other words, that the disintegration of the electrode played no essential part in the discharge.

The quantity of electricity required to effect a discharge, other things being equal, increases with increasing pressure. This increase is at first rapid, then slower, and at high pressures it is nearly proportional to the increase of pressure. It was found that y could be expressed with sufficient accuracy in terms of the pressure p by the empirical formula, $y = A + Bp - Cp^2$, in which the constants A, B, C depend on the size and insulation of the electrodes, their distance apart, and so on.

They arrange the gases in the following order of dielectric strength:—hydrogen, oxygen, carbonic acid, air, nitrogen. It is not a little remarkable that this is the order given by Faraday in the second column (the best) of the results we quoted above.

They find, in agreement with Faraday, that a greater quantity of electricity is required to bring two unequal spheres to the discharging point when the small one is positive than when it is negative. When two equal spheres are used, the value of y is least when both are insulated, greater when the positive sphere is uninsulated, and very much greater when the negative one is uninsulated.

All this is in accordance with theory, provided we assume with Faraday that the limiting tension is greater at positive than at negative surfaces. For example, suppose the surface densities corresponding to the limiting positive and negative tensions to be P and N ($P > N$), and consider the case of two equal spheres of radius a, at so great a distance c apart that $\left(\frac{a}{c}\right)^3$ may be neglected, then by taking three consecutive images the reader will easily find that the charges which must be given to either ball in the case where both spheres are insulated and equally charged, and to the negative ball in the case where the positive ball is uninsulated, and to the positive ball when the negative ball is uninsulated, must be $\left(1-3\frac{a^2}{c^2}\right)4\pi\,{}^2N$, $4\pi a^2N$, $4\pi a^2P$, respectively, in order to produce discharge. The discharge begins at the negative ball in the first two cases, and at the positive ball in the third, and the quantities are obviously in ascending order of magnitude when P is $> N$.

High pressures.

The dielectric strength goes on increasing when the pressure is raised above the atmospheric pressure. Cailletet[1] found that a powerful induction coil worked by eight large Bunsen cells was powerless to effect discharges across $\frac{1}{2}$ mm. of dry gas at a pressure of 40 or 50 atmospheres.

Minimum strength.

On the other hand, however, the dielectric strength does not diminish indefinitely as the pressure decreases, but reaches a minimum.

Morren and De la Rive[2] have sought to determine this minimum dielectric strength by measuring by means of a galvanometer the mean intensity of the current sent through the gas by an inductorium so arranged that only the direct induction current passes; they thus obtain what they call a minimum *resistance*. Morren gives the pressures corresponding to this minimum for various gases; they lie between 0·1 and 3·0 mm. It may be questioned whether any very definite meaning can be attached to results of this kind; for the discharge is discontinuous, and *resistance* in the proper sense of the term cannot be spoken of.

It is clear, however, that a minimum dielectric strength must exist; for, if we go on improving our vacuum, we find that our ordinary machinery fails to send electricity through any considerable length of the exhausted space.

Morgan[3] seems to have been the first to discover that the electric spark would not pass in a vacuum. Having carefully boiled the mercury in a barometer tube, so as to remove the last traces of moisture, he found that the inductive discharge caused by electrifying a piece of tinfoil on the outside of the tube would no longer pass to the mercury, and cause the luminous phenomena usually seen under such circumstances. Masson repeated this experiment in a more satisfactory form. Gassiot[4] greatly improved the exhaustion of vacuum tubes by filling them with CO_2, pumping out as usual, and then absorbing the residual gas by fusing a piece of KHO previously inserted into the tube. He constructed tubes in this way which had sufficient dielectric strength to insulate the pole of his great battery of more than 3500 Zn. Aq. Cu. cells. Hittorf and Geissler[5] have constructed vacuum tubes (by pumping with a Geissler's pump, and heating the whole to 400° to 500° C.) in which the opposition to the discharge of an interval of $\frac{1}{4}$ mm. between two platinum electrodes was greater than that offered by 15 or 20 centimetres of ordinary air.

Different Forms of the Discharge in Gases.—We have said that the subsequent progress of the disruptive discharge when once begun is influenced by a great variety of circumstances. The beginning of the discharge evolves heat, which rarefies the neighbouring air, and therefore weakens its dielectric strength. Owing to this cause the discharge once started tends to go on. Again, if any considerable quantity of electricity escapes into the ruptured dielectric at the first burst, this relieves the tension at the surface of the conductor. On the other hand, the progress of part of the electricity towards the opposing conductor raises the tension at the surface of the latter, so that disruptive discharge is provoked or helped there. If the initial tension is considerable, or the quantity of electricity which passes to begin with very great, glowing metal particles are shot forth into the dielectric, causing a reduction of its strength, which will be very different in different directions. Motions of the air play a great if not a preponderating part in many forms of the discharge. The electrification, &c., of the walls of the tube, and the form of the electrodes and of the tube, both in the neighbourhood of the electrodes and at a distance from them, are as important in their influence on the continuance of the discharge as they are on its start. And, last but not least, much depends on the way the electricity which produces the discharge is furnished,—on the nature of the electromotor, in short. Although we have not yet exhausted the influencing conditions, we have probably said enough to convince the reader that little aid is to be hoped for in this matter from considerations *a priori*. There is a great deficiency even in proximate principles to guide us in the maze of experimental detail; and although most of the experiments are beautiful beyond all conception, yet the mere narration would scarcely interest the reader. Our description of the department will, therefore, consist simply in going round the boundary.

The luminous appearances may be roughly classed under the forms of spark, brush, glow and convective discharge, and dark discharge.

Sparks.

At the ordinary atmospheric pressure the disruptive discharge between two conductors at a moderate distance apart takes place in the form of a brilliant sharply-bounded streak of light, whose apparent breadth is in general small. For small distances the spark is straight, and has the appearance of being thicker, or at least more brilliant, at the ends than in the middle. When the distance is considerably increased the spark assumes the characteristic zig-zag form seen in forked lightning. It seems occasionally to be absolutely broken by perfectly dark spaces. The duration of the discharge in this form, more especially when the resistance of the discharging circuit is very small, as tested by a rotating mirror, appears to be exceedingly short.

We have taken photographs of the sparks of a Holtz's machine by simply moving the camera containing the sensitized plate vertically upwards past the electrodes of the machine. The result is a column of perfect photographs, quite unblurred by the jarring, &c., of the camera stand. Again, if a disc painted with white and black sectors be caused to rotate very rapidly, it appears in ordinary light to have a uniform grey colour; but when it is viewed by the light of an electric spark the sectors are seen exactly as if the disc were at rest, which proves that the illumination lasts for a very short time. Masson founded on this experiment a beautiful method for measuring the intensity of the light given out by the spark. A description of his apparatus, with an account of his results, will be found in Mascart.

The colour of the spark in air is bluish,[6] but at the same time its great brilliancy gives an impression of whiteness. In nitrogen the appearance is much as in air, only the colour tends more to bluish purple, and the spark is more sonorous. In oxygen the spark is whiter and less brilliant than in air; in hydrogen crimson-coloured; in carbonic acid greenish; in hydrochloric acid white, and never broken by dark parts; in coal gas green or red, with occasional dark parts. If the spark be carefully examined, especially when the pressure is greater than an atmosphere, it will be seen that the central bright streak is surrounded by an envelope, of somewhat nebulous form, and of a lavender-blue colour. This envelope tends to spread over the negative electrode, where it is more conspicuous as compared with the central streak than elsewhere. This envelope appears to be due to the glowing metal particles torn from the electrodes. It has, unlike the central streak, a sensible duration, on account of which it happens in many cases that a much greater quantity of electricity passes through it than through the infinitely more brilliant but less enduring part of the discharge. The envelope can be actually separated from the streak by a current of air properly directed, or by the action of a magnet (*vide infra*, p. 74).

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[1] Mascart, t. i. § 187

[2] Wiedemann Bd. ii. § 952

[3] *Phil Trans.*, 1785.

[4] *Phil. Trans.*, 1859.

[5] *Pogg. Ann.*, 1869

[6] Faraday, *Exp. Res.*, 1422.

When the discharge in air at the atmospheric pressure takes place between a *salient* but *not pointed* part of one conductor and another conductor *of considerable surface* (*e.g.* between one sphere 2 cm. diameter and another 13 cm. diameter), the luminous appearance very often takes a characteristic form, which has been called the brush discharge. The name is to a considerable extent descriptive of the phenomenon; if the word broom had been applied it would have been even more appropriate, and a rough idea of the variety of forms the brush may assume will be obtained by thinking of the various forms of the domestic article in question. At the surface of the smaller conductor appears a short, straight, luminous stem differing in appearance very little except in brightness from a *spark*. From this radiate a series of twig-like branches of much inferior brilliancy, having a purplish-violet colour. These subdivide in many cases into still smaller ramifications, and are ultimately lost in the medium. When the large conductor is either altogether absent or very distant, the general tendency of the branches is to spread outwards more and more in all directions; but when the large conductor is brought nearer, the branches have a tendency to bend down towards it, so that the whole assumes an ovoid shape. The brush is generally accompanied by a crackling or hissing sound, or even a musical note. On approaching the hand or a conductor of extended surface, the pitch of this sound rises considerably. This at once suggests that the brush is an intermittent phenomenon. That this really is so was clearly proved by Wheatstone in one of the earlier applications of his rotating mirror.[1] Wheatstone saw in his mirror not one image of the brush, but several arranged in succession at regular intervals. Each of these images corresponds to a single discharge, and each appears less complicated than the brush as viewed by the unaided eye, which is, in reality, a superposition of a considerable number of brushes, the number depending on the time taken by a light impression to fade on the retina. At the same time each individual image is a little drawn out in the direction of motion of the mirror, which shows that the brush has a sensible duration. Faraday speculates very acutely concerning the nature of the brush discharge (see *Exp. Res.*, 1425 *sqq.*). He finds that, although it is generally accompanied by a current of air, yet it is not always or necessarily so. He also carefully illustrates the difference between the positive and negative brush. If we have a small ball on the end of a wire projecting freely into the air, the positive brushes[2] obtained from it are much larger and finer than the negative brushes so obtained. Again, if we charge a large metal ball positively, and bring an uninsulated metal point up to it, a star appears on the point, which gets brighter and brighter as the point approaches the sphere, but the form does not change until the distance is very small. If the sphere be charged negatively, the star appears as before when the distance is considerable, but at a moderate distance (1 to 2 inches) a brush forms, and when the distance is still farther reduced a spark passes. It seems, therefore, that the negative discharge keeps its form unchanged under considerable variety of influencing circumstances, whereas the form of the positive discharge is more readily affected. The explanation of these differences he finds in the fact, which he established by experiments already alluded to, that the limiting tension is smaller at positive than at negative surfaces; so that, *cæteris paribus*, the negative discharge occurs oftener than the positive discharge; but, on the other hand, when the latter does occur, more electricity passes. This, no doubt, accounts for the lower pitch of the sound of the negative brush, and the greater extent and brilliancy of the positive one. Faraday found great differences in the character of the brush in different gases; in none apparently does it reach the brilliancy attained in air or nitrogen. He also observed that rarefaction up to a certain point favoured the production of brushes.

Glow.

When discharge takes place from the rounded end of a wire projecting freely into the air, the brush is very often replaced by a quiet phosphorescent glow, which covers a greater or less extent of the end of the wire. The noise which accompanies the brush is entirely absent in this form of the discharge, and the means by which the brush can be analysed into a series of successive discharges give no corresponding result for the glow. In the rotating mirror it simply stretches out into a uniform band of light. The glow is therefore either a continuous discharge or an intermittent discharge of incomparably shorter period than the brush. Diminishing the discharging surfaces favours the production of glow.[3] Increase of power in the electric machine which is furnishing the electricity has a similar effect. Rarefaction of the air has also a great effect in facilitating the production of glow, especially in the case of negative glow, which is extremely hard to produce in air at common pressures. In Faraday's opinion, the star which is obtained with a positive sharp point is a positive glow; but he thinks it not improbable that the negative star is not a negative glow, but a small negative brush. The glow is invariably associated with a current of air to or from (generally both) the glowing conductor. Everything that favours this air-current increases the glow; *e.g.*, a brush may sometimes be converted into a glow by properly directing an air-current near it. Again, everything that prevents or retards the formation of an air-current has a similar effect on the glow: a glow can be converted into a brush in this way. Lastly, everything which tends to prevent abrupt variation of the tension favours the glow, and everything having an opposite tendency is destructive of it. Faraday concludes, therefore, that the glow is due to a gradual discharge by convection, in which the agents are the particles of the gas. The order of the appearance of spark, brush, and glow at positive and negative surfaces is, in general, the same; but the gradation is different. Positive spark does not pass into brush so soon as negative spark does; but, on the other hand, positive brush turns to glow long before negative brush.

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[1] *Phil. Trans.*, 1834, &c.

[2] By positive brush, of course, is meant brush emanating from a positively charged surface.

[3] *Exp. Res.*, 1527.

Convective discharge.

Intimately connected with the glow is the convective discharge, if indeed they are not degrees of the same phenomenon. "The electric glow is produced by the constant passage of electricity through a small portion of air in which the tension is very high, so as to charge the surrounding particles of air which are continually swept off by the electric wind, which is an essential part of the phenomenon."[1] Now there seems little reason to doubt that at lower tensions[2] discharge of this kind may occur without the luminous phenomenon at the surface of the conductor. If this be so, then the convective discharge is only a different degree of the glow discharge.

Discharge by convection plays a very important part in all electrostatical experimenting. The air in the neighbourhood of an electrified conductor gets charged, forming an electrical atmosphere, which surrounds the conductor, being more extensive in the neighbourhood of salient angles than elsewhere. Such electrical atmospheres are often a source of great inconvenience in the laboratory and lecture-room when delicate electrical experiments are in progress.

A curious little instrument, called the electrical tourniquet or windmill, depends for its action on the electrical wind which accompanies convective discharge. A small rectangular cross, with equal arms, is made of light wire; the extremities of the arms are bent through a right angle in the plane of the cross, so as to point all one way. The little cross thus made is poised, like a compass needle, on a vertical wire connected with an electrified conductor. Convective discharge takes place at the points, giving rise to an electrical wind, the reaction of which causes the little machine to revolve with great rapidity. If the experiment be conducted in the dark, a glow usually appears on the revolving points. The experiment also succeeds when the cross is immersed in a non-conducting liquid.

Dark interval.

We have already alluded to the dark spaces that sometimes appear in the spark in gas at the atmospheric pressure. Faraday observed that a phenomenon of this kind was very common in coal gas. When the discharge takes place in highly rarefied gas, a dark space of this kind almost always separates the positive from the negative light, its situation having a certain degree of fixity with respect to the negative, but not to the positive electrode. It is very difficult to form an idea of the exact nature of the discharge which takes place in this space. Discharge there undoubtedly is of some kind; and pending further investigation, Faraday called it the dark discharge. The fact that its real nature is still undiscovered amply justifies the separate name. Faraday found that it occurred in discharges that pass almost instantaneously, and concluded that it could hardly be due to convection of the ordinary kind, which requires time. De la Rive and Hittorf have made out many peculiarities connected with its appearance in vacuum tubes, the phenomena in which we now attempt briefly to describe.

A variety of forms may be given to the vessel in which the rarefied gas to be experimented on is inclosed.

One of the most common used to be the electric egg, which is simply an oval glass vessel furnished with two small metal spheres for electrodes; the stems which carry these electrodes pass air-tight through tubes cemented to the ends of the vessel; the stem which supports the whole is perforated and fitted with a stop-cock, so that the apparatus can be exhausted to any required extent and then temporarily closed. The commonest of all instruments of this kind now-a-days is the Geissler tube This is simply a glass tube, into which are fused two electrodes of platinum or other metal; a capillary tube allows the apparatus to be connected with an air-pump, and exhausted; when this is done, the capillary tube is sealed up by means of a spirit-lamp. A very common form of such tube is the spectrum tube (see art. LIGHT), consisting of two wider parts, connected by a capillary part, in which the light of the discharge is much more intense than elsewhere. Complicated tubes of all kinds have also been constructed as electric toys.

The reader must not forget that the form of the tube exercises a great influence on the phenomena, whether at the positive or negative electrode. In the summary description that follows the electric egg is referred to, unless it is otherwise stated. We further assume that the electromotor used gives currents in one direction only. A Holtz machine would satisfy this condition, within certain limits at least.

When the gas is rarefied to a considerable extent, the spark loses its sharp outline, becomes interspersed with nebulous portions, and by-and-by loses its characteristic form altogether. As the rarefaction goes on, the discharge ceases to reach from the positive to the negative electrode. The latter now displays a patch of lavender-blue light, separated from the positive light by a dark interval, the length of which depends on the distance between the electrodes. In certain cases the positive light terminates in a cup-shaped depression, whose concavity is turned towards the negative electrode As the rarefaction is still further increased, the positive light tends more and more to fill the tube, although in general it recedes from the negative electrode, over which, on the other hand, the beautiful lavender glow spreads more and more, exhibiting at the same time a growing tendency to fill a limited space *surrounding* the electrode. At a still higher degree of rarefaction, the positive light, which now occupies a considerable space, and takes a shape more or less corresponding to that of the inclosing vessel, is divided transversely into a number of cup-shaped striæ, separated from each other by darker intervals. These striæ vary in form and appearance considerably, according to circumstances. In the neighbourhood of the positive electrode, their concavity is turned towards the positive electrode; but towards the other end of the positive light, the concavity may be turned the other way, especially in the electric egg. The positive light, in vacuum tubes, shows therefore the same remarkable variability, and the negative light the same measure of stability that Faraday remarked in gas at ordinary pressures. The colour of the positive light varies very much in different gases; in nitrogen and air its rosy-red colour contrasts very sharply with the blue of the negative light. The negative light is remarkable for its power of producing fluorescence. It is very dependent as to its extent on the form and size of the uncovered surface of the electrode; anything placed on the electrode cuts it off sharply, as if the light were projected from the electrode and stopped by the obstacle. Disintegration of the negative electrode also goes on very rapidly, so that, after a vacuum tube has been used for some time the glass all round the negative electrode is blackened, browned, &c., as the case may be, with a deposit of finely divided metal. The quantity as well as the quality of this deposit depends very much on the nature of the metal; it is smallest with aluminium, which is on that account much used for electrode terminals. The negative light occasionally shows one, two, or even three stratifications; but in this respect it never equals the positive light. When the rarefaction is carried to the utmost, both positive and negative lights fall off greatly in splendour. The negative light contracts more and more in upon the electrode, and confines itself even there to a small patch near the end, showing, however, a tendency to pass along the axis of the tube towards the positive electrode. The positive light, on the other hand, gradually draws inwards, till at last it is only a star on the end of the electrode, which now disintegrates, owing to the great tension.

Temperature of electrodes.

The temperature at the two electrodes is, in general, very different. The true explanation of this difference has not been made out, although it is doubtless connected with the equally unexplained differences in the light-phenomena. A general rule has been laid down, that the temperature of the negative electrode is always higher when the discharge takes place through the *gas* alone, and the temperature of the positive electrode higher when the discharges pass mainly through particles of disintegrated metal. The former case is commoner in vacuum tubes, where the negative electrode may get white hot, and even melt, while the positive electrode remains quite dark. The latter case is exemplified in the voltaic arc, in which great disintegration of the positive electrode is accompanied by a higher temperature there. Attempts have been made to investigate the temperature in different parts of the tube, and it seems to have been made out that the temperature is lower in the dark intervals than elsewhere.

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[1] Maxwell, *Electricity and Magnetism*, i. § 55.

[2] The reader will not forget the exact sense in which we use the word tension. Of course, low tension does not mean low potential.

When the electromotor is an induction coil, which furnishes discharges alternately in opposite directions, there will be a mixture of positive and negative light at each electrode, unless the maximum tension corresponding to the inverse discharge be so small that the direct discharge alone can break through. If, however, the tube be examined by means of a rotating mirror, or if it be itself fastened to a rotating arm, the images of the different discharges will be separated, and it will be seen that the appearances at each electrode alternate.

With Leyden jar.

Again, when a Leyden jar is discharged through a vacuum tube, the appearances at the two electrodes are often very much alike, particularly when the resistance of the discharging circuit is very small. When the resistance is increased by introducing a column of water or lengths of wetted string, the appearances are similar to those indicated in our summary description. The reason of this is fully explained by the observations of Feddersen. He examined the spark of a Leyden jar by means of a rotating concave mirror. The machine which drove the mirror had a contact-maker, which brought on the discharge when the mirror was at a definite position; the image of the spark was thus thrown by the mirror on a piece of ground glass or a photographic plate, properly placed to receive it. He found that the discharge assumed three distinct characters as the resistance of the discharging circuit was gradually decreased.

Feddersen's results.

1. The discharge was *intermittent*, that is to say, consisted of a series of partial discharges all *in the same direction*, following each other at more or less irregular intervals.

2. When the resistance was reduced to a certain extent, the discharge became *continuous*. The image of the spark on the plate had then the form of an initial vertical strip, with two horizontal strips extending from each end, and gradually thinning off to a point. The vertical strip indicates a single initial spark, and the horizontal bands the finite duration of the light from the glowing metal particles, &c., near the electrodes.

3. When the resistance is very small, the discharge is *oscillatory*, *i.e.*, consists of a succession of discharges alternately *in opposite directions*. These oscillations are due to the self-induction of the discharging circuit; we shall examine the matter more carefully under Electromagnetic Induction.

It is obvious that when the discharge is either *intermittent* or *continuous*, the luminous phenomena will be of the normal form sketched above, but when the discharge is *oscillatory* there will be a mixture of positive and negative appearances at each electrode, the independent existence of which cannot be detected by the unaided eye.

This is the place to remark that it is rarely that the discharge is of the simple form (2), *i.e.*, consists of a single continuous discharge; in by far the great majority of cases it consists of a series of partial discharges. With the inductorium, both varieties (1) and (3) may occur according to the length of the air space, the resistance of the whole secondary circuit, and so on. A number of very beautiful experiments have been made to illustrate these principles, which it would take us beyond our limits to describe. Good summaries of the results of Felici, Cazin and Lucas, Donders and Nyland, Ogden Rood and Alf. Mayer, will be found in Mascart and Wiedemann. Recent researches of a very important character have been made by Wullner[1] and Spottiswoode[2] on the discharge in vacuum tubes. They employ the rotating mirror. It would be premature to attempt to sum up or criticise their results, suffice it to say that they show an amount of agreement which augurs well for the future of this branch of electrical science. The striæ seem, according to them, to play a more essential part in the phenomenon than was perhaps previously expected. Spottiswoode, in fact, seems to incline to the view that all discharges having a dark interval are really stratified, although, owing to their rapid motion, the strata may not be distinguishable by the eye alone.

In connection with this subject it may be well to mention the early experiments of Wheatstone,[3] to determine the so-called velocity of electricity in conducting circuits. Six balls, 1, 2, 3, 4, 5, 6, were arranged in a straight line on a board; 2 and 5 were connected with the coatings of a charged Leyden jar; discharge passed by spark from 2 to 1, then through a large metallic resistance to 3, thence by spark to 4, then through a large metallic resistance to 6, and thence by spark to 5. It was found, as Feddersen observed later, that the introduction of the metallic resistance increased the duration of the sparks at all the intervals, so that the images in the mirror were *lines* of small length; but, in addition, the spark between 3 and 4 began a little later than the sparks at 1, 2 and 5, 6, which were simultaneous. From this the velocity of electricity has been calculated, by taking the interval[4] between the sparks to be *the time which the electricity takes to travel through the metal wire between the intervals.* Faraday long ago pointed out that this interval depends on the capacity of the wire, and may vary very much according to circumstances. It is very great in submarine telegraph wires for instance (*vide supra*, p. 36). Accordingly, the values of the so-called velocity of electricity, which have been found by different observers, differ extremely.

The sketch we have just given of the disruptive discharge in rarefied gases must be regarded as the merest outline. There are many points of great importance to which we have not even alluded. Hittorf's investigation on what has been called the "resistance" of different parts of a vacuum tube during the discharge has not been mentioned, although it led to results of much interest, which must come to be of great importance when the clue to an explanation of the whole phenomena has been found. The reader who desires to study the matter will find in Wiedemann an excellent account of Hittorf's work, with references to the original sources. We have not so much as raised the delicate and difficult questions concerning the spectroscopic characteristics of the discharge. A good part of this subject belongs indeed more properly to the science of Light.

Kinnersley's experiment.

Miscellaneous Effects, chiefly Mechanical.—Owing to the heat suddenly developed by the electric spark, and perhaps to a specific mechanical effect as well, there is a sudden dispersion in all directions of the particles of the dielectric. This commotion may be shown very well by means of Kinnersley's older form of the thermo-electrometer; or Gauss's instrument may be used if we replace the thin wire by a couple of spark terminals. When the spark passes, the liquid in the stem sinks suddenly through a considerable distance, even if the spark be of no great length (2 to 3 mm.).

Very curious effects are obtained when an electric spark is repeated several times at a little distance above a plate strewed with finely powdered chalk. After a time the chalk is seen to be divided by a network of fine lines, resembling the markings on shagreen. If a plate of glass be covered with powdered charcoal, and the spark passed *through* the powder, it arranges itself in a series of striæ closely resembling those seen in a vacuum tube.

The power of the spark to induce chemical combination (in particular, combustion) is due no doubt mainly to its high temperature.

The discharge through non-conducting liquids may take place in the form of spark or brush. The brush, however, is poor compared with that obtained in air, and is very hard

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[1] *Pogg. Ann.*, "Jubelbd.," 1874.

[2] *Proc. R. S.*, 1875-6, 7.

[3] *Phil. Trans.*, 1834.

[4] A better statement would be "the time that elapses before sufficient electricity has reached 3 and 4 to raise the tension at their nearest points to the disruptive limit."

to get. When the spark passes, pressure is suddenly transmitted through the fluid in all directions, and if it be inclosed in a tube the tube is generally broken, even when the spark is by no means long. When the surface of the liquid is free, a considerable portion is usually projected into the air. The convective discharge is very marked in liquids. If two small balls connected with the electrodes of a Holtz's machine in action be dipped in paraffin oil at a small distance apart, the whole liquid is thrown into violent motion by the convection currents, runs up the wires which lead to the balls, and spouts off in little jets.

There is also a distinct heaping up of the liquid between the balls, and if one of them be gradually withdrawn from the liquid, for a centimetre or so it raises a column after it, which adheres until the machine is stopped. It is very probable that other effects due to the alteration of the apparent surface tension, owing to the difference of electrical stress in the air and oil, are present in these phenomena, but this is hardly the place to discuss the matter.

The electric discharge passes with great facility through card-board and other bodies of loose texture. In all probability the air in such cases has quite as much to do with the resulting effects as the solid body.

Lullin's experiment. A curious experiment of this kind is often made. Two points are arranged so as to touch the opposite sides of a piece of card-board. If the points be opposite each other, the discharge passes straight through, leaving in the case of small charges a tiny hole with burnt edges. If, however, the points be not opposite each other, the perforation occurs in the neighbourhood of the negative point. The peculiarity is no doubt connected with those differences between positive and negative discharges in air which we have several times noticed above. In fact, it is found that in an exhausted receiver the card is pierced at a spot very nearly equidistant from the two points.

Discharge in solids. In other cases the main part of the dielectric strength depends on the solid material. The power of such bodies to sustain the electrical tension is often very considerable. Yet there is a limit at which they give way. A thickness of 6 centimetres of glass has been pierced by means of a powerful induction coil.

In such experiments special precautions have to be taken to prevent the spark from gliding over the surface of the glass instead of going through; this is managed in some cases by embedding the glass along with the terminals of the coil in an electrical cement of considerable insulating power; in ordinary experiments, however, it is in general sufficient to place a drop of olive oil round one of the terminals where it abuts on the glass. The appearance of the perforations depends considerably on the quantity of electricity that passes in the discharge. In some cases the glass cracks or even breaks in pieces. In some large blocks we have seen a perforation in the form of several independent threads, each of which had a sort of beaded structure, which may possibly be in some way analogous to the stratifications in vacuum tubes.

Surface electrification. *Discharge along the Surface of a Body, Dust Figures, and Dust Images.*—The class of phenomena referred to under this head are remarkable for the methods by which they are usually demonstrated. They were at one time much studied on account of the light they were supposed to throw on the nature of the so-called electric fluid or fluids. Though no longer regarded in this light, they have reference to an extremely important and comparatively little studied subject, viz., the distribution of electricity over the surface of non-conductors. It is easy to see that the demonstration of surface electrification on insulators is beset with difficulties of a peculiar kind. A very convenient method is to project on the surface a powder electrified in a known way; this powder clings to the parts oppositely electrified to itself, and avoids those similarly electrified, so that the state of the surface is seen at once. Lycopodium seed and powdered resin have been used in this way; they are sifted through linen cloth, the lycopodium becoming thereby weakly positive, and the powdered resin strongly negative. If the lycopodium be used, it covers both positive and negatively electrified patches, only the latter more thickly than the former. The powdered resin, on the other hand, covers the positive and avoids the negative regions. The most effective powder, however, is a mixture of flowers of sulphur[1] and red lead. In the process of sifting, the red lead powder becomes positively and the sulphur negatively electrified, and the powders separate themselves. The sulphur colours positive regions yellow, and the red lead colours negative regions red. The result is very striking; and the test is found to be very delicate.

Lichtenberg's figures, &c. The dust figures of Lichtenberg are one of the best known instances of the kind of experiment indicated above. A sharp-pointed needle is placed perpendicular to a non-conducting plate, with its point very near to or in contact with the plate. A Leyden jar is discharged into the needle, and the plate is then tested with the powder. If the electricity communicated to the needle was positive, a widely extending patch is seen on the plate, consisting of a dense nucleus, from which branches radiate in all directions. If negative electricity was used, the patch is much smaller and has a sharp circular boundary entirely devoid of branches. This difference between the positive and negative figures seems to depend on the presence of the air; for the difference tends to disappear when the experiment is conducted in vacuo. Riess explains it by the negative electrification of the plate caused by the friction of the water vapour, &c., driven along the surface by the explosion which accompanies the disruptive discharge at the point. This electrification would favour the spread of a positive, but hinder that of a negative discharge. There is, in all probability, a connection between this phenomenon and the peculiarities of positive and negative brush and other discharge in air; Riess, indeed, suggests an explanation of the latter somewhat similar to the above.

There is another class of figures, to which Riess gives the name of electric images, of which the following may be taken as a type. A signet or other engraved piece of metal is placed on a plate of insulating material, and *steadily* electrified by means of a dry pile or otherwise positively or negatively for half an hour or so. When the metal is removed and the plate dusted, an exact figure of the stamp appears, consisting of a red or yellow background on which the engraved lines stand out free from dust. There is no difference between positive and negative electricity here as far as *form* is concerned, and the colour of the figure indicates charge on the plate opposite to that on the metal. The phenomenon appears to be due simply to the electrification of parts of the non-conducting surface opposite the metal.

Figures of Karsten. Another class of phenomena, to which Riess gives the name secondary, depend, not on the electrification of the surface, but on permanent alterations produced by the discharge, whether in the form of spark or otherwise. Sometimes these are directly visible to the eye or touch, *e.g.*, the roughening and discoloration which mark the path of the spark over a polished glass surface. In some cases they are chemical alterations, which may be shown by means of the proper reagents, *e.g.*, the separation of the potash in the spark traces on glass. In certain cases they become evident on breathing upon the glass; of this description are the images of Karsten. A piece of mirror glass is placed on an uninsulated metal plate, and on the glass is placed a coin or medal. Sparks are taken for some time between the coin and an electric machine, and then the glass plate is removed and breathed upon. A representation of the coin then appears on the glass, often complete to the smallest detail. The reader who is interested in these matters, historically or otherwise, will find a variety of information, with directions how to find more, in Riess's *Reibungselectricität*, Bd. ii. § 739 *sqq.*

Electromagnetism and Electrodynamics.[2]

Mention has already been made of the discovery of Oersted, that the electric current exerts a definite action on a magnetic needle placed in its neighbourhood. This discovery formed the starting-point of that division of electrical science with which we are now to deal. It was natural, once the action of a current[1] on a magnet was observed, to look for the reaction of the magnet on the current, and after seeing two currents act on the same magnet, it was reasonable to expect that the currents would act on each other. Yet it may be doubted whether the first of these results is a legitimate deduction from the discovery of Oersted, and the second certainly is not so. Before we can apply the principle of the equality of action and reaction we must be quite certain of the source of the *whole* of any action to which the principle is to be applied. Again, two bodies A and C may act on B owing to properties acquired by virtue of B's presence, so that in the absence of B they need not necessarily act on each other. A good example is the case of two pieces of perfectly soft iron, each of which will act on and be acted on by a magnet, but which will not act on each other when the magnet is not near them.

The questions thus raised by Oersted's discovery were experimentally settled by Ampère. He found that a magnet or the earth (which behaves as if it were a magnet) acts on the current, and the direction of these actions is found to be consistent with the principle of equality of action and reaction. As no experimental fact has yet been quoted against the application of this principle in such cases, we shall assume it henceforth. Ampère also discovered the action of one electric current on another, and thereby settled the second question. We may conclude, therefore, that the space surrounding an electric current is a field of magnetic force just as much as the space around a magnetized body.

The next step is to determine the distribution of magnetic force, or what amounts to the same thing, to find a distribution of magnetism which shall be equivalent in its magnetic action to the electric current. This also was completely accomplished by Ampère. In expounding his results we shall follow the order of ideas given by Maxwell,[2] which we think affords the simplest view of the matter, and is the best practical guide that we know of through the somewhat complicated relations to which the subject introduces us. We shall in addition give a sketch of the actual course which was followed by Ampère, and which is adhered to by the Continental writers of the present day.

Fundamental principle. It results alike from the fundamental experiments of Ampère and the elaborate researches of Weber, to both of which we shall afterwards allude, that an electric current circulating in a small plane closed circuit, acts and is acted upon magnetically exactly like a small magnet placed perpendicular to its plane at some point within it,[3] provided the moment of the magnet be equal to the strength of the current multiplied by the area of the circuit,[4] and its north pole be so placed that the direction of the axis of the magnet (from S-pole to N-pole), and the direction in which the current circulates are those of the translation and rotation of a right-handed (ordinary) screw which is being screwed in the direction of the axis. In this statement we have spoken of a *small* closed circuit. The word "small" means that the largest dimensions of the circuit must be infinitely smaller than its distance from the nearest magnet or electric current on which it acts, or by which it is acted on.

We may break up our small magnet into a number of similar magnets, and distribute them over the area of the small circuit, so that the sum of the moments of all the magnets on any portion w of the area is wi, where i is constant. We thus replace the circuit by a "magnetic shell" of strength i, which, if we choose, may be represented by two layers parallel to the area, one of north the other of south magnetism, the surface density of which is $i \div \theta$, where θ is the distance between the layers.[5]

Finite circuit and magnetic shell. Starting from the principle thus laid down we can derive all the laws of the mutual action of magnets and electric currents.

Consider any finite circuit ABC (fig. 29). Imagine it filled with a surface of any form, and a network of lines drawn on the surface as in the figure, dividing it up into portions, such as *abcd*, so small that they may be regarded as plane. It is obvious that any current of strength i circulating in ABC may be replaced by a series of closed currents, each of strength i circulating in the meshes (such as *abcd*) of the network on the surface; for in each line such as *bc* we have two equal and opposite currents circulating whose action must be *nil*. Now, we may replace each of the small circuits by a magnet as above, or by a magnetic shell of strength i. The assemblage will constitute a magnetic shell of strength i filling up the circuit, whose magnetic action, at every point *external*[6] to the shell will be the same as that of the current. The north side of the shell is derived from the direction of the current by the right-handed screw relation given above.

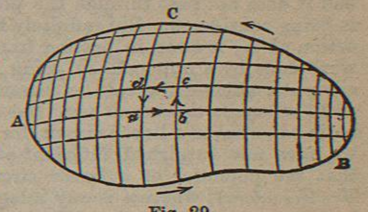

Fig. 29.

If dS be an element of the surface of a magnetic shell of strength i, D its distance from P, and θ the angle which the positive direction of magnetization (which is normal to dS) makes with D, then the magnetic potential[7] at P is given by

$$V = i\iint \frac{\cos\theta}{D^2}\,dS \quad . \quad . \quad . \quad . \quad (1),$$

the integration extending all over S.

When properly interpreted this double integral is found to represent the "solid angle" subtended at P by the surface S, or, as it may also be put, by the circuit ABC which bounds it. Hence, solid angles subtended by the north side being taken as positive, and the usual conventions as to sign adhered to, we may write

$$V = i\omega, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2),$$

where ω is the solid angle in question.

Potential of shell. We see, therefore, that the potential of a magnetic shell at any point P is equal to the product of the strength of the shell into the solid angle subtended by its boundary at P. Now the potential of such a shell is continuous and single-valued at all points without it. (With points within it we are not now concerned, since the action of the current at such points is not the same as that of the shell.) If, therefore, a unit north pole start from any point P and return to the same, after describing any path which does not cut through the shell, *i.e.*, does not embrace the current, the work done by it will be *nil*. Let us now examine what happens if the path cuts through the shell S. Take two points P and Q, infinitely near each other, but the one P on the positive side, the other Q on the negative side of the

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[1] First used by Villarsy in 1788.

[2] Throughout this section the reader is supposed to be familiar with the experimental laws of magnetism (see art. MAGNETISM). If he desires fully to understand the mathematical developments that occur here and there, an occasional reference to the analysis used in the theory of magnetism will also be necessary, if he is not already familiar with it.

[1] "Current" is used here and in corresponding cases as an abbreviation for the "the linear conductor conveying a current."

[2] *Electricity and Magnetism*, vol. ii. §§ 475, &c.

[3] Naturally the centre of the area if it is symmetrical.

[4] We shall see directly what system of units this statement presupposes.

[5] The reader who finds difficulty with the magnetic shell may adhere to the small magnet; it will be found sufficient for most practical purposes.

[6] This limitation is the equivalent of the limitation *small* applied to the elementary plane circuit, and follows therefrom.

[7] We need scarcely remind the reader that all the definitions of potential, &c., in the theory of electrostatics apply here if we substitute + and − magnetism for + and − electricity. The unit of + magnetism is sometimes called a unit north pole.