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A new electrometer specially arranged for radio-active investigations. Part I, in:
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Physics. - - "*A new electrometer, specially arranged for radio-active investigations*". Part I. By Miss H. J. FOLMER. (Communicated by Prof. H. HAGA).

(Communicated in the meeting of May 30, 1914).

Introduction.

In trying to find an accurate method for measurements of the natural ionisation of air in closed vessels, radio-active radiation of the elements, etc., researches in which very small ionisation currents are to be measured, it seemed to me that the need is felt of an electrometer, which, besides possessing a great sensibility of charge, will also be able to measure very minute currents with *accuracy*.

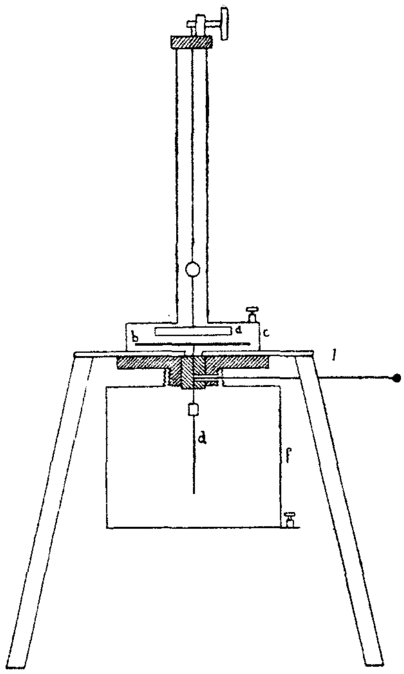
As to the mentioned conditions, the latter is fulfilled by C. T. R. WILSON's electroscope (the gold-leaf type), which owes this favourable quality to the very simplicity of the system; this namely renders it possible to bring about the ionisation which is to be measured, in the air contained in the apparatus itself, to avoid connecting wires, together with electrostatic and other influences, the disturbance caused by insulators being confined to that of a single one. In my opinion this is the reason that this electroscope is generally preferred for various measurements requiring great accuracy to say a sensitive DOLEZALEK electrometer, which lacks these advantages, notwithstanding the fact of a much greater sensibility of charge of the latter; in consequence of this *sudden* changes in the natural ionisation of air in closed vessels, for instance, the existence of which is accepted by many investigators, cannot manifest themselves clearly when the electroscope is used; moreover measurements of small currents will take much time.

This has led me to construct an electrometer, the principle and the method of working of which I shall discuss in what follows, and which in my opinion can supply the mentioned need. It appeared from the results obtained, that with this apparatus currents can be measured both very accurately and very sensitively; accordingly it seems to me, that for these reasons the apparatus may be very suitable for various radioactive researches requiring the above mentioned qualities, as was also corroborated by experience.

Description of the principle of the apparatus.

In the figure a schematic representation of the arrangement is given [1]); the apparatus consists of:

[1]) An accurate description of the apparatus will follow in a 2nd communication.



two separate spaces, viz. the measuring space c: a flat brass cylinder, and the ionisation space f: a brass cylinder of volume 1 litre; the two cylinders are insulated from each other by ebonite.

In the measuring space is the metal needle b, supported in the middle by a second metal needle d, insulated by amber; $b + d$ together form the conductor, which is charged by the ionisation current.

In c is also found the very thin aluminium strip a, which a few mm. above b is fastened to a thin metal rod with mirror, suspended on a Wollaston wire, which is fastened to a torsion head insulated by means of ebonite.

Through a perforation in the amber and in the ebonite a rod l can be brought in contact with the needle d.

In this way a, $b + d$, c, and f, can therefore be separately brought in a conductive connection with a storage battery or with earth; c rests on a bottom plate, to which legs are fastened which support the apparatus.

The charging of the apparatus before use.

In what follows we shall examine from the course of the lines of force, what state arises in the space c, and how this takes place, when the system is charged: the lower cylinder f is of no account as regards this, as it does not belong to the measuring system proper.

The method of charging is founded on this that the two needles a and b, which with untwisted position of a form an angle, let us say of 30°, will *still* have this position with respect to each other, when the system is in the charged state, in which latter case, however, lines of force run between the different conductors.

We begin to charge a to a constant potential, e.g. to, $+ 20$ volts, keeping b and c still at potential 0 volt. If for the sake of simplicity we first imagine the state as it would be without the presence of b, the course of the lines of force would be as follows: lines of force would start from a, and end upon the bottom, the walls, and the lid of c; in consequence, however, of the unequal distance from a to those different parts of c, the potential gradient per unit of length or the electric force, as also the density of the lines of force, or the value of the tensions directed along the lines of force in the space round a would be of very unequal value; how great, however, the variation in different directions might be, yet there would be complete symmetry in the course of the lines of force with respect to the vertical plane in which the needle itself is situated. The presence of b, however, disturbs this symmetry in the following way:

1. The lines of force starting from a in the direction of b will no longer end on c, but on b; besides, on account of their diminished length, therefore on account of the increased electric force, they become there *denser* than before.

2. There will be inflection of lines of force; some lines of force, viz. those which, when not subjected to the influence of b, would run beside b from a to c, will pass into lines of force from a to b under the influence of b.

This disturbance caused by b will give rise to the formation of a resulting electrostatic couple, acting on those halves of the side faces of a, which are directed to the side of the acute angle between a and b, so that consequently a is deflected to the side of b, and the angle between a and b will become such that the formed torsion couple of the suspension wire will be in equilibrium with the electrostatic directive couple.

In order to make a return to the untwisted position, c is charged to a negative potential, which brings about the desired change; for

1. then the density of the lines of force between a and c will increase, which causes a slighter variation of lines of force on those halves of the sides of a which are directed to the side of the acute angle between a and b;

2. some lines of force between a and b will deflect and become lines of force between a and c.

In case of a sufficient negative potential of c the above mentioned electrostatic resulting couple will be annihilated through this change. The course of the lines of force has now become more symmetrical (of course not quite), while a returns to the untwisted position.

In this way e. g. a state of charge is realized for $a = +20$ V., $b = 0$ V., $c = -3$ V.

For the sake of simplicity a whole number was taken for the potential of c, the consequence of which is, that in the final state the needle is only approximately in the untwisted position.

Measuring method of ionisation currents.

A quantity of radio-active substance is placed on the bottom of the ionisation cylinder f; the system is charged to the state : $+ 20$ V., 0 V., $- 3$ V.; f is then brought to a potential value, dependent on the strength of current to be measured. While a, c, and f maintain their potential values, b is insulated by breaking the contact with l; the ions formed, let us say the positive ones, will then charge b to a constantly increasing potential, with the consequence that the number of lines of force between a and b will decrease, and a couple will be formed, which will cause the needles to slowly recede from each other, and that the quicker as the current is the stronger (to return later on to particulars of the motion).

Consideration.

It will be seen from the arrangement of the electrometer, how the before mentioned advantages of the WILSON-electroscope are realized in it; in the space f namely the ionisation current is *directly* carried to the needle $b + d$, this needle being perfectly insulated by a single piece of amber. The separation of ionisation space and measuring space has, moreover, this advantage that the measuring system is not contaminated with radio-active impurities, while the ionisation space and the rod d, which can be removed, as regards the part that lies in f, can be easily cleaned.

As to the *measuring* system proper, the principle of it differs from that of the quadrant electrometer; it has been thus chosen on purpose that the lines of force formed by the ionisation current contribute as *much* as possible and as *favourably* as possible to the movement of the needle a.

This is not the case in the quadrant electrometer; there namely the movement is caused by the lines of force which run between the quadrants and the rims of the needle, whereas the vertical lines of force between needle and quadrants do not contribute anything to the moving couple.

In my opinion it would not be possible to modify the quadrant electrometer in such a way that, while maintaining the principle of the quadrants, many lines of force are not retained at the same time which in a measurement either give *no* movement, or will even *counteract* the movement. The latter might be possible, if the flat needle should be replaced by a horizontal wire, in which way a large horizontal surface is, indeed, avoided, but on the other hand the formed lines of force would act on the two sides of the needle, when the latter is rotated. The advantage of the described apparatus lies in this that the lines of force between a and b, which are subjected to a change on ionisation, will mostly arise on *one* side of the *vertical strip*. This removes the last mentioned drawback, a large injurious horizontal surface also being avoided. I think that with this apparatus I have obtained a sensibility of charge, greater than is possible with a DOLEZALEK-electrometer, the same thickness of wire given.

The realization of a greater sensibility of charge.

The sensibility of the apparatus appeared to be capable of great variation, the suspension wire being left unaltered, and that by varying the state of charge, whereas, for the rest, the method of charging and measuring remains the same. To make the system more sensitive, a is not charged to + 20 V, but say to + 32 V, after which a negative potential value is imparted to c such that a has turned back to an almost untwisted position. The potential of c will also be more strongly negative, of course, for this state than for the state (+ 20.0, — 3) V; the state of charge will then become e. g. (+ 32,0, — 6) V.

In order to understand what causes this modification of charge to bring about greater sensibility of charge, we must examine in the apparatus 1. *the variation of the potential sensibility*. 2. *the variation of the value of the capacity*; for these two factors together determine the sensibility of charge.

1. The former is to be found from the curves I, in which examples of some states of charge are given; to investigate the potential

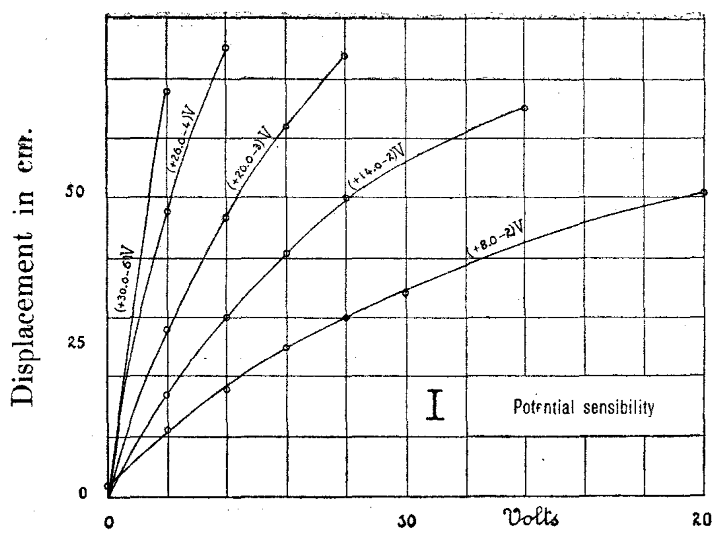


Fig. 1.

sensibility *b* was increased every time by 2 Volts in potential for every state separately. The state, as indicated over every curve, always represents the initial state. All the measurements following here were made with a provisional apparatus; the suspension consisted of a WOLLASTON wire 7 μ thick, and 97 mm. long. (Scale distance 1.5 m.).

From these curves appears the greater potential sensibility of the system for greater potential difference between *a* and *b*; for the state (+ 32.0, —6) V e. g. a displacement of almost 700 mm. was found for 2 V potential increase of *b*; for (+8.0, —2) V it amounted to ± 500 mm. for 20 Volts. The state (+32.0, —6) V does not represent the *most sensitive* state that could be obtained.

I think the cause of this greater potential sensibility is the following:

When *a* recedes from *b* in consequence of a potential increase of *b*, which is brought about by increase of charge of *b*, the negative induced charge on *b* will diminish in consequence of this *motion*, or rather the potential value of *b* will be *diminished*; for a positively charged body (*a*) recedes from *b*. The greater the potential difference is between *a* and *b*, the greater will be the potential diminution in question for a definite angle; in other words the potential diminution of *b* required for a receding of *a* over a definite angle will be the less, i. e. the potential sensibility will be the greater. Besides the said change of the induced charge at the same time increases the angular displacement, which is another reason for greater potential sensibility.

2. It follows from the foregoing, that greater potential sensibility obtained in this way, must be attended by an increasing capacity; for when through a definite addition of charge to *b* in a state with greater potential difference between *a* and *b* a slighter potential increase will set in in consequence of the motion of *a*, this will imply a greater capacity of *b*. Capacity measurements (method HARMS, Phys. Zs. 1904) give the same result; the capacity in the state (+ 8,0—2) V amounted namely to 5,2 e.s. units; that in the state (+ 20,0—3) V 6,0 e.s. units. Both values are the mean from a great many determinations.

What is the reason why, in spite of this increase of capacity, the increase of potential sensibility more than counterbalances it, will appear from the application of the following consideration of the capacity.

Though for an electrometer the sensibility of charge is in direct ratio to the potential sensibility, and at the same time in inverse ratio to the value of the capacity, it does by no means follow from this that the sensibility of charge will be greatest for a capacity as small as possible, and a potential sensibility as great as possible; for the latter quantities are not independent of each other, as appears clearly among others in what was said under 2. therefore I cannot entirely concur with LABORDE's statement, in his: "Methodes de mesure, employées en radioactivité, page 66", where he says: "l'appareil le plus sensible aura une grande sensibilité aux Volts et une faible capacité"; in this statement the above mentioned relation is namely not taken into account.

Thus in consequence of the existing mutual dependence of capacity and potential sensibility it will be possible — and it will be shown here that this really applies to the discussed electrometer — that it will be favourable for the sensibility of charge, to take the capacity not as *slight as possible*, when namely an accompanying increasing potential sensibility more than compensates the disadvantage of this procedure.

That this case presents itself in the described apparatus may be shown by first examining of what the capacity of the apparatus, i.e. of the needle $b+d$ really consists. This capacity consists of: capacity of the part *b*, which refers to arising or vanishing lines of force leading to *a* or *c*, and capacity of *d*.

Now I would distinguish in this capacity between:

a. useful capacity, by which I mean capacity which has an influence on the motion of *a*;

b. injurious capacity which lacks this influence, and which is really a disadvantage here, because it binds charge of the ionisation current without making it demonstrable. Of the above mentioned capacity only that corresponding to the lines of force between *a* and *b* is certainly almost entirely useful capacity (see below); the rest is injurious.

And in this lies the cause why the state with greater potential difference between *a* and *b*, though attended with greater capacity, can yet mean greater sensibility of charge; for this increase of capacity concerns here the capacity of *b* with respect to *a*; this is increased, (according to 2) hence the useful capacity of *b* is increased; the greater now the ratio of useful to injurious capacity is, the greater the sensibility of charge.

For the rest, as regards the value of the injurious capacity in the apparatus, the following remarks may be made:

1. The injurious capacity of *d* with respect to *f* will not be of great influence, since the distance to *f* is great.

2. So far the lines of force starting from the lower *rim* of *a*, or from the *back* of *a*, ending on *b*, were not taken into account; they represent injurious capacity. This influence will make itself slightly felt in the middle of the needle, but will have little effect there on the motion.

3. It is difficult to say anything definite about the value of the injurious capacity of *b* with respect to *c*.

At any rate it will also appear from what follows, how for *very sensitive* states the total influence of the injurious capacity may almost be disregarded.

In the case of the quadrant-electrometer, on the other hand, the injurious capacity is that of large surfaces with respect to a metal needle lying close by.

Before confirming what has been said above about this increased sensibility of charge for greater potential differences between *a* and *b* by the communication of some experimental results, a few particulars may be added about the mode of motion of the needle during the current measurement.

Mode of motion of the needle during the current measurement:

When the needle *b* is charged starting from potential 0 V by means of an ionisation current, when therefore the potential difference between *a* and *b* decreases, *a* will begin to move away from *b*; consequently a motion of the scale division under the crosswire will take place through the reflection of the mirror, which, however, will not be uniform. For the different positions occupied by *a* both the potential sensibility and the value of the capacity of *b* will be different; for the smaller the angle with *b*, the greater is the potential sensibility, as well as the capacity.

The causes are the following: 1. With a smaller angle the distance between *a* and *b* is smaller and therefore the diminution of the induced charge for a definite change of angle greater.

2) With a smaller angle the potential difference itself is also greater, and this again causes a greater decrease of induced charge for a definite angle.

For both reasons greater potential sensibility, but at the same time greater capacity is to be expected at a smaller angle, but here too for the same reason as for conditions of charge with greater potential difference between *a* and *b*, the result will be a greater sensibility of charge

In agreement with this the curves I show, how for every state of charge the potential sensibility decreases with greater angle between *a* and *b*.

Capacity determinations gave the further result that the capacity amounted to 5.75 e.s. units for the state (+ 20,0—3) measured from an angular displacement (recession), corresponding to 550 mm. scale displacement, whereas it gave the value 6 e. s. units, when this displacement only extended over 250 mm.

Measurement of the current.

With the different above mentioned states of charge ionisation currents were measured, obtained with two different very slight quantities of polonium, which were placed in a dish on the bottom of f; the larger quantity is called A, the smaller B. The velocity with which the scale moved under the cross wire was determined, and then the intensities of current were derived in absolute measure from this by means of the knowledge of the capacities and potential sensibilities holding for some of the states of charge.

The curves II represent the result of the measurements for the quantity A; it appears from this, that in accordance with expectation the sensibility of charge increases for states with greater potential difference between a and b; at the same time this confirms what

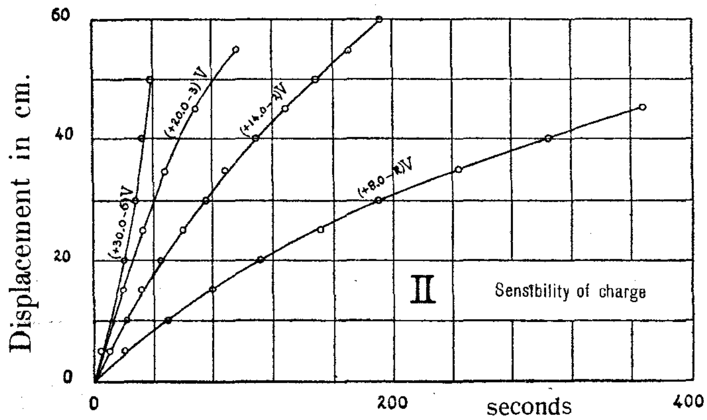


Fig. 2.

was discussed before, that namely the sensibility of charge for one and the same state is greatest, when a is nearest b.

From the experiment in itself the ratio of the current intensities of the two quantities of polonium could already be derived, and that even for each state of charge taken by itself. It will namely be equal to the ratio of the times required by a to pass through the same angle for the quantity A and for B. This ratio, which would have to yield the same value for every state of charge, amounted successively to 2.5, 2.7, 2.7, mean 2.6.

According to the above it was now possible at the same time by means of the measured capacities and the known potential sensibilities to determine the currents for A and B in ampères, from the formula: $i_A = \dfrac{C \times \text{V-increase per sec.}}{9 \times 10^{11}}$, in which C represents the capacity of the needle $b + d$. As mean values from the values for the 3 most insensitive states we thus obtained:

$$i_A = 1.3 \times 10^{-13} \text{ (quantity } B)$$
$$i_A = 3.3 \times 10^{-13} \text{ (,, } A)$$

Limits of sensitivity of the apparatus.

Besides being dependent on the state of charge of the system, the sensibility of charge can also be modified by varying the thickness of the suspension wire and the angle between the needles.

It was now of interest to ascertain how far the influence of a change of the state of charge in this respect could extend, how far in other words the apparatus might gain, resp. lose sensibility of charge by a constantly increasing or diminishing potential difference between a and b. Experiment showed, that there are limits on either side, at which the apparatus presents a very peculiar character; this will successively be examined for a smallest sensibility, and then for a greatest sensibility.

a, *Limit of smallest sensibility.*

Though for the just mentioned state of charge $(+8, 0, +2)\ V$ the phenomena were similar to those for the other states of charge, yet the limit of sensibility appeared to be close in the neighbourhood, viz. at the state: $(+4, 0, 0)\ V$; this will most clearly appear from the experiment in which the potential sensibility was examined by

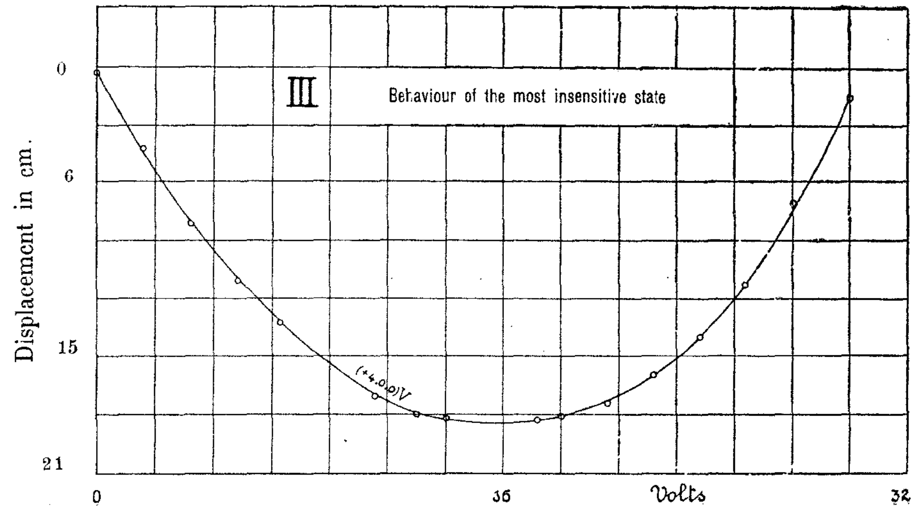


Fig. 3.

the regular increase of the potential value of b. It appears from curve III how, in contradistinction with the other states, a first recedes from b, and then approaches b again.

The explanation of this deviation from the ordinary phenomena is very obvious; for the potential value of a being low, b will *soon* rise above this value in potential value, and this more and more; hence the diminution in lines of force between a and b first continues, till the potential value of b has risen to $+4\,V$; then lines of force arise again between a and b, whose number increases with the rise of the potential of b, so that finally the needles will, instead of receding, approach each other.

In accordance with expectation it appeared from the experiment for the current measurement that the needle first receded from b, stopped, and then approached b.

This state of charge appeared, therefore, to be unsuitable for the current measurement, of course under for the rest entirely definite circumstances of thickness of wire, height, and angle of the needles.

b. *Limit of greatest sensibility.*

In the following examples of states of charge illustrating this case a certain difference with the foregoing ones may be observed; for the rest this modification was taken voluntarily; b is here namely in the initial state already at positive potential, while the potential value was *lowered* during the measurement, in other words in contrast with the preceding cases a approached to b through increase of the lines of force between a and b.

In the following examples the potential decrease for b amounts every time to $2\,V$, and it is always stated how much then the deviation is for a, expressed in mm. of scale displacement.

(1) state (+ 80, + 60, + 60,) V.
b + 58 V. 82 mm.
„ + 56 „ 85 „
„ + 54 „ 110 „
„ + 52 „ 145 „
„ + 50 „ 250 „

(2) state (+ 80, + 40, + 36,) V.
b + 38 V. 130 mm.
„ + 36 „ 197 „
„ + 34 „ the needle turns.

(3) state (+ 80, + 30, + 26,) V.
b + 28 V. 201 mm.
„ + 26 „ the needle turns.

(4) state (+ 80, + 10, + 4,) V.
b + 8 V. the needle turns.

(5) state (+ 120, + 40, + 32) V.
b + 38 V. the needle turns.

(6) state (+ 120, + 10, + 2) V.
b + 8 V. the needle turns.

The phenomenon that occurred now was the following: when e.g. in the 3rd state b was charged to + 26 V, after having first been brought to + 28 V, we did not once more observe a deviation which amounted to somewhat *more* than that for the change of the potential value of b from + 30 V to + 28 V (since the sensibility at smaller angle *increases*), but a passed over so great an angle that the whole scale disappeared from the field, and a assumed *almost* a position parallel to b: the needle turned suddenly. In state 4 this phenomenon occurred immediately at the first potential decrease of b with 2 V, and the same applies to the 5th and 6th states, whereas in contradistinction with this the first state exhibited stable states throughout the scale for definite potential values of b. The experiment seemed therefore to point to the existence of an unstable state of equilibrium of a, which gradually shifted to an increasing angle with b as the state of charge became more sensitive. To ascertain, whether this displacement was a gradual one, the turning point was approximated as nearly as possible for every state separately; this was done by diminishing b in potential value not by 2 Volts every time, but only by parts of 1 Volt. The result of this was that, as had been expected, the 2nd and 3rd states were still realisable throughout the scale, the 4th, 5th, 6th states on the other hand only partially, but again in such a way that the said unstable state of equilibrium, hence the turning point, occurred at a greater angle, as the state of charge was more sensitive.

When after the turning a had reached its new state of equilibrium, it was not possible to make a return to its position through a slight potential increase of b, which, considered in itself, would give rise to a state of charge with a stable equilibrium *outside* the region of turning. This too pointed to the existence of an unstable equilibrium.

The explanation of the existence of such an unstable equilibrium at the point of turning seems to me the following:

In what precedes the change was already discussed of the induced charge on b, in consequence of an angular displacement of a; we saw how this change takes place for a definite angular displacement to a greater degree, the greater the potential difference is between a and b, and the smaller the angle is between the needles.

Taking this into consideration we may ask what will take place when e.g. the state $(+83, +30, +26,)\,V$ is realized, and when the negative charge is continually supplied to b.

In this the ratio of useful to injurious capacity will namely continually change for the before-mentioned reasons; it will become continually greater; at a definite angle the influence of this injurious capacity can even all but vanish. This circumstance can also be expressed thus, that then even a supply of negative charge will no longer make the potential of b go down, because the approach of a to b brought about by this supply just compensates the expected potential decrease.

The angle, for which this consideration holds, will still be found outside the region of turning and may be realized by means of a storage battery.

If more and more negative charge is added at this angle to b, e.g. through an ionisation current, the potential value of b will even continually rise in consequence of the preponderating influence of the approach of a to b. Finally the state becomes this, and it is then that the turning takes place, that for a further approach of a to b a supply of charge to b is not even required any longer. For the mere induced charge on b called forth by the approach will be more than sufficient to give rise to an electrostatic couple, which can be in equilibrium with the formed torsion couple.

That, however, in case of such a turning the parallel state is not entirely reached, which was already pointed out, may be accounted for in this way that the lines of force between a and b at decreasing angle will also act on the back of a in appreciable quantity, and this more and more as the angle becomes smaller, so that through this circumstance the electrostatic couple, which tends to make the angle between a and b smaller, is counteracted. It will follow from this, that after the turning, the two needles will always *continue* to form a (generally small) angle with each other.

It follows therefore from this explanation of the angle of turning, as was already pointed out on p. 547, that, when the measurement is made in the neighbourhood of this angle, the capacity which must then be taken into account, will chiefly consist of useful capacity, by which the sensitivity of the state is to be explained.

In conclusion a single example of a measurement of air-ionisation and of Rubidium-ionisation.

In these measurements the needle a was brought to potential zero; the state of charge was: 0 V., — 26 V., — 32 V.

The ionisation space contained only air; volume 1 litre; the number of seconds successively found for the passage through 10 mm. was: 43, 24, 31, 32, 55, 55.

Then a quantity of Rubidium salt was placed in a dish with an area of 50 cm², on the bottom of f; it was found that successively: 9, 10, 10, 11 seconds were required for the passage of 20 mm. In this case f was at + 80 V.

Physical Laboratory of the University at Groningen.