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A STUDY OF THE ELECTRIC SPARK IN A MAGNETIC FIELD

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A study of the deflection which magnetic and electrostatic fields produce upon the electric discharge at low pressures has given a clue to the nature of the particles concerned in the discharge, and has made possible measurements of their velocity and of the ratio of their charge to their mass. A similar study of the spark-discharge at atmospheric pressure has not been published, and it is the purpose of the present paper to present the results of such a study. The investigation has been undertaken with the idea that if a proper combination of conditions could be secured, a magnetic field might cause a deflection of such a character and magnitude as to separate the constituent parts of the spark, thus securing, as it were, a differentiation in space. Moreover, since the reflection from a mirror in rapid rotation indicates the time-changes which occur, the image thus obtained of the spark dispersed in a magnetic field would show the twofold separation of time and of space, and it was hoped that this separation might lead to a more detailed acquaintance with the mechanism of the electric spark.

Professor J. J. Thomson in his book, *The Conduction of Electricity through Gases*, makes on p. 522 the following statement:

> The effects produced by a magnetic field upon the spark at atmospheric pressure are very slight, although the halo of luminous gas which surrounds the course of the sparks when a number of sparks follow each other in rapid succession is drawn out into a broad band by the magnetic field.

He also states (on the same page) that Precht has found an effect of the magnetic field upon the spark at atmospheric pressure, if the spark terminals consist of a sharp point and a blunt wire; but Precht[1] has described the character of this deflection only so far as to say that its direction agrees with the electro-dynamic laws. Precht's paper is mainly concerned with a study of the different conditions in which one form of the discharge—spark, brush, or glow—becomes

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[1] *Annalen der Physik*, **66**, 676, 1898.

changed into another, and of the changes in the potential difference of the terminals occurring under these different conditions.

The method of using a rapidly rotating mirror to show the separate oscillations which occur in the spark when a condenser is placed in the discharge circuit, was first employed by Feddersen,[1] who made use of it successfully to measure the period of the oscillatory discharge, and thus confirmed the theoretical work of William Thomson (Lord Kelvin). Following him many others have used it for similar measurements.

The use of a rotating mirror and later of a rotating film to gain an insight into the constitution of the electric spark was first made by Schuster and Hemsalech,[2] later by Schenck.[3] A glance at Plate XIV, Fig. 1, showing the appearance of the oscillatory spark when viewed in a rapidly rotating mirror, will make clear the summary of their combined results. The three general features of this discharge as given by Schenck are:

> 1. A brilliant white straight line due to the first discharge, which is sometimes followed by one or two similar weaker straight lines at intervals of half the complete period of the condenser.
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> 2. Curved lines of light, which shoot out from the poles toward the center of the spark-gap with a velocity constantly diminishing as they move away from the poles. It will be noticed that, as the light advances from one pole, the light moving away from the opposite pole is either very weak or absent altogether.
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> 3. A rather faint light, generally of a different color from the curved lines of light, which fills up the spark-gap and persists for a certain length of time, especially in the center of the spark-gap, after the oscillations die out.

Schuster and Hemsalech (*loc. cit.*) first found that sufficient self-induction in the discharge circuit causes the air lines to disappear from the spectrum of the spark. Later Hemsalech[4] discovered that when the self-induction is increased, the so-called spark lines disappear, whereas the arc lines in the spectrum of the spark become brighter. Schenck (*loc. cit.*) in turn made this difference the basis of a division of the lines of the spark spectrum into three groups, this division occupying the first part of his paper. These several experimental results as arrived at by Schuster, Hemsalech, and Schenck have all been noted during the present investigation, though their

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[1] *Pogg. Ann.*, **116**, 132, 1862.

[2] *Phil. Trans.*, **193**, A, 189, 1900.

[3] *Astrophysical Journal*, **14**, 116, 1901.

[4] *Comptes Rendus*, **129**, 285, 1899.

bearing upon the problem here proposed is less immediate than that of other observations made by them.

The results which have a more intimate bearing here do not relate to the disappearance of the air, spark, and arc lines under certain conditions, but to what is true of them under all conditions. Since the photographs of the spectrum lines taken upon a rapidly rotating film showed the air lines to be entirely absent in all the spectra except that of the initial discharge, Schuster and Hemsalech concluded that only the initial discharge passed through the air.

By a similar method of studying the spectrum lines—the only variation being the use of a rotating mirror instead of a rotating film—Schenck brought out an interesting difference between the spark and arc lines, viz., that the spark lines appear sharply beaded to the end of the line, whereas the arc lines show only indistinct traces of beading, which do not extend to the end of the line. In other words, he concluded that the spark lines are due entirely to oscillations, while the arc lines are due partly to the oscillations and partly to something else which retains its luminosity after the oscillations cease. The spark lines are in the spectrum of the streamers which are described as the second feature of the spark; the arc lines in that of the vapor already mentioned as the third feature.

Furthermore, Schenck (*loc. cit.*) has found that the streamers emanate from the cathode and he has concluded that they do not carry the current. This view is supported by Hemsalech,[1] who, after identifying the streamers with the metallic vapor, advances the theory that the electric charge is not carried by the metallic vapor, but by the nitrogen. As addenda to his paper, Schenck gives the results of his investigation of the effect of a strong magnetic field upon the spark, the investigation having been concerned with the spark in a magnetic field of 10,000 units, both with and without the help of the rotating mirror, though his account as published includes only one feature of the change produced by the magnetic field. I quote from this account:

> With no magnetic field the spark lines and the arc lines extended clear across the gap. With the magnetic field the spark line of magnesium λ 4481 extended outward from each pole only about one-quarter of the way across the gap, leaving

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[1] *Comptes Rendus*, 140, 1103, 1905.

the center free from light of this wave-length, while the arc triplet at λ 5200 extended clear across as it did without the field. When examined with the mirror revolving, the line λ 4481 was broken up into a series of short streamers separated by intervals of darkness, while the arc triplet λ 5200 was in the form of a luminosity which advanced slowly (with a velocity not greater than 0.5×10^4 cm per second) toward the center of the spark-gap being crossed by a series of streamers. The noise of the spark was increased by the magnetic field.

It will be noticed that this description of the image given by the rotating mirror when the spark is in the magnetic field, is not essentially different from that given when the spark is out of the field. Other results relating to the disappearance of the spark lines under certain conditions, though in themselves of minor importance, are necessary to an understanding of conclusions applied by Walter[1] to the results of Schuster and Hemsalech, and involved in the discussion of the present paper. Walter has shown that if the self-induction in the discharge circuit having as spark terminals an alloy of zinc and copper, is increased, the disappearance of the spark lines of zinc before those of copper cannot be explained by the fact that the melting-point of zinc is lower that than of copper, an explanation suggested by Kowalski and Huber[2] in connection with their results. The basis of Walter's objection lies in the fact that under similar conditions he found the spark lines of lead to persist longer than those of copper; whereas, if the difference in the melting-points were the determining factor, the spark lines of lead should, like those of zinc, disappear before the spark lines of copper, since the melting-point of lead is also lower than that of copper. Accordingly Walter,[3] referring to a conclusion reached in one of his earlier investigations, viz., that the metallic vapor in the spark is formed at the negative pole, is led to decide that the metallic vapor must be a result of the disintegration of the cathode. He therefore thinks that the amount of disintegration which occurs at the cathode may be the important factor in determining which lines shall persist longest when the self-induction in the discharge circuit is increased, and he finds that the lines of that metal which suffers most disintegration at the cathode persist longest.

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[1] *Annalen der Physik*, **21**, 223, 1906.

[2] *Comptes Rendus*, **142**, 994, 1906.

[3] *Boltzmann-Festschrift*, 647, 1904.

This conclusion, together with Schenck's observation that the spark lines are affected by the magnetic field, while the arc lines are not, Walter considers a sufficient explanation of the differences which Schenck and Hemsalech have observed in the behavior of the spark lines and arc lines. The metallic particles torn from the cathode by disintegration he thinks carry with them an electric charge which they do not lose until they have reached the center of the spark-gap. The spark lines are characteristic of the light from the metallic particles which carry an electric charge; the arc lines, of that from the metallic particles which have lost their charge.

To explain Hemsalech's result that increase of self-induction causes the spark lines to disappear from the spectrum and the arc lines to become brighter, he says that increase of self-induction lengthens the period of oscillation and decreases the current in the single oscillations. This decrease of current causes a longer interval to elapse between disintegration and luminescence of the particles, thus giving time for a greater number of particles to lose their charge. With added self-induction the ratio of the uncharged particles to those charged increases. Therefore the arc lines characteristic of the uncharged particles are brighter than the spark lines characteristic of the charged particles.

Returning to the results of Schuster and Hemsalech, we find that by means of the curvature which a rotation of the photographic film produces in the metallic spectrum lines, they have obtained as the magnitude of the velocity of the particles of many different metals a value of 4×10^4 cm per second. Schenck, on the other hand, obtaining a value of 25×10^4 cm per second, is led to believe that the difference between his values and those of Schuster and Hemsalech may be due to the fact that they measured the slope of the locus of the extremities of the streamers, while he measured the slope of the streamer itself.

The present investigation may be divided into three parts:

I. A study of the visible space-changes which the presence of a strong magnetic field causes in the spark.

II. A spectroscopic analysis of the different parts into which the spark is spread out under the influence of the magnetic field, this analysis being made solely for purposes of identification.

III. A study of the image of the spark given by a rapidly rotating mirror when the spark is in a magnetic field. The object of this part of the experiment was to get a second differentiation of the spark, viz., a differentiation with respect to time of the space-changes described in Part I.

Three types of electric spark were studied in each of the three parts of this investigation.

1. The spark obtained when neither capacity nor self-induction has been introduced into the secondary circuit of the induction coil.

2. The spark obtained when a capacity of 0.0005 to 0.012 microfarads has been introduced into the secondary circuit.

3. The spark obtained when a capacity of 0.0005 to 0.012 mf and a self-induction of 0.003 henries have been introduced into the secondary circuit.

APPARATUS

The spark was obtained from an induction coil, the primary of which was supplied by a direct current of one to four amperes taken from the 110-volt mains. The potential of the secondary could be raised high enough to produce a 32-cm spark between its poles. With a capacity of 0.012 mf and a self-induction of 0.003 henries in the secondary circuit, a spark of about 2 cm length passed between the metallic terminals. The capacity was obtained from Leyden jars arranged in parallel in the secondary circuit and was varied by gradually changing from a $\frac{1}{4}$-gal. jar to six 1-gal. jars, each 1-gal. jar giving a capacity of about 0.002 microfarads. The self-induction was obtained by placing in the secondary circuit four wire spools arranged in series. An adjustable resistance in the primary circuit served to change the spark from a very noisy to a hissing one. An approximately uniform magnetic field was obtained over a distance of about 2 cm by using truncated cones as the pole-pieces of a large DuBois electro-magnet.

The spectroscopic analysis was made by visual observations and photographs. The former were made by means of a calibrated prism-spectroscope which was mounted upon a carriage that could be moved at right angles to the rays of light falling upon the slit of the spectroscope. In this manner the spectra given by the different parts of the spark could be conveniently studied. The spectrograms were made by means of a Fuess quartz-prism-spectrograph with camera attached.

For the third part of the investigation the image of the spark was reflected from a plane metallic mirror made by Brashear. This mirror was 5 cm in diameter and was mounted so that its rotation was about a horizontal axis. It was driven by a means of an electric motor and could be rotated at a speed of 200 revolutions per second, although a speed of about 50 revolutions per second usually sufficed. The speed of the mirror was measured by the impressions which a bristle attached to its axis made upon a revolving drum. These impressions showed that after the mirror had been in rotation for a short time its speed was practically constant and even such deviations from its constant value as occurred were found to be well within the limit of experimental error.

I. EFFECT OF THE MAGNETIC FIELD

The deflection produced by the magnetic field is most striking when the spark is allowed to pass along the lines of magnetic force or perpendicular to them, the deflection taking the form of circles in the latter case and of spirals in the former. (See Plate XIV, Figs. 3 and 2.) The spirals seem to be wound about cones of revolution, having different angles of divergence, whereas the circles all lie in a plane perpendicular to the lines of magnetic force. In a magnetic field of 1050 units the central threads do not participate in this spiral or circular form.

To appreciate in full detail this effect of the magnetic field upon the spark, a description of the three types of spark-discharge, as they appear both in and out of the field, will be necessary. The first type consists of one or two reddish-white threads which pass directly across the gap and are accompanied by a reddish, luminous vapor that assumes a yellow tinge when the current through the primary circuit is increased. Without the magnetic field this vapor forms an envelope about the central threads: in a parallel field it is deflected into a spiral sheet; in a transverse field into two semicircular sheets which are in the same plane. If the current through the primary circuit is sufficiently small, there is only one such spiral sheet in the first case, and only one plane semicircular sheet in the second. If the current is increased, two spiral sheets or two semicircular ones are present and the latter two are in the same plane, one of them being on either side of the spark-gap. If, however, the spark terminals are drawn sufficiently far apart, one of the two spiral or semicircular sheets disappears entirely. In a field of 12,000 units, however—the strongest that could be obtained with the amount of current available, viz., 19 amperes—no deflection of the central threads could be noticed in either position of the magnetic field.

It was found that a small capacity in the discharge circuit introduced several reddish-white threads into the semicircular and spiral sheets. These threads took the form of spirals in a parallel field, the form of semicircles in a transverse field, and all lay in a single plane perpendicular to the lines of magnetic force. A slightly larger capacity in the discharge circuit made these threads more brilliant and increased their number. Strengthening the magnetic field also increased the number of these threads and their brilliancy. An increase in magnetic field-strength seems therefore to produce the same effect as an increase in capacity.

The second type of spark consisted of a bundle of very brilliant white threads, which were accompanied by little or no vapor. With a capacity greater than 0.002 mf this vapor was not present. In the magnetic field it assumed a circular or spiral form, according to the position of the spark-gap, and was accompanied by thin, brilliant white threads, which likewise were parts of circles or spirals. (Plate XIV, Fig. 5.) This vapor was yellowish in color, whatever terminals were used, and was spread out into a sheet that was so thin as to be almost invisible. The bundle of threads across the gap could not be changed by any available strength of field.

Plate XIV, Fig. 4, shows the central threads and metallic vapor of the third type of spark as they appear without the magnetic field. The threads are not so brilliant as those of the second type of spark, and have the same reddish color for all the metals tried as terminals. The color of this metallic vapor, however, varies with the metal used as spark terminal. With aluminium it is a bright green and shoots out from the electrode instead of enveloping it. With magnesium this vapor is yellow-green; with calcium, pink; with zinc, cadmium, and lead, orange-red with a blue core extending a short distance from the electrode. This vapor does not appear to advance farther from the electrodes as the spark length is increased. It is therefore possible to separate the poles to such an extent that this vapor seems to be entirely absent from the center of the spark. With a given capacity in circuit the length of this vapor increases, however, with an increase of self-induction.

The figure just mentioned was taken from a photographic plate which was not sensitive to the reddish-yellow vapor enveloping the brilliant threads when no magnetic field is present. If the spark terminals are sufficiently far apart or the current through the primary is small this vapor is entirely absent. In the presence of the magnetic field it is changed to bright threads unless the spark terminals are close together. These threads are parts of circles or spirals according to the position of the spark terminals in the magnetic field. Strengthening the magnetic field increases their curvature. The color of these threads varies with the metals used as spark terminals. With aluminium they are reddish-white; with magnesium, red; with calcium, blue; with cadmium, reddish-purple; with zinc, lead, and bismuth, reddish-white. As the capacity and therefore the period is increased, these threads become broader, fewer in number, more red in color—where aluminium is concerned—and tend to depart from the plane perpendicular to the lines of magnetic force in a transverse field. Changing the amount of self-induction in the circuit does not seem to introduce any change into the form or number of the threads; but, if with a capacity of 0.002 mf in a circuit the self-induction is entirely removed, the threads are brilliant white instead of being reddish in color, and they disappear from the immediate region of the central threads, thus decreasing their number considerably. (Compare, Plate XIV, Figs. 7 and 5.) When self-induction is present, these threads which take the form of circles or spirals, according to the position of the spark-gap, can be obtained with a capacity as great as 0.012 mf. Without self-induction it is impossible to obtain any spiral or circular threads with a capacity greater than 0.002 mf. The number of these threads present when the third type of spark is in a magnetic field, passes through a maximum as the capacity is increased from 0.0005 to 0.012 mf, this maximum number occurring when the capacity is about 0.002 mf.

The number of threads present in the second type of spark also passes through a maximum, but here the maximum number occurs when the capacity has a much smaller value, comparable with that obtained from a small parallel-plate condenser. On the other hand, the width of the threads in both types of spark does not pass through a maximum for the range of capacities used, but steadily increases as the capacity is increased. If the electrodes are so far apart that without the magnetic field no vapor envelops the central threads, none of these circular or spiral threads is present when the magnetic field is on. It the electrodes are close together, the vapor is spread by the field into a yellow, circular or spiral sheet, instead of being broken up into brilliant circular or spiral threads.

It requires a much stronger field, however (about 12,000 as compared with 1050), to secure a noticeable change in the central threads. They are twisted by a very strong field along the spark length into a spiral, much like the thread of a screw, and of small radius. (See Plate XIV, Fig. 6.) A field at right angles to the spark length seems to cause a very slight general curvature in these central threads and also to make them appear crenate, the whole being concave to the spark-gap. The number of spiral turns or small semicircles does not in the latter case remain constant, and this irregularity suggests that these spirals or semicircles may be brought about by a sudden change in the velocity of the particles resulting from a loss or gain of electrons.

With this field of 12,000, the metallic vapor of the third type of spark also undergoes a deflection. In a transverse field it certainly assumes a circular form, but in one that is parallel, its form though much changed is too indistinct to be called that of a spiral.

The results thus obtained when any of the three types of spark is in a magnetic field are interesting if compared with the results obtained by Wehnelt,[1] when a hot lime cathode was used for the discharge at low pressures. He found that the particles emitted by a hot lime cathode bring to luminescence the gas through which they pass, and this luminescence indicates the spiral, or circular paths in which charged particles under the influence of a parallel or transverse magnetic field have been shown theoretically to move.

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[1] *Annalen der Physik*, 14, 425, 1904.

The present investigation seems to show that also at atmospheric pressure there are particles which describe luminous paths in the form of spirals and circles. A much stronger field is necessary to produce the deflection here than at low pressures and the radii of the spirals and circles are much smaller.

These observations seem to justify two conclusions, at least, as regards those particles with which luminescence in the spark at atmospheric pressure is associated:

1. They obey in general the laws of motion which experiment and theory have shown charged particles to obey when at low pressure and under the influence of a magnetic field.

2. The obedience to these laws certainly lends strong support to the view that the particles carry an electric charge.

For two reasons it has at present seemed impracticable to find out whether the curvature of the path of these particles, as given by actual measurement, satisfies an equation deduced from theoretical considerations. The electrical conditions are seriously complicated by the necessity of having the electrodes sufficiently close for the passage of a spark at atmospheric pressure, and it would therefore be difficult to find the true values and directions of the electrical forces. The mathematical theory of the behavior of charged particles in a magnetic field has been worked out only in a general way for atmospheric pressure.

Figs. 7 and 8 show a twofold asymmetry in the deflection produced by a magnetic field: (1) an asymmetry at the electrode itself; (2) an asymmetry in the width of the two semicircular, luminous sheets. The latter asymmetry will be considered first.

Figs. 7, 8, 10, and 11 show the difference in the width of the two semicircular sheets. This difference also seemed to exist in the two spiral sheets, but their position as well as their spiral form made it more difficult to compare their respective widths. When the direction of the current through the primary, or that of the magnetic field is reversed these two sheets exchange places (compare Figs. 11 and 10 with Fig. 8). Furthermore when the current through the primary is decreased, or the distance between the spark terminals is increased, both of the sheets become steadily narrower, until finally a stage is reached where only one of the two is present.

The difference in the width of the two sheets can hardly be explained by the fact that the magnetic field may not have been entirely uniform throughout the region of the spark, since this difference in width was found to persist even in that part of the field which was far from uniform. An explanation might be sought in the fact that on one side of the spark-gap the magnetic field, due to the passage of the current, reinforces the permanent field given by the electro-magnet, while on the other side of the spark-gap, it weakens the permanent field. This explanation, however, would require both sheets to be produced at the same time and this simultaneous passage seems improbable since both sheets are later found to be due to particles of like charge. Fig. 9 seems to indicate that the two sheets are not formed at the same time. This photograph was taken when both sheets appeared to be present; yet it shows only one sheet of threads, thus suggesting that the exposure ($\frac{1}{60}$ sec.) was short enough for the set of threads on one side of the spark-gap to be photographed before that on the other was formed.

At the spark terminals the ends of the sheet are asymmetric in the following respect. One end of the semicircular boundary rests on the point of the electrode, while the other end of the boundary is at some distance from the point of the opposite electrode, as may be seen in Figs. 8, 10, and 11.

It has already been stated that the image given by the rotating mirror shows the particles with which these luminous sheets are connected to be most probably negative. If they are negative, then the direction of the field, together with the direction of the deflection, shows that they *advance* from the point of the electrode and *end* in a straight line extending for some distance along the other electrode.

In terms of the brilliant circular threads, characteristic of the spark which results when both capacity and self-induction are inserted into the secondary circuit, this asymmetric form at the electrode may be described thus: The threads all proceed from the extreme end of the negative electrode and end at different points on the positive electrode, these different points being in a straight line and all lying in the plane of the sheet which is perpendicular to the lines of magnetic force. (See Plate XIV, Fig. 7.)

Actual measurement has shown that these circular threads do not possess the same radius of curvature. The asymmetry at the spark terminal may, accordingly, have no deeper significance than the fact that the circular threads are compelled to end upon different points of the positive terminal because their curvature is different, whereas they all start from the same point of the opposite, negative terminal because its potential is higher than that of any other part.

It has already been noticed, too, that if the conical end of the metal terminal is not perfectly smooth, the sheet sometimes starts from one or two other points in addition to the extreme point of the spark terminal. These few points were very different, however, from the line of points in which the sheet ended on the opposite spark terminal—that line of points lying, together with the axis of the spark terminal, in a plane which was at right angles to the magnetic field. Except at the few points from which the sheet seemed to proceed, a space could be seen between the sheet and the terminal from which the particles appeared to start. At the opposite, positive terminal no such separation could be seen between any part of the sheet and the spark terminal. When, therefore, the sheets seemed to start also from other points of the negative terminal, it was supposed due to the fact that an unevenness of the surface of the terminal caused these points to act as additional centers of discharge.

Fig. 10 shows the change which occurs in the position of the sheets when the direction used above for the magnetic field is reversed. It will be seen that the two sheets interchange sides as though each were turned through an angle of 180° about an axis along the spark length.

Fig. 11 shows another difference in the position of sheets, occurring when the current through the primary is reversed, the sheets here undergoing what might be termed a diagonal inversion. Not only does each sheet turn through an angle of 180° about an axis along the spark length, but each end turns, as it were, through another angle of 180° about an axis perpendicular to the spark length and in the plane of the sheet.

The first type of inversion is in entire agreement with such a change in the deflection, as a moving charged particle would experience in a magnetic field in which the direction has been reversed. The second type is also what the electro-dynamic laws would lead

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one to expect for reversal of current through the primary of the induction coil.

II. A SPECTROSCOPIC ANALYSIS OF THE DIFFERENT PARTS OF THE SPARK

An image of the semicircular, reddish sheet presented in a transverse magnetic field by the first type of spark was focused upon the slit of a quartz spectroscope. The slit was at right angles to the spark length so that if any differences existed in the various parts of the sheet they might be shown upon the same plate. A magnetic field sufficiently weak to keep out of the sheet all reddish, circular threads was chosen.

Three different spectrograms were made of each of the following metals: aluminium, bismuth, zinc, cadmium, and lead. The first shows the spectrum of the outer part of the semicircular sheet; the second, that of the part containing the bright threads which pass straight across from pole to pole; the third, that of the third type of spark, taken merely as a means of comparison, and for this purpose it answers very well, inasmuch as the presence of self-induction brings into prominence the metallic lines. Plates were taken with the first spectrum directly above the third; others, with the second above the third. The first two spectrograms were given exposures of one hour; the third, of a minute.

As a result of these experiments the luminous sheet was found to present the same spectrum for each metal tried. This was the spectrum of the nitrogen bands and was found to correspond with that obtained from a low-pressure discharge tube containing nitrogen. The spectrum of the bright threads across the gap showed lines, identified visually with the so-called air lines, and lines corresponding in position to the metallic lines which show prominently in the third spectrogram. These three spectra may be seen in Figs. 12 and 13.

Since the sheets here studied show only the nitrogen bands in their spectrum, it seems probable that whereas their form indicates the path of the charged particles through the air, their luminescence is merely that of the air particles and is not in any way shared by a light characteristic of the metallic terminals from which the charged particles appear to come. On the other hand, since the central threads have the metallic lines in their spectrum, there is reason to believe that they are, in some way, associated with particles which emit a radiation characteristic of the metallic terminals; but which cannot be considered as charged until a deflection or some other evidence is obtained.

The presence of the magnetic field introduces into the intensity of the lines a difference which is interesting. It will be remembered that, with the magnetic field absent, a yellowish vapor envelops the central threads, if sufficient current passes through the primary; also that with the field present, this vapor is spread out into a plane sheet passing through the spark-gap and perpendicular to the magnetic field, thus leaving the region about the central threads free from vapor except in the plane of this sheet. If the spark in the magnetic field is viewed side-on, i. e., if the spectroscope is placed so that no luminous vapor intervenes between it and the central threads, the metallic lines are brighter than when the field is absent. On the other hand, if the spectroscope is placed with its slit in the plane of the sheet of luminous vapor, so that the width of this sheet is between it and the central threads, the metallic lines are fainter than when the vapor surrounds the central threads, as always occurs when there is no field. Since an hour's exposure showed no evidence of these metallic lines in the spectrum of the vapor of the first type of spark, it seems probable that the decrease in the intensity of the metallic lines is due merely to the passage of the light through a cloud of particles and not to any such absorption as could cause a reversal.

The difference of intensity just described has also been noticed in the brightest metallic lines shown on the spectrograms of the third type of spark. When this type of spark is viewed side-on, these lines seem at least twice as bright in the field as out of it.

By extending to the second type of spark the spectroscopic analysis made for purposes of identification, it was found that the bundle of brilliant white threads which pass directly across from pole to pole and are undeflected by any available field have the well-known spectrum which presents itself when capacity is introduced into the secondary circuit, a spectrum consisting of bright air lines and fainter metallic lines. The spectrum lines of the circular threads

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have the same wave-lengths as those of the non-deflectable threads, but they are much fainter. Throughout this paper the word *non-deflectable* is used in a purely relative sense, viz., that the central threads could not be deflected in any available strength of field of 12,000 units. Only for this type of spark is the spectrum of the circular threads the same as that of the threads which pass directly across the spark-gap.

In the third type of spark the investigation was concerned with the spectrum of the bright circular threads, that of the brilliant white central threads, and that of the vapor which extends several mm from the electrodes. All three different spectra were studied for electrodes of aluminium, zinc, bismuth, cadmium, lead, calcium, and magnesium, and no attempt was made to measure the lines with greater accuracy than was necessary for purposes of identification. For the visible spectrum a calibrated prism-spectroscope served to identify the arc, spark, and air lines accurately enough with those given for these metals in the charts of Hagenbach and Konen. The accompanying photographs show the spectrograms of the three different parts of the spark of each metal (taken directly, one above the other, upon the same plate). Plate XIV, Fig. 14, shows the spectrogram obtained when magnesium terminals were used. Fig. 15 shows the spectra of the central threads of each metal, taken one directly above another, and all by focusing upon the slit that part of the spark which is free from the metallic vapor. The time of exposure was two minutes for the spectra of the circular threads and of the central threads; one minute for those of the vapor close to the poles. For the spectra of the central threads the spark-gap was lengthened until the center appeared free from the metallic vapor enveloping the poles. The spectrograms obtained for the seven metals used as spark terminals, together with the visual observations upon the spectra of these metals, gave in general the following results:

1. The circular threads show spectra composed of faint air lines and the bright arc lines characteristic of the metal used. The spark lines appear to be entirely absent.

2. The central threads across the gap show the spectra of the air lines. Plate XIV, Fig. 15, shows that these spectra are practically the same for all the metals used. On some of them the metallic lines

show so faintly that the suggestion is rather that of a diffuse light reflected upon the slit than that of a light coming directly from the threads themselves. This view seems especially valid if one considers that with the spark terminals closer together the metallic lines of this type of spark are very much brighter than the air lines.

3. The vapor near the poles could not be isolated from either the central or the circular threads. Accordingly spectra taken in its region near the spark terminals showed very bright arc and spark lines together with very much fainter air lines. The other two spectra described above in 1 and 2 do not present the spark lines showing these spectra.

Varying the capacity or the self-induction changed only the intensities of the spectrum lines.

III. STUDY OF THE SPARK PLACED IN A MAGNETIC FIELD AND REFLECTED FROM A MIRROR IN RAPID ROTATION

To measure the velocity of the streamers, Schenck, and Schuster and Hemsalech used a method based upon a measurement of the slope of the streamer as given by the mirror in rapid rotation. As the luminescent vapor advanced from the spark terminal toward the center of the spark-gap, the light from this vapor reflected from the mirror when stationary and focused upon the photographic plate described a straight, horizontal line, a true representation of the path of the vapor. When the mirror is in rotation, however, this image is drawn out in a direction perpendicular to that in which the vapor is advancing. The resultant path on the plate is curved because the velocity of the vapor decreases as it approaches the center of the spark-gap.

This method, based upon a measurement of the apparent change of form introduced by the rotation of the mirror, would involve serious complications if it were used to measure the velocity of the particles from which arise the brilliant, circular threads of the spark of the third type. Measurement shows that the curvatures of the threads in a single spark vary considerably among themselves. Accordingly, even if two images of the same single spark-discharge were obtained—the one with the mirror in rapid rotation, the other with it at rest—it would be very difficult to match the threads in the two images and then to measure the change of curvature introduced by the mirror. The existence of such a curvature change, however, suggests a simple method of measuring the velocity of the particles associated with the circular threads, and this method has been adopted in the present investigation. The method is this. The spark is made to pass in a horizontal plane parallel to the horizontal axis of the mirror. The spark terminals are so placed that with the mirror at rest the two ends of each circular thread are at exactly the same distance from the bottom of the photographic plate. When the mirror is set in rapid rotation, the image of each thread shows one end to be farther from the bottom of the plate than the other, this distance being greater for a long thread than for a short one. Evidently a time-interval must have elapsed between the formation of the two ends of the thread, and the existence of this time-interval shows that the luminosity of the circular threads must somehow be produced by the movement of a single set of particles from one pole toward the other, and not by two sets of particles which start simultaneously each from its own pole. From this time-interval may also be calculated the average velocity of particles. This average velocity is equal to the length of the circular path, divided by the time-interval above mentioned. This time-interval bears the same ratio to the time of one revolution of the mirror as that borne to 2π by the angle which is swept through in describing the distance a ($a=y_1-y_2$, measured along the axis of y, Fig. 16) between the two ends of the thread. By means of a comparator, reading to thousandths of a millimeter, the distance a was measured upon a photographic plate which was moved parallel to the path described by the image of the spark across it. Readings to hundredths of a millimeter were found to be within the limit of experimental error. The length of the circular thread itself was measured by making a fine flexible wire coincide with an enlarged image of the thread, and then measuring the length of this wire after it had been straightened. Two errors are introduced into this latter measurement by the relative motions of the mirror and the particles. These two errors, being of opposite sign, offset each other. When the particle and the mirror are moving in the same direction, the length of the path of the moving particle is shorter in the image than it is in reality, whereas, when they move in opposite directions, the path of the particle is longer in the image than in reality. As both these cases occur in the same semicircular thread the sum of the two errors becomes practically zero. Errors due to a displacement of the image by the rotation of the mirror were found to be well within the limit of experimental error. The spark terminals, besides being placed in such a position, were chosen of such a width and form that they could introduce no serious error into the measurement of a. The accompanying table gives the values of the velocities thus calculated from measurements upon the circular threads.

TABLE I

Number of 1-gallon Leyden Jars in Circuit	Values of the Velocity in cm per sec.
1	6.3×10^4 to 8.5×10^4
2	4.8×10^4 to 6.7×10^4
3	4.4×10^4 to 6.0×10^4
4	4.3×10^4 to 4.9×10^4
5	3.8×10^4 to 7.0×10^4
6	3.9×10^4

It is seen that the velocities are roughly of the order 5×10^4 cm per sec. Within the limit of error it cannot be said that there is any difference for threads of different curvature, nor is there a serious difference when the capacity is gradually changed from that given by one 1-gallon Leyden jar to that given by six 1-gallon Leyden jars.

This method may possibly be used to measure the velocity of the particles associated with the central threads, if the spark length be so adjusted that the threads remain in the same plane throughout their length.

This difference in the position of the two ends of a circular thread, as shown in the image reflected from the rotating mirror, also led to a determination of the sign of the charge carried by the particles whose velocity has just been calculated. According to the direction in which the mirror rotated, the end of the thread last formed was nearer or farther from the horizontal edge of the photographic plate. Thus from the direction of rotation and the position of the ends of the thread on the photographic plate, it was found which end of the thread was first formed, and this fact in turn indicated the pole from which the particle started and the direction in which it was moving. This direction, together with that of the deflection and that of the magnetic field, gave the sign of the charge carried by the particle. It was thus found that a negative charge is carried by the particles to which the easily deflected, circular threads are due.

As already stated, the equations of motion of a charged particle in a magnetic field are still, so far as atmospheric pressure is concerned, very general and incomplete. Moreover, the electrical conditions, complicated by the nearness of the electrodes required for the passage of a spark at atmospheric pressure, introduce other difficulties, so that it is not easy to arrive at an equation which will accurately represent the motion of these charged particles connected with the circular threads. The use of the equation $\frac{1}{\rho}=\frac{eH}{mv}$ in order to find the magnitude of $\frac{e}{m}$ would have no other justification than the fact that the path of these particles has approximately the same circular form as that of the particles in a low pressure discharge under similar magnetic conditions, the curvature of this form in the latter case satisfying the equation just mentioned. Some of the photographs show a change in the curvature of the threads at a distance of about 2 mm from the spark terminals. The radius of curvature then becomes smaller but has a constant value to within 2 mm of the opposite terminal, when it may become greater by as much as 5 per cent. In the present investigation

$H=1050$ c.g.s. units,
$V=5\times 10^4$ cm per sec.

ρ varied from 0.4 cm to 0.7 cm, as may be seen in the accom-

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panying table which gives the values of ρ for different amounts of capacity in the secondary circuit. If these values are substituted in the equation $\frac{1}{\rho}=\frac{eH}{mv}$, $\frac{e}{m}$ varies from 1.2×10^2 to 0.7×10^2.

TABLE II

Number of 1-gallon Leyden Jars in Circuit	I Series of Measurements Values of ρ in cm	II Series of Measurements Values of ρ in cm
1	0.56	$\left\{\begin{matrix}0.42\\0.70\end{matrix}\right.$
2	0.60	$\left\{\begin{matrix}0.52\\0.54\\0.60\\0.65\end{matrix}\right.$
3	0.55	$\left\{\begin{matrix}0.50\\0.54\\0.60\end{matrix}\right.$
4	$\left\{\begin{matrix}0.60\\0.55\\0.48\end{matrix}\right.$	0.43 0.45 $\left\{\begin{matrix}0.57\\0.43\end{matrix}\right.$
5	0.45	0.45
6	0.40	$\left\{\begin{matrix}0.40\\0.43\end{matrix}\right.$

Two or more values of ρ for the same number of Leyden jars are those belonging to different threads upon the same photograph, not several values of ρ belonging to the same thread. $\left\{\begin{matrix}0.57\\0.43\end{matrix}\right.$ are the radii of curvature of different parts of the same thread, 0.57 being the ρ of the parts near the spark terminal.

Measurements were also made upon the slope of the streamers to find how the value obtained for these velocities agreed with the values obtained by Schenck, and Schuster and Hemsalech, Schenck having obtained a value of about 25×10^4 cm per sec.; Schuster and Hemsalech one of 4×10^4 cm per sec.

The measurements made here upon the streamers have shown a decrease in the velocity as the slope was measured from the electrode toward the center of the spark-gap, the values of the velocities ranging from 1×10^5 cm per sec. to 4×10^3 cm per sec. Measurements were taken only upon the part of the streamer which is not in the same direction as the path of the image across the plate.

Moreover, by closely examining the streamers it will be noticed that the second streamer advances farther toward the center of the spark-gap than the first, the third farther than the second, etc., the the brightness of each diminishing as it nears the center of the gap. The slope of each succeeding streamer becomes after a short time less abrupt than that of its predecessor and their points of junction finally lie on one continuous line, which is almost parallel to the path of the image across the photographic plate. It will also be noticed that the space between successive oscillations increases. This increase in space means that the interval of time between the oscillations becomes greater as they die out and this suggests that each streamer, before it joins the next one, approaches the center of the gap more nearly than its predecessors, for the reason that the vapor is there given a longer time to diffuse toward the center. The decrease in slope shows that the change in the velocity of the vapor becomes less abrupt with each successive oscillation, suggesting that the sum total of the forces which act upon the vapor changes less abruptly with each oscillation. This would naturally be expected from the curve of an oscillatory discharge. These observations, together with the results given on p. 141, lead one to think that Schenck may have been mistaken in suggesting —as he did, to explain the difference between his values for the velocity of the streamers and those of Schuster and Hemsalech—that they measured the slope of the *locus* of the extremities of the streamers. Such a locus is almost parallel to the path of the image of the spark across the photographic plate and a measurement of it could not possibly give for the velocity a value comparable with that secured by Schuster and Hemsalech. It seems possible therefore that the velocities measured were actually those of different parts of the streamer; Schenck having measured that of the part very near the electrode; Schuster, that of the part somewhat nearer the center of the spark-gap.

This possibility suggested that there might be for some of the metal terminals a noticeable difference in the parts of the streamer itself. With zinc, cadmium, and bismuth a difference in color was noticed. For a very short distance, not exceeding 2 mm, the streamer was of a brilliant blue color like that of the blue cone noticed in the vapor about the electrode. Then it changed to a dull blue and afterward to an orange-red like that of the vapor at some distance from the electrode. Furthermore the color of the bright blue core is like that of the bright points of light seen where the sheet of vapor of the first type of spark just touches the metal terminals, and where the circular threads touch the terminals in the third type of spark, provided that a capacity less than 0.012 mf is present in the circuit.

Plate XIV, Fig. 17, shows the spectrum of the spark when the spark length is parallel to the slit of the spectroscope. The spark line λ 4481 of magnesium is seen to be present only in the region of the spark terminals, whereas the other lines extend entirely across the spark-gap. When other metals were used as terminals, similar plates, showing the spark lines present only in the neighborhood of the terminals, were obtained.

The photographs show that the vapor represented by the very bright part of the streamer exists for a short time in each oscillation, but does not persist until the next oscillation at that electrode has begun: it therefore does not receive a fresh addition from each successive oscillation. The rest of the vapor, on the other hand, does persist until after the second or still later oscillations have begun, and thus presents a continuous background of light, reinforced by each successive oscillation. Schenck, it will be remembered, found that the image of the spark line given by the rotating mirror was sharply beaded and that the parts of the line are separated by intervals of complete darkness. The arc lines, on the other hand, showed only indistinct traces of beading, such as would be given by a continuous background of light crossed by streamers. These two facts taken in connection with the foregoing description lead to the following inference. The bright core, entering with each oscillation and completely dying out before the next begins, has some association with the spark lines which show by their distinct beading that they arise from something ending before the next oscillation has begun. The rest of the vapor, on the other hand, bears some relation to the arc lines which, by their indistinct beading and continuous background, show that they are associated with something persisting throughout and receiving fresh additions with each successive oscillation.

By allowing the light from the spark to fall first upon a plane grating, and then upon the rotating mirror an attempt was made to see if the spark lines extended only as far as the bright blue core and if they died out before the next oscillation. But for every metal tried, the spark lines in the visible spectrum were too close to the arc lines, and the image given by the mirror in rotation lasted too short a time to give any positive results in this connection.

This method of using a grating objectively and at the same time a mirror in rotation, did however show that the continuous spectrum is in the form of the irregular first discharge which extends across the spark-gap. (See Plate XIV, Fig. 1.) This figure also shows instead of one or two discharges as Schenck has observed (cf. p. 122) that there may be as many as six or seven discharges following the path of the first discharge.

The velocity of the streamers Schuster and Hemsalech found to be about 4×10^4 cm per sec. The order of the value obtained in the present investigation for the average velocity of the particles connected with the circular threads is 5×10^4 cm per sec.; and the close agreement between these two values led me to try to see if there were any relation between that part of the streamer measured by Schuster and Hemsalech, and the circular threads. It was thought that if an effect of the magnetic field upon the metallic vapor could be found, some relation between this vapor and the circular threads might be traced. Accordingly the oscillatory spark obtained with a capacity of 0.012 mf and a self-induction of 0.003 henries was made to pass in the strongest available magnetic field, in order to show whether the metallic vapor acts in a manner at all analogous to that characteristic of the brilliant circular threads occurring under conditions which are similar in every respect to the preceding except that less capacity is present in the discharge circuit. To obtain oscillations sufficiently separated for the study of the vapor just described a capacity of 0.012 mf was necessary, and this type of oscillatory spark showed no deflection in the magnetic field used for obtaining the circular threads. In a field of 12,000 units, however, the metallic vapor of this oscillatory spark was deflected into the form of broad, circular rings much like the circular threads, except that they were broad and not brilliant. It is possible that a much stronger field might introduce narrow, brilliant threads, just as an increase in the strength of the field introduced threads into the sheet of vapor belonging to the first type of spark. The brilliant blue core still remained close to the spark terminal at the two ends of each broad ring of vapor. If the magnetic field had caused any change in the core, this change would be difficult to detect because of the shortness of the core.

Photographs both in and out of the magnetic field were then taken with the mirror in rotation, in order to show whether the magnetic field produced a difference in the streamers. Both the bright core and the other vapor of the streamers showed irregularities when the spark was in the magnetic field, and these irregularities were such as a curved deflection might introduce into the motion of the particles giving the streamers. This suggested that the bright core, as well as the rest of the metallic vapor, was associated with charged particles, and additional evidence for this theory was afforded by the circular form of this vapor in a very strong field. If then every luminous part of the spark is associated with charged particles, Walter's theory that the arc lines are due to particles which have lost their charge seems doubtful. In whatever part of the spark the arc lines may originate, it seems probable that they must in any case arise from a luminescence excited by charged particles, since every part of the oscillatory spark suffers some deflection in the magnetic field, and this deflection obeys the electro-dynamic laws.

These arguments taken alone are, of course, insufficient to prove that the bright core seen in the third type of spark and the bright points of light seen in the first type of spark at the terminals have as their characteristic spectrum lines the spark lines and that the vapor envelope has the arc lines; but they give a definite support to the theory. Such a theory if proved would add weight to Schenck's suggestion that the spark lines are due to peculiar vibrations arising when the atoms are torn from the metal terminals, whereas the arc lines are due to the more fundamental vibrations which persist after the abnormal vibrations have died out.

BRIEF SUMMARY OF RESULTS

The three types of spark studied are described on p. 126.

1. When the spark is placed in a magnetic field, the direction of

which is parallel to that of the spark-gap, the first type of spark presents two sheets of vapor in the form of spirals. In the field at right angles to the spark length this vapor is in the form of two semicircular sheets, one being on each side of the spark-gap in a plane perpendicular to the direction of the magnetic field.

In the second type of spark (if the capacity did not exceed 0.002 mf) and in the third type of spark brilliant spiral threads in a parallel field and brilliant circular threads in a transverse field took the place of the spiral and circular sheets respectively. In the first and second types of spark the bundle of threads across the gap could not be deflected by a magnetic field of 12,000, the strongest to be obtained with the available amount of current, viz., 19 amp. In the third type the metallic vapor and the threads across the gap were deflectable in a very strong field and in a manner analogous to that of the circular and spiral threads.

The character of the deflection seems to furnish good reason to infer that the particles with which luminosity is associated possess an electric charge. A twofold asymmetry is present in the deflection of the circular sheets of the first type and of the circular threads of the second and third types, viz., an asymmetry as to the terminals and as to the width of the two sheets or sets of threads. Reversing the direction of the magnetic field, or that of the current through the primary of the inductive coil, changes the position of the sheets and of their ends. Decreasing the current through the primary, or lengthening the spark-gap sufficiently, causes one sheet, or set of threads to disappear.

2. The circular sheet of the first type of spark gives the spectrum of the nitrogen bands. The central threads show that of the metallic lines and the air lines.

The second type gives the same spectrum for the bundle of central threads as for the circular threads, viz., that of the very bright air lines and the fainter metallic lines.

In the third type of spark the central threads show the same spectrum lines for each of the seven different metals which were used as spark terminals, these lines being identified with the air lines.

The spectrum of the circular threads shows the arc lines in addition to the air lines.

The spectrum of the part of the spark about the terminals shows the spark lines in addition to the arc and air lines. This gives the combined spectra of the metallic vapor, the circular and the central threads, because the metallic vapor could not be isolated.

These facts, together with certain observations presented at the end of this paper, give further evidence that the spark lines may be due to abnormal vibrations arising when the atoms are torn from the metal terminals; whereas the arc lines in the spark spectrum may be due to the more fundamental vibrations.

3. The value of the velocity of the particles associated with the circular threads is approximately 5×10^4 cm per sec. and this velocity is of the same order as that obtained for the streamers when they are measured close to the spark terminals.

These particles carry a negative charge.

They move in paths of different curvature.

Substituting in the equation

$$\rho=\frac{mv}{eH}$$

the values found for their velocity and for the curvature of their paths, $\frac{e}{m}$ is found to vary from 1.2×10^2 to 0.7×10^2.

The present investigation seems to show that in the electric discharge at atmospheric pressure there are negative particles which in a magnetic field describe luminous paths in the form of spirals and circles, similar to those described by the negative particles emitted by a hot lime cathode[1] in the discharge at low pressure.

The velocity of these particles in the discharge at atmospheric pressure is of the order of 5×10^4 cm per sec. whereas that of the particles in the discharge at low pressure is from 1.6×10^8 cm per sec. to 1.07×10^9 cm per sec.

It does not follow that these negative particles at atmospheric pressure are themselves luminous. The bright spiral and circular paths seen in a magnetic field may mean simply that the particles excite to luminescence the gas through which they pass. The nitrogen bands which constitute the spectrum of the spiral and circular sheets in the first type of spark seem to indicate either that the nega-

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[1] Wehnelt, *loc. cit.*

tive particles associated with these sheets are capable of exciting a luminescence in the gas through which they pass, but have no luminescence of their own, or that the particles of air have themselves become ionized as well as excited to luminescence. The arc lines, however, which appear in addition to the air lines in the spectrum of the third type of spark, suggest that the charged particles here not only bring to luminescence the gas through which they pass but also that they themselves emit a radiation characteristic of the metal from which they appear to come.

The average velocity of the particles associated with these circular threads seems to be of the same order as that of the metallic vapor, as long as the latter is still close to the spark terminals. This agreement of the velocities and further the fact that the arc lines are present in the spectra of both the threads and the vapor, suggest some analogy between them.

Little that is definite can be said about the central threads. In the first and second types of spark they could not be deflected with a magnetic field up to 12,000, whereas in a field of this strength the central threads in the third type of spark assumed the form of spirals and semicircles, having a radius so small that measurements like those of the easily deflected threads were impossible. Thus far the spectra of these threads in the third type of spark give no clue to the nature of their mechanism.

The present investigation was suggested by Professor W. B. Huff, of Bryn Mawr College. I wish to acknowledge my indebtedness to him and to Dr. James Barnes, of Bryn Mawr College, for their helpful suggestions and criticisms during the course of the investigation.

Physical Laboratory
Bryn Mawr College
March 1908

DESCRIPTION OF PLATE

FIG. 1.—Oscillatory spark taken with the mirror in rotation. Speed of mirror —50 revolutions per sec., C=.012 mf., L=.003 henries. The lower figure shows the first discharge and six weaker discharges (*a*) which follow approximately the same path; also the short, curved streamers (*b*). The upper figure shows the trailing light (*c*). If the spark passes when the mirror is in exactly the right position, all these features may be seen in the same spark-discharge. P. 122.

FIG. 2.—Spirals. Spark-length parallel to the magnetic field. *Al* terminals. P. 127.

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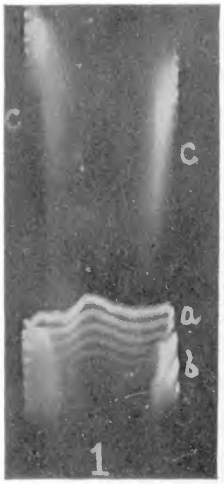
PLATE XIV



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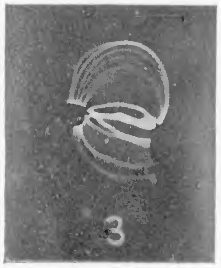
2


4


6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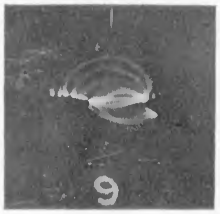
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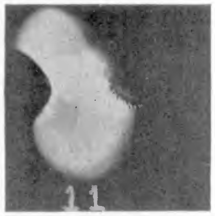
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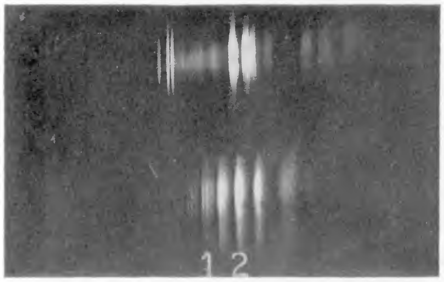
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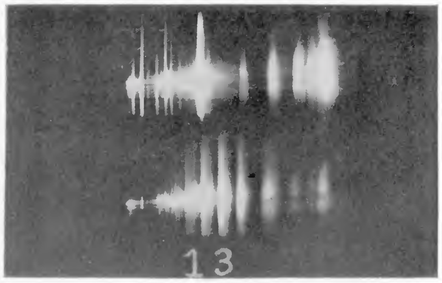
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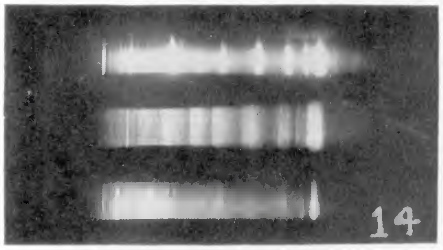
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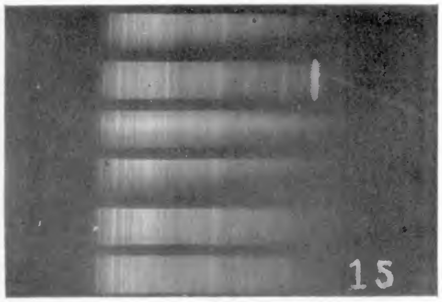
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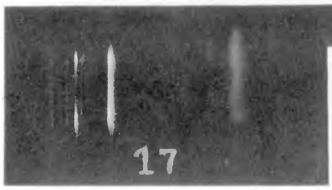
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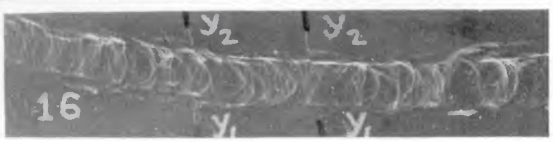

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FIG. 3.—Circles. Spark length perpendicular to the magnetic field. The shape of the terminals did not permit complete semicircles below. P. 127.

FIG. 4.—Oscillatory spark with terminals too widely separated for the presence of the circular threads. It shows the vapor about the terminals and the irregular, central threads. P. 128.

FIG. 5.—Spark with a capacity of 0.0005 mf and no self-induction. It shows the bundle of bright threads straight across the spark-gap and the circular threads on one side of the gap. To the eye they were also present on the other side, but the short exposure of 1/50 sec. evidently "caught" the spark at an interval when they were present on one side only. Pp. 128 and 129.

FIG. 6.—Spiral form of the central threads in the oscillatory spark ($C=0.012$ mf, $L=0.003$ henries). The radius of curvature is too small for them to appear clearly in the photograph. P. 130.

FIG. 7.—To show the twofold asymmetry in the circular threads. Pp. 129, 131, and 132.

FIG. 8.—Asymmetry of sheets. Pp. 131 and 132.

FIG. 9.—Circular threads present only on one side of the spark-gap. P. 132.

FIG. 10.—Same, but direction of magnetic field reversed. Pp. 131, 132, and 133.

FIG. 11.—Same as 8 but direction of current through the primary reversed. This shows the bright points of light where the sheet meets the terminals. In figs. 8, 10, 11, on the left-hand side the sheets are partly hidden by the spark terminal. Pp. 131, 132, and 133.

FIG. 12.—Lower spectrum, that of the sheet in the first type of spark, taken with the outer edge of the sheet focused upon the slit. Upper spectrum that of spark, obtained with C, and L in the circuit, taken for purposes of comparison. *Cd* terminals. These spectra are not in focus on the right owing to the plane surface of the photographic plate. P. 134.

FIG. 13.—Lower spectrum that of the central threads and sheet of the first type of spark taken close to the terminal. Upper spectrum that of the spark, obtained with C and L in circuit, taken for purposes of comparison. *Mg* terminals. P. 134.

FIG. 14.—Spectra of three different parts of the oscillatory spark ($C=0.002$ mf, $L=0.003$ henries). Upper spectrum that of the metallic vapor, central threads, and circular threads, taken close to the spark terminal. Central spectrum that of the circular threads. Lower spectrum that of the central threads, taken in the center of the spark gap with terminals so far apart that center was free from metallic vapor. *Mg* terminals. P. 136.

FIG. 15.—Spectra of central threads of oscillatory spark taken in the following order from the top of the figure: *Al*, *Mg*, *Zn*, *Cd*, *Ca*, *Bi*. P. 136.

FIG. 16.—To show the images of the circular threads, secured with the mirror in rotation, upon which the measurements of the velocity of the particles associated with the circular threads were made. P. 138.

FIG. 17.—Spectrum of the spark ($L=0.0015$ henries) of magnesium taken with the spark length parallel to the slit of the spectroscope. P. 143.