderclouds. Arguments for and against the process have been presented by Mason (1976) and Moore (1976).

3.3. **Field Dependent Ice–Ice Interactions**

The experiments discussed below investigated the magnitude and the sign of the charges separated when 100 \(\mu\text{m}\) diameter ice spheres collided with smooth artificial hailstones. Because of difficulties in arranging a truly linear field (see section 3.2) the experiments were restricted to radial electric fields, produced by applying equal voltages to the field rings.
Figure 5. Histograms of the charges transferred to the hailstone when 100 μm diameter ice spheres collided with a smooth cylindrical hailstone, at a velocity of 8 m s⁻¹, and at a temperature of −10 °C, in radial fields which were incremented by 40 kV m⁻¹ from zero to −200 kV m⁻¹ (A) and zero to +200 kV m⁻¹ (B).
Figure 5 shows histograms of the charge transfer measured with fields of up to \( \pm 200 \text{ kV m}^{-1} \) (a positive field was defined as one which induced positive charge at the surface of the hailstone). The field was increased in steps of \( 40 \text{ kV m}^{-1} \), and between each field change the charge separations with zero field were measured again. The effect of the applied fields was to broaden the histogram rather than to shift the histogram as a whole towards lesser or greater charges. It can also be seen that the effect of the fields was not symmetrical, the change in average charge transfer for a field of \( -80 \text{ kV m}^{-1} \) being approximately four times greater than the corresponding value for a positive field of the same value. The negative charging occurring in the absence of a field is discussed in Gaskell and Illingworth (1980).

It was not possible to observe directly events in which an ice sphere collided with the hailstone and separated zero charge, but this appeared to be a very rare occurrence, as a charge measurement at the lower induction ring was nearly always preceded by an event at the hailstone. In contrast to the situation with supercooled water droplet experiments, the magnitude of the charge measured at the lower ring was not generally consistent with the values detected at the upper ring and the target; most of the ice spheres appeared to be charged on collisions with the wind-tunnel after rebounding from the hailstone, and so the signal at the lower ring could not be used as an independent check of the charge transfer measured at the target.

The histograms gradually broaden with increasing field, a maximum charge of \(-40 \text{ fC}\) being measured at a field of \( 200 \text{ kV m}^{-1} \). The histogram for negative fields shows that for each increase in magnitude of the field, a greater percentage of the events charged the hailstone positively and the positive section of the histograms become broader. At a field strength of \(-200 \text{ kV m}^{-1}\) the maximum charges transferred to the hailstone were \(+47.5 \text{ fC}\), which is of a similar magnitude to the maximum charges transferred with a field of \(+200 \text{ kV m}^{-1}\). In fact there is a similarity between the positive and negative field histograms at the higher field values, which suggests that the charge transfer mechanism behaves symmetrically under the action of these higher fields. This suggestion can be seen more clearly in Fig. 6 which displays the effect of electric field on the average charges transferred. The gradient of the line extrapolated through the average values reduces at high negative fields, approaching a value similar to that for the positive fields. The charge transfer predicted by the inductive effect is also shown in the figure.

The enigmatic role of surface conductivity in the inductive charging mechanism has been discussed in section 2. As the surface conductivity is temperature dependent (Jacquard 1967; Maeno 1973) an experiment was performed to investigate field dependent charging over a range of temperatures from \(-5^\circ\text{C}\) to \(-25^\circ\text{C}\). The experiment was conducted by measuring the charges separated with zero, \(100 \text{ kV m}^{-1}\) and \(-100 \text{ kV m}^{-1}\) fields, at a particular temperature. The wind-tunnel was then switched off, to prevent excessive sublimation of the hailstone, while the cold-room was cooled to the next temperature; the experiment was then repeated. There was no significant variation of either field or non-field-dependent charging, over the temperature range measured.

4. **Discussion of results and conclusion**

When supercooled droplets collided with and separated from a hailstone in the presence of an electric field, the charge transfer was found to be in agreement with the inductive theory prediction. However, measurements of the transit time of the water droplets indicated that only glancing collisions were followed by separation and so the maximum charge that a hailstone can acquire by this mechanism is very small and is thought to be unimportant inside thunderstorms.
Figure 6. A combined graph of the average charge transferred against field for the results in Fig. 5. The full line shows the charge transfer predicted by the inductive effect when 100 μm diameter spheres collide with a plane which has a field $E$ at its surface.

The charge transfer measured when ice spheres collided with a hailstone in the presence of radial fields was found to be independent of temperature between $-5^\circ C$ and $-25^\circ C$, the histograms were broadened rather than shifted as a whole to greater or lesser charges and the charge transfer was not symmetrical under the influence of positive and negative fields of the order of 100 kV m$^{-1}$. These facts make the field dependent charging results difficult to explain purely in terms of the inductive effect, as described in section 2.

In the absence of a field Gaskell and Illingworth (1980) proposed that charge flowed from one ice surface to another because of a difference in surface potential of the two ice surfaces. They further suggested that the charge carriers present at the contact interface were the ions of Fletcher’s (1968) liquid-like layer on the surfaces of the ice. The action of an external field will be to alter the surface charge density of the two approaching ice surfaces.

Henry (1956) has considered the redistribution of ions which are attached to two surfaces but which have different energies and concentrations on each, when the two surfaces are brought into contact. He showed that the charge transfer per unit area of contact is given by:

$$
\sigma = \left(\varepsilon_0/Z_c\right) \left[ \Delta V_c - \left( kT/\varepsilon \right) \ln \left( \left[ \sigma_A - \sigma \right]/\left[ \sigma_B - \sigma \right] \right) \right] .
$$

(11)

where $\Delta V_c$ is the difference in potentials at cut-off distance $Z_c$ for ions crossing the gap, and $\sigma_A$ and $\sigma_B$ are the initial number of ions per unit area on the surfaces $A$ and $B$.

The first term in Eq. (11) is the charge transfer due to differences in the binding energy of the ions on the two surfaces, and the second term expresses the diffusion of charge from one surface to another if the ion abundancies are different. In the absence of a field $\sigma_A$ equals $\sigma_B$ we consider the first term only; if the radius of contact is 10 μm and 12 fC of charge are transferred then $\sigma$ is about $3 \times 10^{-4}$ C m$^{-2}$. The action of an external field will have a negligible effect on $\Delta V_c$ but will make the second term in Eq. (11) non-zero. A field of
100 kV m\(^{-1}\) should change \(\sigma_A\) and \(\sigma_R\) by \(\pm 10^{-6} \text{ C m}^{-2}\), which is only a small fraction of the existing charge surface charge densities, and so it is difficult to explain the experimental points in Fig. 6 quantitatively in terms of Eq. (11). At present we can only conclude that the results are not explicable in terms of the inductive mechanism.

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