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VI. On the ratio of the velocities of the two ions produced in gases by Röntgen radiation; and on some related phenomena

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Mr. Rennie, by whom these experiments were made during the recent Christmas holidays, had previously experimented on a platinum plate which had been made the positive pole in an electrolytic cell with an electromotive force of one volt, tending to decompose water acidulated with sulphuric acid; the other pole being a piece of platinum wire. After the plate had been one hour under this influence in the electrolytic cell he removed it, and dried it by lightly rubbing it with a piece of linen cloth. He then placed it in the Volta-condenser, and found it to be negative to a platinum plate in ordinary condition; the difference observed was $\cdot 27$ of a volt. This experiment was made on October 21; and on November 8 it was found that the difference had fallen from $\cdot 27$ to $\cdot 07$. Mr. Rennie also made similar experiments with the platinum disc made the negative pole in an electrolytic cell, and found that this rendered the platinum positive to undisturbed platinum to a degree equal to about $\cdot 04$ of a volt. The effect of soaking the platinum plate in dry hydrogen gas, alluded to in my first postscript, which also was observed by Mr. Rennie, was found to be about $\cdot 11$ of a volt. Thus in the case of polarization by hydrogen, as well as in the case of polarization by oxygen, the effect of exposure to the dry gas was considerably greater than the effect of electro-plating the platinum with the gas by the electromotive force of one volt.

[K.]

VI. *On the Ratio of the Velocities of the Two Ions produced in Gases by Röntgen Radiation; and on some Related Phenomena.* By JOHN ZELENY, B.Sc., Assistant Professor of Physics, University of Minnesota*.

IT is the object of this paper to show that the positive and negative ions, which take part in the conduction of gases exposed to Röntgen rays, move with different velocities when in the same electric field; to determine the ratio of these velocities in several gases; and to consider various phenomena which are consequences of or are affected by the difference in the two values.

The subject matter will be treated under the following subdivisions:—

- § 1. The method for determining the ratio of the two velocities.
- § 2. The apparatus used.
- § 3. The form of tube used for constancy of radiation.

* Communicated by Professor J. J. Thomson.

- § 4. Manipulation and results.
- § 5. Difference of velocity shown by blowing along a charged wire.
- § 6. Difference of velocity shown by using an alternating E.M.F.
- § 7. Metals and air oppositely charged when exposed to Röntgen rays.
- § 8. Air charged negatively discharges faster to a surface than when charged positively.
- § 9. Distribution of electrification between two plates.
- § 10. Dependence of blowing methods upon the velocity of the blast.
- § 11. Potential gradient between two plates.
- § 12. Remarks.

The extension of the idea of ionization to the various types of conduction through gases has enabled us to explain most of the observed phenomena.

While in many liquids some ionization occurs at ordinary temperatures, in gases high temperatures are required, and it is brought about, in addition, by the action of various agents upon the cold gas.

The charged carriers that exist in the gas due to any of these causes, and take part in the conduction, are all called ions, no matter whether in the various cases they may differ in their structure or properties.

It is known from the changes in concentration at the two electrodes that in liquids the two ions do not move with the same velocity; and this is attributed to a difference in size. In gases a difference of velocity has not heretofore been determined.

A. Schuster (Proc. Roy. Soc. xlvii. p. 553) gives some reasons for believing that the negative ions in gases move faster than the positive ones; and J. J. Thomson (Phil. Mag. Dec. 1895) explains some phenomena in electrodeless tubes by assuming that the negative ion in oxygen and hydrogen travels faster than the positive one. Rutherford (Phil. Mag. Nov. 1897, p. 436), in determining separately the velocities of the two ions in air for conduction under the influence of Röntgen rays, did not observe any difference.

The dependence of the quantitative values obtained in certain determinations (§ 9 and § 10) upon the sign of the electrification used led me to undertake the present investigation, in which it is shown that a difference of velocity does exist, and its amount is determined.

While methods are not wanting for determining with more or less accuracy the sum of the two velocities, a reliable method

for obtaining the two velocities separately has not yet been devised.

The method described below deals with the ratio of the two velocities, which is the quantity under consideration. The two actual velocities can, if desired, be obtained by means of this ratio from the value of the sum.

§ 1. The Method.

The method employed for determining the ratio of the velocities of the two ions is based on opposing a stream of gas to the velocity due to the electric forces.

Fig. 1.

Suppose A and B in fig. 1 to represent two plates made of wire gauze, the space between which is exposed to Röntgen rays. If the plates are connected to the opposite poles of a battery C which maintains a potential-difference of U volts between them, then if d is the distance between the plates in centimetres, and we suppose for the present a uniform potential gradient, the fall of potential between them is $\frac{U}{d}$ volts per centimetre.

Under the action of this electric force the ions move in opposite directions between the plates, and if u is the velocity with which a positive ion moves and v that with which a negative one moves when the potential gradient is one volt per centimetre, then the velocities of the positive and negative ions are $u \frac{U}{d}$ and $v \frac{U}{d}$ respectively.

These velocities may be increased either by increasing U or by decreasing d .

Suppose now a current of gas to move through the plates from A to B, having in all of its parts a uniform velocity of H centimetres per second.

The resulting velocity for the positive ions will be $H - u \frac{U}{d}$, and for the negative ones $H + v \frac{U}{d}$.

By properly changing the value of U the positive ions can be made to move from A to B, from B to A, or to have a zero resultant velocity.

In the last case $H = u \frac{U}{d}$.

By reversing the poles of the battery C the negative ions can in turn be forced to move against the stream, and a potential-difference V be found such that now

$$H = v \frac{V}{d}.$$

Hence it follows that

$$\frac{u}{v} = \frac{V}{U}.$$

In practice, however, it is impossible to obtain a perfectly uniform stream of gas, or a uniform potential gradient between the plates. The potential gradient is changed by the presence of free charges due to the separation of the two kinds of ions (§ 11); and the electric force thus varies for different points between the plates, and it cannot be assumed to be proportional at any point to the voltages used on the plates. This necessitates the experimental determination of the potential gradient between the plates, as from it is obtained the actual electric force which acts to bring the ions to either plate.

Owing to the irregularities in the gas-stream, some ions reach the plate A while their velocity due to the electric force is less than the average velocity of the opposing blast; so that it is not possible to find very accurately when the two opposed velocities are equal by simply increasing gradually the electric force, and observing the charges that reach the plate.

But the irregularities that exist in the gas-stream are quite uniform when averaged over a period of time, so that for different determinations the gas-blast may be considered as an unknown constant quantity. And for obtaining the ratio of the two ionic velocities, instead of finding under what electric forces the two ionic velocities are separately just equal to that of the blast, it is sufficient to find what electric

forces must be used in the two cases respectively, in order to give the same charge to the plate, against the same blast, in the same time. The two ionic velocities then bear the same relation to that of the gas-stream, and to find the ratio of the two velocities for the same electric force it is only necessary to take the inverse ratio of the electric forces used in this case. Thus, if U is the potential-difference between the plates required to force a certain number of positive ions to the plate A in a given time against the gas-current, and if V must be used to drive the same number of negative ones under the same conditions against the same blast, then if U' and V' are the experimentally determined potential gradients effective in bringing the ions to the plate A , in the two cases respectively,

$$uU' = K, \quad \text{and} \quad vV' = K,$$

where K is a constant depending upon the velocity and nature of the blast used, and upon the rate at which the ions are brought to the plate.

Hence

$$\frac{v}{u} = \frac{U'}{V'}.$$

The ratio $\frac{U'}{V'}$ as found experimentally (§ 11) for the apparatus used (§ 2) is nearly equal to $\frac{U}{V}$, the ratio of the potentials used, the deviation being, for the most part, due to the differences in the distribution of the free charges in the two cases, caused by the difference between the velocity of the two ions.

§ 2. The Apparatus.

The apparatus used for carrying out this method was arranged as is shown in fig. 2.

P and Q are two 9 centim. square brass plates. To openings in their centres are attached the brass tubes R and S of 3.6 centim. diameter, which are fastened to the board N so that the two plates are parallel and 4 centim. apart. The space between the plates is made to form a closed box by covering the top and sides by glass plates which are blackened uniformly on the inside surfaces with lamp-black for preventing the accumulation of static charges.

K is a wire gauze covering completely the opening in Q , and T is an insulated circular wire gauze with 7 meshes per centimetre, which is placed in, but does not quite fill, the opening in the plate P . The wire that supports it leads through the ebonite plug M to a pair of quadrants of the

electrometer E, which may be connected to earth by the key H.

G is a plug of glass-wool which serves to make more uniform the stream of gas, and to free it from dust and any electric charge. The rubber tubes D and F lead to two gas-bags, each of a capacity of about 135 litres. By putting an excess weight on the bag connected to D the gas is forced through the apparatus into the second bag. It can then be forced back and be used over again.

The induction-coil and the tube are situated in a lead-covered box which is connected to earth, and of which C represents the upper part.

The rays from the source O pass through the aluminium window A and into the box P Q through its wooden bottom. By means of the adjustable lead strips L the rays can be prevented from impinging upon the plates P and Q, and the amount of gas exposed can be regulated. The plate P is connected to earth while Q is connected to one pole of the storage-battery B, the other pole of which is also to earth.

When the rays are entering P Q and the ions are travelling in opposite directions in the box, the charges they give to P, Q, and K are conducted to earth, while those they give to T gradually change its potential, and at an approximately uniform rate so long as this potential is small compared to that of Q. When the distribution of the free charges in the gas has assumed a steady state, all changes in the potential of T are due to ions giving up their charges to it.

If a stream of gas is now blown through the apparatus in the direction from T to K, the ions moving against the stream in the direction from K to T travel slower than before, and the potential of T changes less rapidly.

A smaller number of the ions reach the gauze because more are lost on the way by recombination, similarly as when the ions move slower due to a smaller E.M.F. used.

In addition, in this case, any accumulation of ions is opposed by their motion sidewise out of the current, due to their mutual repulsion to those parts where the accumulation is less.

Again, if the velocity of the ions is but a little more than that of the opposed blast, some of the ions which tend to move against the gas-stream are blown away by the blast, since their presence, if moving in the other direction, would decrease the electric force below that sufficient to force the ions against the stream.

When the ions are moving to the gauze T against the gas-stream, none of them can pass between the meshes of the gauze into the tube R, as there is no electric force in that direction; but if the ions are moving with the stream, then some and even most of them can be blown through the gauze, to the wires of which the electric forces tend to draw them.

§ 3. *A Form of Tube for Constant Radiation.*

It is of the utmost importance, if accurate work is to be done, to have a constant source of the Röntgen rays.

Among a large number of tubes tried for this purpose one type has proved far better than the rest.

The tubes of this class which I have so far employed have maintained a satisfactory constancy, until by prolonged use the glass became quite dark from the metal sputtered from the electrodes.

The general form of the tubes used is shown in fig. 3.

Fig. 3.

The concave aluminium cathode is situated in the tube B C while the anode, made of a sheet of platinum backed by an aluminium disk, is situated in the bulb F. The parts back of both electrodes are covered by tightly fitting tinfoil. The little bulb D contains a small piece of charcoal which helps to maintain a constant vacuum by the state of equilibrium between the free and the absorbed gas. With the use of a

good interrupter, which is always a very important factor, a comparatively uniform emission of rays is obtained, together with a steady unwavering fluorescence.

The main advantage of this form appears to lie in the fact that the cathode is within the contracted part B C, which during action remains quite free from surface electrification, so that the flickerings due to the surface discharges from this part of the tube are absent.

It has been found convenient in testing whether a tube is giving out rays at a uniform rate, to employ two parallel plates, one of which is connected to a constant source of potential and the other of which is connected at the same time to an electrometer, and to earth through such a high resistance as a column of xylol. As rays are allowed to fall between the two plates, conduction takes place between them, and the plate that is connected with the electrometer-quadrants assumes a certain potential such that the leak to earth through the high resistance is equal to the current between the two plates. Any variation in the intensity of the radiation is indicated by a corresponding variation in the electrometer-reading, so that by simply watching this it is possible to see the amount and nature of the variations in the radiation. With such an arrangement permanently set up one can conveniently compare from time to time the strength of the rays which are being used for any purpose; or if an electrometer can be spared for this, the relative strength of the rays can be directly observed at any instant.

§ 4. *Manipulation and Results.*

In the practical working of the method the readings were taken in the following manner:—The pair of quadrants of the electrometer, connected with the gauze T, was joined to earth by means of the key H. The rays and blast were then allowed to run a short time so as to establish a steady state in the conducting gas between the two plates. The electrometer-zero was now read, and the quadrants were disconnected from earth. At this instant a stop-watch was started, and a definite interval afterwards, usually 20 seconds, the rays were stopped by cutting off the current from the coil, and, finally, the electrometer-deflexion was read.

The following table shows how, for air, the quantities of electricity which reach the gauze in a given time vary when the air-stream is kept constant while the potential of Q is varied in amount and sign.

TABLE I.—Air.

Potential of Q in volts.	Electrometer deflexion.	Potential of Q in volts.	Electrometer deflexion.
+10	0.0		
+20	+ 1.5		
+30	+ 3	—30	— 5
+40	+ 4.5	—40	— 8
+50	+ 7	—50	—13
+54	+ 8	—54	—18
+58	+11	—58	—26
+64	+14.5	—64	—43
+68	+21	—68	—55
+72	+28.5	—72	—68
+76	+36	—76	—80.5
+80	+48		
+88	+71		

These results are shown graphically in fig. 4, where the abscissæ represent the voltages used and ordinates the corresponding deflexions obtained.

At B the potential gradient has increased to such a value that the ions are beginning to make their way against the main blast of air. That some reach the gauze for points between A and B is due to irregularities in the stream of air. It is possible also that there are some few ions in a gas that travel faster than the majority of the ions.

Curve I. represents the case when the negative ions, and curve II. the case when the positive ions are moving against the stream respectively.

It is seen that the velocity of the positive ions for the same potential gradient is less than that of the negative ones, since to drive the same quantity to the gauze against the air-current a greater potential gradient is required for the positive than for the negative ions.

In air the difference of velocity of the ions is quite large, but in some gases it is small or nothing at all.

Fig. 4.

The following table shows some readings obtained when the gas used was carbonic acid gas. The velocity of the gas-blast used in this instance was much smaller than in the case just cited.

TABLE II.—CO₂.

Potential of Q in volts.	Electrometer deflexion.	Potential of Q in volts.	Electrometer deflexion.
+10	+ 4.5		
+16	+ 9.5	-16	- 9.0
+18	+14.5	-18	-15.0
+20	+23.5		
+22	+31.0	-22	-31.0
+26	+56.0	-26	-55.5
+28	+65.5	-28	-67.0
+30	+77.0	-30	-78.5

These results are represented by curve II. in fig. 5.

Fig. 5.

It appears that in carbonic acid gas the two ions travel with almost, if not exactly, the same velocity.

Curve I. shows how the deflexions increased with the voltages used when there was no blast and the gas was at rest, and comparing with curve II. the retardation of the ions, due to the blast, is made apparent. Curve II. is in fact a displaced curve I., the displacement being caused by a decrease in the velocity of the ions produced by and equal to the velocity of the gas-stream. The electric force necessary to give to the ions a velocity equal to the average velocity of the blast is then obtained from the voltage represented by this displacement and from the distance between the plates. Thus, by measuring this potential gradient and the velocity of the blast, the velocity of the ions can be determined. The writer has not, in this investigation, attempted to develop this method, but it may be freer from objections and more accurate in practice than methods heretofore used. A single determination made with air gave roughly for the velocities of the positive and negative ions respectively, 2.1 centim., and 2.6 centim. per second for a potential gradient of one volt per centimetre.

The ionic velocities in different gases can be compared from the curves obtained for these gases when in each case the velocity of the opposing blast used is the same.

In determining the numerical value of the ratio of the two ionic velocities in any gas from the relation $\frac{u}{v} = \frac{V'}{U'}$ it is necessary not only to find two voltages for which the quantities of electrification that reach the gauze in a given time are the same for the two cases, but also to determine what in these cases are the effective potential gradients producing the motion against the gas-stream.

The consideration of the gradients existing in the apparatus used under these conditions is deferred to § 11, where the subject of potential gradients in gas conduction is treated. It is there shown that although the actual gradients differ considerably from a uniform gradient between the plates, yet for the two cases in question the *ratio* of the effective gradients is not much different from the ratio of the voltages used on the charged plate.

The difference that exists between these two ratios has been treated as a correction which has to be added to the ratio of the two voltages used, and which amounts to about 2 per cent. for the case of air.

In using curves like those shown in fig. 4 for obtaining the ratio of the voltages required to give the same deflexion with the two kinds of ions respectively, the ratio is simply taken of the abscissæ corresponding to two points on the curves which have equal ordinates, as is indicated by the dotted lines.

The place on the curves that is used must be above the turning-point B of the curves, but must not be so high as to be near the turn in the curves which appears when the saturation value of the electric current is approached. In practice the parts of the curves in the neighbourhood of the letter C were used, as deemed most favourable for accuracy. However, in making a determination the values are not best obtained from complete curves.

The curves are found simply as a preliminary part of the operation, so as to be able to tell what are the proper potentials to employ for the particular gas and blast in question. Suppose that in the case shown in fig. 4 it is decided to use -60 volts for the potential of the charged plate when the negative ions are dealt with; it is seen that to obtain an equal deflexion with the positive ions a voltage between +72 volts and +74 volts must be used. To determine the exact value readings are taken, as described, with the plate Q

charged in succession to -60 , $+72$, and $+74$ volts, and these are repeated several times. From the deflexions obtained when the $+72$ and $+74$ volts were used, the exact voltage is found by interpolation which would give the same numerical deflexion as was obtained with the -60 volts.

The ratio of the potential values thus found, plus the correction necessary to reduce this to actual potential gradients, gives the required value of the ratio of the two ionic velocities. By using different velocities for the gas-blast, determinations are made by the use of entirely different sets of potential values.

The following table gives the values obtained for the ratio of the velocities of the two ions in the various gases used at atmospheric pressure.

TABLE III.—Ratio of Velocities of Ions.

Gas.	Velocity of Negative Ions. Velocity of Positive Ions.	
Air. N and O	1.24	$\pm .005$
Oxygen. O	1.24	$\pm .005$
Nitrogen. N	1.23	$\pm .01$
Hydrogen. H	1.14	$\pm .01$
Coal-gas. H and others	1.15	$\pm .01$
Carbon dioxide. CO_2	1.00	$\pm .005$
Ammonia. NH_3	1.045	$\pm .015$
Acetylene. C_2H_2	0.985	$\pm .015$
Nitrogen monoxide. N_2O	1.105	$\pm .01$

The probable errors given include only the errors in determining the voltage ratio that it was necessary to use to obtain the same quantity of the two kinds of electrification; and do not include any errors made in determining the correction that had to be applied to this ratio to reduce it to the ratio of the potential gradients actually existing in the apparatus.

In a mixture like coal-gas, where there are probably several sets of ions, the value obtained may correspond for the most part to the set having the greatest velocities, depending upon how much greater these are than the others.

On account of the large volume required, and on account of the nature of the apparatus, no attempt was made to obtain the gases very pure, especially since a small amount of impurity cannot affect the result sensibly.

The number and kind of gases used was necessarily limited

to those which do not attack the materials of which the apparatus was made.

§ 5. *Difference of Velocity shown by Blowing along a Charged Wire.*

A simple way for showing the difference of velocity for the two ions in air is to expose to the rays or to blow Röntgenized air into an aluminium tube which is connected to earth, and in the axis of which is supported an aluminium wire that can be charged from a battery.

During the conduction through the air there is an excess of ions near the wire and by the wall of the tube, of the kind that is moving towards these two places respectively.

If by a proper arrangement a current of air is blown only along the surface of the wire and out through an insulated tube filled with glass-wool which is connected to an electrometer, then when the wire is charged negatively a greater quantity of positive electrification is blown out into the glass-wool than is obtained of negative when the wire is charged positively to the same voltage. This shows that the positive ions are moving across the tube in the electric field with a smaller velocity than are the negative, since they are more readily carried away by the same stream of air, blown at right angles to the electric force (see § 9 and § 10).

§ 6. *Difference of Velocity shown by using an Alternating E.M.F.*

Another way to show the difference of velocity of the two ions produced in air is to use an alternating E.M.F. between two parallel plates, or between the wire and the tube in the arrangement described in § 5.

In the case of the two parallel plates which are connected to a source of alternating E.M.F., and the space between which is exposed to the rays, the rapidly alternating electric force causes the ions to travel back and forth between the plates over paths whose lengths are determined by the period of alternation, by the average value of the potential gradient between the plates, and by the velocity of the ions themselves.

Those near the plates are brought against the sides; but if the velocity of the two ions were the same there would be no permanent separation of the two kinds, and so no formation of a free charge anywhere between the plates. But since the velocity of the negative ions is greater than that of the positive, these, at each alternation, are brought to the plates from a greater distance than are the positive, and there is thus left an excess of positive ions in the

space between the plates. By blowing the air into a tube containing glass-wool these are collected, and give a positive deflexion on an electrometer connected to the tube.

If the plates are moved so close together that in the excursions which the positive ions make during an alternation they travel a distance greater or equal to that between the plates, then at every alternation of the E.M.F. all of the ions in the space between, both positive and negative, are forced to the plates, and a stream of air does not now carry away with it any charge.

The path traversed by a positive ion in the time of an alternation is the distance between the plates when a current of air just ceases to carry away a charge; and this can be made the basis for a determination of the velocity of this ion.

§ 7. *Metals and Air oppositely Charged when exposed to Röntgen Rays.*

The results of various observers differ as to whether metals and air which are exposed to Röntgen rays are left charged positively, negatively, or not at all.

Some of this confusion has already been cleared away by the fact that when two different metals are dealt with at the same time, the effects observed are due, at least approximately, to a reduction of the charges on the metals due to the contact-difference of potential.

But there still remain those cases where a piece of metal is enclosed on all sides by parts made of the same metal. It is evident that if the metal receives a charge from the ionized air, this itself must remain electrified with a charge of the opposite sign.

It will be shown that an electrification does take place, and that a metal placed in air which is, or recently has been, exposed to Röntgen radiation receives a negative charge while the air itself remains positively electrified. The cause of this effect will first be pointed out, and then the arrangement of the apparatus for augmenting it will be readily understood.

The difference of velocity of the two ions in air leads us to believe that they are not of the same size (§ 12), and it follows that they do not diffuse at the same rate when in a field of no force, the smaller negative ones diffusing the faster. Near a boundary the initial uniform distribution of both ions is disturbed by their impacts against the surface, during which circumstance something takes place that is at least externally equivalent to a giving up of the charge to the surface. A difference in concentration of the ions is thus

produced between the parts at the boundary and those more distant, which causes a diffusion of both kinds of ions towards the place of lesser concentration (equations for this kind of diffusion are given by Townsend, *Phil. Mag.*, June 1898); and this is more rapid for the negative ions than for the positive. A larger number of negative ions thus impinges upon the metal and this becomes negatively charged, while the air is left positive due to the excess of ions of that sign.

The effects obtained experimentally under ordinary conditions are appreciable though small, and to increase them it must be remembered that the accumulation of each of the charges tends to counteract further separation, and that since the effects are due to action at a boundary, an increase in the surface of the metal will increase the amounts obtained.

The arrangement of the apparatus used is shown in fig. 6.

Fig. 6.

LL is an aluminium tube 45 centim. in length and 4 centim. in diameter. At one end, insulated by E, is the aluminium cylinder D, which has in its centre a plug of glass-wool S, and is connected to a pair of quadrants of an electrometer. A gas-bag is connected, by means of the tube T, to the aluminium cylinder A, which is filled with glass-wool to prevent dust and all stray electrification from entering the apparatus. C is a spiral made out of a 9 centim. wide sheet of thin aluminium which is wound so that the separate spirals are 1 millim. to 2 millim. apart. The tube D and the wires leading to the electrometer are metallically shielded, and everything except D is connected to earth.

The rays from the source O pass through the aluminium window H of the lead box II, then through the tube LL at B, and are finally all stopped by the lead piece F, which covers closely that part of the apparatus.

If now a current of air is blown from the bag through the apparatus when the rays are not acting, or if the rays are turned on when there is no air-current, the electrometer connected to D receives no charge.

If, however, the air-blast and the rays are in action at the same time, the air entering at A becomes partly ionized at B, and in passing through the spiral C more of the negative ions strike against and give their charge to the sides of the spiral because of their greater diffusion-velocity; so that, on leaving C, the air has a positive electrification due to the larger number of positive ions present.

In passing through the glass-wool S the charges on all of the remaining ions of both kinds are given up, and the electrometer shows a positive deflexion.

The arrangement has the advantages that all the air in passing through the spiral is near to a boundary, and that no charge is allowed to collect at the places of separation, since the metal parts are connected to earth and the charged air is blown away.

As the action is allowed to continue the deflexion of the electrometer increases with the time but with continually decreasing increments, because of the leakage through the ionized air on the inside between the tubes L and D caused by the electric force due to the charge acquired by D.

The deflexions that are obtained in a given time depend upon the velocity of the blast; for if this is too slow there is time while the air is passing through the spiral for all of the ions of both signs to recombine or to strike the walls of the spiral, in which case no deflexion is obtained; and, on the other hand, if the blast is too rapid there is not time enough in passing through for the best possible separation of the ions. Some intermediate value, where all of the negative ions just manage to reach the spiral, will give the largest value of the positive deflexion obtained. In a sample case, by letting the action continue for six minutes the quadrants of the electrometer became charged positively to 2.5 volts. The spiral C was then taken out from the apparatus and the positive charge now obtained was but a minute portion of the former, showing the great advantage of making the air pass through the narrow openings.

There is a searching test, however, for showing that the effect under consideration is due to a difference of velocity of the ions. It has been shown (§ 4) that in carbonic acid gas the velocities of the two ions are very nearly the same. With this gas therefore the effect should disappear. Some of this gas was accordingly placed into the gas-bag and the experiments repeated with the spiral C in position, with the result that a small positive deflexion was obtained, but it was so very small compared to that with air that it is easily attributed to some traces of admixed air in the CO₂. Experi-

ments with air just before and just after those tried with the CO_2 all gave the large positive deflexions already mentioned.

It is evident, since when air was used it came out of the spiral charged positively, that it must have given a negative charge to the metal; but this effect has also been obtained independently by means of the following arrangement:—A large closed aluminium cylinder, 15 centim. in diameter, connected to earth, contained in its axis a short insulated aluminium tube, 3 centim. in diameter, from which an aluminium strip led to the outside of the large cylinder to an electrometer connexion. Both cylinders and the wire strip were made from the same sheet of aluminium. A pencil of rays allowed to pass through both cylinders surrounded the inner one with ionized air which gradually gave to it a negative charge, as was indicated by the connected electrometer. A similar arrangement was used with all of the parts made of zinc, and a negative charge was again obtained upon the zinc.

The charge does not continue to increase long, for the accumulated electrifications tend to counteract further separation. By blowing a gentle stream of air past the central cylinder, so as to remove the excess of positive electrification in the neighbourhood of the metal, the charge obtained is increased.

§ 8. *Air charged negatively discharges faster to a surface than when charged positively.*

Rutherford has shown (Phil. Mag. April 1897, p. 246) that when air, electrified by being blown away from an electrode in conduction under the action of Röntgen rays, is allowed to pass through tubes of various materials it loses its charge more rapidly when this charge is negative than when it is positive. This result is another consequence of the difference of velocity of the two ions.

When the charged particles enter the tube in question the forces that tend to bring them to the sides of the tube, in addition to those due to irregularities in the current, are those of diffusion and of mutual repulsion.

Since under both of these forces the negative ions move the faster, it follows that in passing through a given length of the tube in the same time more of the ions will reach the walls if they are negative than when they are positive.

The equation for the motion of a charged gas due to mutual repulsion is given by Townsend (Phil. Mag. Feb. 1898, p. 134).

§ 9. *Distribution of Electrification between two Plates.*

When conduction is taking place between two plates, through air exposed to Röntgen rays, free electrification is distributed between them; and it is of importance in some experiments to know the nature of this distribution, and how it is affected by the difference of velocity of the ions.

The electrification of the air is due to an excess of ions of one sign, and to find directly the way in which this excess is distributed the following experiments were performed:—

Fig. 7.

In the apparatus used (fig. 7) P and Q are two parallel, 9 centim. square, zinc plates. These are enclosed in a metal-lined box RS, and by means of insulated wires are connected to the opposite poles of a battery N, whose middle point is to earth. C and D are two slits, having a flat opening 2 centim. by 3 millim., and being made of an imperfect insulating material with a conductivity a little larger than that of the conducting air.

They extend well into the space between the plates, and are fastened to two slides, A and B, which allow the box with its plates to move up and down between them by air-tight joints. By means of F air can be blown through the slit C into D, and out through the insulated plug of glass-wool E, which is connected to a pair of quadrants of an electrometer. After the air-blast has been going a little time a definite

pressure is established in the box RS, and a narrow stream goes between the two openings C and D, which disturbs but little the surrounding air. In this way it is possible, by moving the slits relative to the plates, to carry out the air from any particular region between the two plates and to measure its charge.

As the plates are symmetrically placed and symmetrically charged relative to the box, which is to earth, the space between their central portions is in a fairly uniform field when the plates are close together.

The source of rays is placed so that the radiation passes through the side of the box RS in a direction perpendicular to the plane of the figure, and impinges uniformly upon the air between the plates.

In taking readings the blast and rays were turned on for a short time to establish a steady state, and then the electrometer quadrants, with the connected glass-wool, were disconnected from earth; and after 30 seconds the rays were cut off and the electrometer deflexion read.

The following Table gives the deflexions obtained in a sample case where the plates were 5 centim. apart, and were charged to +70·5 volts and -70·5 volts:—

TABLE IV.

Distance of centre of slits from negative plate.	Deflexion.
centim.	
·5	+168
1·0	+ 74
1·5	+ 42
2·0	+ 22
2·5	+ 1
3·0	- 16
3·5	- 40
4·0	- 65
4·5	-138

The results are shown graphically in fig. 8, where the abscissæ represent distances of the slits from the negative plate, and the ordinates represent the deflexions obtained, which are proportional to the densities of the free electrification existing at the various points between the two plates.

Fig. 8.

Fig. 9.

Leaving the voltages on the plates as before, but increasing the distance between them to 16 centim., which necessarily sacrifices the uniformity of the field and decreases the potential gradient, deflexions were obtained which are shown graphically in fig. 9.

It is seen from both curves that near each plate there is an electrification of the opposite sign to that of the plate, and that the quantity of the electrification falls off rapidly with the distance from the plates.

The two oppositely charged layers at the plates exert a powerful polarization effect, and are able to reduce by a large part of itself the electric force in the middle between the plates, as will be shown in considering the potential gradient between two plates during conduction (§ 11).

The formation of these free charges at the plates is readily understood from a general consideration.

The two kinds of ions, as soon as they are formed by the rays, are given a resultant motion in opposite directions through the air by the action of the electric force, and this motion continues until they reach one of the plates or suffer recombination. If we consider a narrow layer of air at one of the plates, some ions of the kind that is moving towards that plate are entering this layer at one side, and some are leaving it at the other or plate side. Ions of the opposite sign, however, are only leaving this layer, as none can enter from the side bounded by the plate. There are thus two systems of ions, one of which is moving towards a boundary, and the other of which is moving away from the same boundary.

This motion produces an excess at each plate of the kind of ions that are moving towards that plate.

The charge is not primarily due to any accumulation of the ions, but simply to a separation of the two kinds that are produced. At other points between the plates the ions may be equally numerous, but if the two kinds are equally abundant they produce no resultant effect.

The formations of the two charges are limited in amount by the action of the new electric and diffusion forces produced by them.

The difference of potential between the plates has a large effect upon the production of the charges.

If the ions are moving very slowly the charges exist almost entirely at the plates; but as the potential gradient increases the charge in the layer increases in amount and the charged area itself increases in extent.

And as the two ions travel with different velocities for the same potential gradient there is a greater excess of positive at the negative plate than there is of negative at the positive plate. That this is the case is seen by referring to Table IV., where it is shown that the amount of positive blown out by the rapid blast always exceeds the amount of negative obtained.

Thus far the rate of ionization has been supposed uniform for all points between the plates. This would be the case if the rays acted uniformly upon all of the air between but did not strike the plates themselves, and under those conditions the free charges at the plates would be independent of the kind of metal of which the plates are made. When, however, the rays impinge upon a metal it is known that there is an increase in the ionization of the gas at the surface which depends in amount upon the kind and state of the metal used (Perrin, *Comptes Rendus*, t. cxxiv. p. 455). This increase in the ionization at the surface increases the number of the ions that are moving away from the plate, and as these mingle with those travelling towards the plate which usually produce the excess there, this excess is decreased in amount, and in some instances it is even reversed in sign.

Again, if the rays are allowed to pass through but a small central portion of the space between the plates, then the free charges extend on either side at least from the plate to the part exposed, for the electric forces bring ions of but one sign to each of the unexposed portions of the space.

It is clear from the nature of the polarization that has been shown by the above experiments to be present, that it has but a short duration after the electric field which produced it has been removed.

Still the following arrangement served to show its existence directly by obtaining a reverse current. Two parallel, 11 centim. square, insulated, aluminium plates were used, one of which was connected to a pair of quadrants of an electrometer and also at first to earth, while the other was connected to one pole of a battery of cells. A mercury commutator was constructed by means of which, in rapid succession, the charged plate could be disconnected from the battery and connected to earth, and then the earth connexion leading to the second plate be broken. This was all done in a small fraction of a second, and the motion of any charges remaining in the gas after that time would produce an effect upon the plate connected to the electrometer.

With the distance between the plates about 10 centim. and

the potential of the initially-charged plate at 40 volts, an effect was obtained which amounted to a deflexion of about half a volt, and which was always of the sign contrary to that of the initial charge on the opposite plate, and hence corresponded to a reverse or polarization current. The two charges left near the plates without any external electric force simply move towards each other, and so in a direction opposite to the motion of the same ions during conduction. If the rays were cut off as soon as the commutator was turned the electrometer deflexion became permanent, but when the rays were allowed to continue the charge which the insulated plate quickly assumed, due to the polarization, was now slowly dissipated by the action of the new ions formed.

§ 10. *Dependence of Blowing Methods upon the Velocity of the Blast.*

It is a fact of some importance, and one which has not been fully considered by some observers, that in attempting to remove moving carriers from any space by a stream of gas, the number so obtained may not be dependent so much on the total number present as upon the relative velocity of the blast to that of the moving carriers.

Rutherford has shown (Phil. Mag. April 1897) that in blowing ionized air along a charged wire which is placed in a tube a maximum value is reached for the amount of free electrification blown out, as the potential of the wire is gradually increased.

A number of experiments have been made with the apparatus shown in fig. 7, which show how the quantity of electrification removed from a plate by a given blast depends not only upon the electric field used, but also upon the sign of the ions which are being carried out.

In the case to be considered the plates were placed 4.1 centim. apart, and the slits were placed as near as possible to one of the plates, the other of which was always connected to earth. A blast of the same velocity was used throughout, and readings were taken of the amounts of electrification obtained in a given time as the potential of the plate was changed in amount and in sign.

The following table gives the results obtained in a sample case :—

TABLE V.

Voltage of plate 1 cell=2.07 volts.	Deflexion with plate negative.	Deflexion with plate positive.
cells.		
0	+ 10	+ 10
10	+112	- 57
20	+187	-104
30	+201	-106
35	+206	-110
40	+190	-108
50	+174	- 76
60	+139	- 49
80	+ 85	- 12
100	+ 42	- 5
120	+ 21	+ 2.5
160	+ 5.5	+ 2.5
204	+ 1.5	+ 2

Fig. 10.

The numbers show in a marked way that the velocity of the positive ions is less than that of the negative.

The small deflexion obtained with both plates to earth is very likely due to a diffusion effect in the narrow slits of the apparatus, as is explained in § 7.

The above results are shown graphically in fig. 10.

It is seen that the electrification blown out at first increases rapidly with the voltage used, and that it reaches a maximum which is followed by a rapid decrease.

The following consideration will show in a general way the cause of these changes in this particular case:—

In fig. 11 AD represents a section between the two slits M and N, of the air which is moving from right to left with a constant velocity V.

The ions are forced to cross this moving layer by the action of the electric force between the plates.

Fig. 11.

If u is the velocity of the ions travelling towards the plate P when in a unit electric field, their velocity in a field F is Fu . When this velocity is small compared to that of the blast, *i. e.* so long as $\frac{Fu}{V} < \frac{AC}{AB}$, all of the ions which cross

AB moving towards P, and those which cross CD moving from P, will be carried by the blast into the slit M. The nature of the charge carried into M will depend mainly upon the relative number of the two kinds of ions thus entering the area AD; and as CD is very close to the plate the number coming in from that side is small compared to the number entering at AB, and so the sign and the amount of the charge depend for the most part upon the number crossing AB. (Exceptions, due to surface ionization, are mentioned later.) At first the number entering is nearly proportional to F , and the straight part of the curve from A to B in fig. 10 is obtained.

When $\frac{Fu}{V} = \frac{AC}{AB}$, ions that are entering at B take the path BC due to the two velocities, and just manage to get into the slit M. As F is increased still more, those ions only

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can enter M which cross AB in Ax , as those crossing in Bx reach the plate P.

The point x moves towards A as F is increased. When this state is reached, the number of ions crossing AB is, in our case, still increasing with F, and so the amount obtained is dependent upon the two opposing actions, *i. e.* the increase in the number crossing AB, and the decrease of Ax , the area from which ions can reach the slit. This corresponds to the maximum part B of the curves. When F becomes so large that a saturation-current is obtained, the number of ions crossing AB is constant, and as F increases, the number that reach M is proportional to the decreasing Ax . Since $F \cdot Ax = \text{a constant}$, the curve representing F and the number of ions now approaches an hyperbola, as is shown by the part C of the curves in the figure. Finally, for high values of F, no matter how many ions enter the blast, none are carried out. For the sake of brevity, the predominating action has alone been outlined, and various factors which take part have not been considered, but from what has already been said the effect of these can be followed.

For the same velocity of the blast, the nature of the curves obtained depends also upon the distance between the plates. When these were moved nearer together, the saturation-current was obtained while all of the ions crossing AB were still being blown into M. In that case a curve similar to the above has a maximum which turns sharply, and is not so blunt as those in the figure.

In other cases increased ionization at the metal surface plays an important part, and this is especially so when the plates are close together, so that the surface-ionization is a large part of the total ionization between the plates. Here complex curves are obtained, due to the opposing and at times even predominating influence of this surface-ionization. With the rays striking the plates which were close together, the sign of the charge blown out was the same as that of the plate along which the current of air passed, or the reverse of what was obtained above, for here nearly all of the ionization was near the metal surfaces.

For a somewhat larger distance the surface-ionization predominated for the smaller voltages only, and as more ions were drawn from the space between the plates by the higher voltages the sign of the charge obtained was reversed.

These facts show in what a radical manner the electrification, obtained by means of a current of air, is dependent upon the velocity of the blast, upon the velocity and distribution of the ions, and upon the arrangement of the apparatus.

§11. *Potential Gradient between two Plates.*

It has been shown in §9 how the free electrification is distributed between two plates between which conduction is taking place through air, and it is evident that this electrification must exert a marked influence upon the electric field between the plates.

The variation of the potential between two such plates has been investigated by means of the following apparatus. A and B in fig. 12 are the two parallel, 11 cm. square plates situated above and being perpendicular to the top of the lead box which contains the induction-coil and the tube.

Fig. 12.

The rays coming out through an aluminium window pass through the air between the plates, covering a volume indicated by the dotted lines.

The plates are connected to the two poles respectively of a battery C, whose middle point is to earth.

To determine the potential at different points between the plates when the rays are acting, a fine wire M, of the same metal as the plates, was used. It was stretched between two insulated parts R and S of a glass frame N, as is shown in the lower figure, and was connected to a pair of quadrants of an electrometer by means of the wire K. For small voltages the other pair of quadrants was connected to earth,

and for higher voltages it was connected to a source of potential nearly equal to that of the place to be measured. By means of the part E, sliding on the rod D, the wire can be moved to any part of the field, and its position observed on the scale M by means of the pointer F.

In taking readings, the wire is simply allowed to remain in the desired position until it assumes the potential of the place due to the ions in the air, as is indicated by the electrometer deflexion remaining stationary.

In the following example the plates and wire were made of aluminium, and the plates were 3 centim. apart and connected to the opposite poles of two storage-cells the point between which was to earth.

The readings obtained are given in Table VI., together with readings calculated for a uniform gradient such as exists when the rays are not acting.

TABLE VI.—Potential between Plates.

Distance from Negative Plate.	Observed Potential.	Potential calculated from a uniform gradient.
mm.	volts.	volts.
0	-2	-2
1	-1.26	-1.87
2	-1.16	-1.74
4	- .94	-1.47
6	- .78	-1.20
11	- .33	- .53
16	+ .11	+ .13
21	+ .60	+ .80
26	+1.11	+1.47
28	+1.31	+1.74
29	+1.42	+1.87
30	+2	+2

It will be seen that the deviations from the straight potential gradient are considerable, and that the fall of potential is very rapid at the plates, being greater at the negative plate. The reason for this is that the amount of positive electrification at the negative plate is greater than that of negative at the positive plate, due to the difference in velocity of the two ions as has been shown in § 9.

The results are represented by the curve in fig. 13. The field near the centre is quite uniform, as there is little or no

free charge there, but near the plates, where most of the charge exists, the changes are very rapid. When the potential between the plates is increased, the fall at the plates also increases.

Fig. 13.

Thus, by using 6 cells the fall was practically three times that obtained above with the 2 cells.

The conditions affecting the amount of free charges at the plates are necessarily applicable to the changes of potential resulting from them. These have already been given in §9, where it will be seen what effect surface-ionization and other causes have upon the fall of potential near the plates.

Having obtained the potential curve experimentally, it is possible to calculate from it the density of the electrification at the various points between the plates.

Let V be the potential at a distance x from the point where the curve (fig. 13) crosses the line of zero potential. Then if ρ is the density of the electrification at the point x

$$\frac{d^2V}{dx^2} = -4\pi\rho \quad \text{as} \quad \frac{d^2V}{dy^2} = \frac{d^2V}{dz^2} = 0.$$

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Integrating,

$$\frac{dV}{dx} = -4\pi \int_0^x \rho dx + C,$$

where

$$C = \left(\frac{dV}{dx} \right)_0,$$

the value of $\frac{dV}{dx}$ at $x=0$; and

$$\int_0^x \rho dx = Q_x,$$

the total charge in a volume of unit cross-section extending from $x=0$ to $x=x$.

Hence

$$Q_x = - \frac{\frac{dV}{dx} - \left(\frac{dV}{dx} \right)_0}{4\pi}.$$

The value of

$$- \frac{\frac{dV}{dx} - \left(\frac{dV}{dx} \right)_0}{4\pi}$$

can be obtained for any point x from the curve in fig. 13 by the equivalent expression

$$- \frac{\tan \theta - \tan \phi}{4\pi},$$

where θ and ϕ are the angles indicated in the figure.

From such values a curve can be plotted showing the relation between Q_x and x .

If V and x (fig. 13) are measured in absolute units, then the ordinates of the curve obtained will represent Q_x in absolute units of electrification.

Fig. 14 shows such a curve derived from fig. 13.

Since the ordinates represent the total quantity of electrification for a unit cross-section between $x=0$ and $x=x$, the quantity between any two points x_1 and x_2 is obtained from the difference of the ordinates for these two points, and by dividing this by $x_1 x_2$ the average density between the two points is obtained.

The curve shows that for such small potential gradients as that used the free electrification is confined mostly to the boundaries, the space between being almost free from any charge. As the potential gradient is increased, electrification is obtained farther from the plates, and with large voltages

the fall of potential near the plates is very large, and the charges extend all through the space between them.

In the case above (fig. 13) the fall of potential at the cathode was $\frac{3}{4}$ of a volt, being more than one third of the total potential of the plate. This fall was due to the presence of electrification of an average density less than 2×10^{-4} (fig. 14). If we take the charge on each carrier to be the

Fig. 14.

atomic charge, or about 10^{-10} absolute units, it would require about 10^6 carriers per c.c. to produce the density observed. Taking the number of molecules in 1 c. c. as 10^{20} , the ratio of the excess carriers to the total number of molecules is given by $\frac{1}{10^{14}}$. From calculations based on the current passing

through a gas during conduction under Röntgen radiation, it is known that we are able to obtain an ionization that is between 100 and 1000 times as large as this ratio; so that, by a sufficient separation of the two kinds of ions, it is possible to have a fall of potential amounting to more than 100 volts, a value comparable to that due possibly to the same cause, at the electrodes in discharge-tubes.

In determining the ratio of the velocities of the two ions by the method described in §1, it is now evident that it was important to know the potential gradient in the apparatus used (§2) for the conditions under which the readings were taken.

To determine this, one of the glass side-plates of the box PQ (fig. 2) was replaced by an ebonite one, which had at its middle an air-tight horizontally movable slide. This slide carried the wire used for finding the potential of the different points in the air-current between the plates. On the inside end the wire had a loop which occupied a symmetrical position in the air-stream, while the other end was connected to a pair of quadrants of an electrometer.

Two potentials for the plate Q were found (as in §4), one positive and the other negative, which with a certain air-blast produced in the same time the same numerical deflexion of the electrometer connected to the gauze T.

The gauze was now connected to earth, and the potential gradients were determined separately while each of these two actions was in progress. In doing this, both pairs of quadrants were at first connected to a battery-potential supposed to be equal to that of the point in the apparatus which was under investigation; and when the blast and rays had acted a sufficient time for a steady state to be reached, the pair of quadrants connected to the wire was insulated from the

Fig. 15.

battery, and any change now taking place in the electrometer deflexion indicated whether the potential given to the wire by the battery was larger or smaller than that of the point in question. Potential gradients determined in this way with air in the apparatus are shown in fig. 15.

It is seen that the chief difference between the two gradients in the two cases is that when the negative ions are moving against the stream there is a proportionally greater fall of potential near the charged plate than for the similar case with the positive ions.

The change from the straight gradient is due to the excess of the ions moving towards the charged plate, and this excess is greater for the slower-moving positive ions than for the negative ones; and in both cases, for the same reason, the fall at the charged plate is less than when the air is at rest.

Near the plate from which the blast is coming, the curves are necessarily almost similar, from the nature of the condition that brings the same amount of the two ions to the gauze in the two cases. Since the ratio of the electric forces acting in the two cases is actually found from the figures to be nearly constant for points extending almost to the centre, and as this includes the most efficient part of the field, it is not necessary for our purpose to decide just how far out from the gauze the forces influence practically the number of ions that reach the gauze.

The ratio obtained for the two gradients at these places is nearly, but not quite, equal to the ratio of the potential values used, and the difference is mainly due to the greater fall of potential at the charged plate when the negative ions are moving against the stream, as this leaves proportionally less to be distributed in that case over the remainder of the space. The correction calculated from the figures for air amounts to about 2 per cent., which is to be added to the ratio of the positive potential used to that of the negative; and as this correction is chiefly due to the difference of velocity of the ions, the value obtained for air has been applied to the other gases in proportion to the difference of velocity obtained for them.

§12. *Remarks.*

From the table on p. 132, § 4, it is seen that for all of the gases tried, where a difference of velocity for the two ions exists, with one possible slight exception, the velocity of the negative ion is the greater. It is also seen that for such simple gases as O and N the difference is considerable, while for CO₂ there is no appreciable difference, a result which could scarcely be anticipated. It would appear from these results that some relation exists between the ion and the charge carried by it which is dependent upon the sign of the charge, and which varies with the constitution of the ion.

In contemplating the cause of the difference of velocity of

the two ions, we must look to the size of the ions and to the charges carried by them, for upon these two factors the velocity itself depends.

As to the charges on the two kinds of ions, the simplest assumption we can make is that they are equal, for if we assume an unequal distribution we are led into a difficulty in imagining a process whereby the two charges are distributed upon an unequal number of carriers, and so that the charge upon each of those of one sign is just a little different from that upon those of the other sign.

We are thus led to suppose, as in liquids, that the observed velocity difference is due to an inequality in the size of the two ions. Why the two ions, even if they are formed of groups of molecules, should in a simple gas be of a different size is a question to which definite answers cannot be given in the present state of our knowledge, or rather ignorance, of the relation between matter and electricity, but is one which must be borne in mind in considerations of this relation.

In conclusion, I desire to express my best thanks to Prof. J. J. Thomson for many valuable suggestions.

Cavendish Laboratory,
April 12, 1898.

VII. *On the Mechanical Forces acting on a Piece of Iron carrying an Electric Current.*

To the Editors of the Philosophical Magazine.

GENTLEMEN,

THE subject of the forces acting on a piece of iron carrying a current, which is raised by Lord Rayleigh in the June number of the *Philosophical Magazine*, is one of so much interest and importance that I hope the following remarks may not be considered superfluous.

To find the force on the piece of iron, let us begin by considering the force exerted by the system of the iron and currents on an external magnetic system; this force is equal to the force due to the currents calculated by the same rule as if they were flowing through a non-magnetic substance, say copper, *plus* the magnetic forces due to the magnetization induced or permanent in the iron. It follows from this by the equality of action and reaction that the force acting on the iron will be a force due to the action of the magnetic field on the currents through the iron, this force to be calculated as if the currents were flowing through copper *plus* the force due to the magnetic field on the magnetization in the iron. From this it follows that if A, B, C