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SOME PROPERTIES OF THE ELECTRIC SPARK AND ITS SPECTRUM

DISSERTATION

SUBMITTED TO THE BOARD OF UNIVERSITY STUDIES OF THE JOHNS HOPKINS UNIVERSITY FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

BY
CHARLES CARROLL SCHENCK
JUNE, 1901

JOHNS HOPKINS UNIVERSITY
Baltimore, Maryland

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ADDENDA.

SOME PROPERTIES OF THE ELECTRIC SPARK AND ITS SPECTRUM.

By CHARLES C. SCHENCK.

I.

IT is well known that in many spectra the lines are not arranged in haphazard order, and many attempts have been made to divide lines into different groups according to their characteristic behavior, and to associate together lines in the spectra of closely related elements. Professor Ames[1] was the first to point out the intimate connection between certain lines in the arc spectrum of zinc and cadmium, thus determining the so-called homologous lines, and Kayser and Runge have since succeeded in dividing the chief lines in the arc spectra of many elements into their well-known principal, and first and second subordinates series.

The object of the first, or preliminary, section of this paper is to divide the principal lines in the spark spectrum of cadmium into three groups, each having characteristic properties peculiar to itself.

Kirchhoff[2] showed in 1861, and Thalen[3] in 1866, that the spark spectra of certain elements could be transformed into spectra closely resembling the simple flame spectra by inserting a wet string in the circuit containing the Leyden jar and the spark gap, so as to increase its resistance, or by causing the spark discharge to pass through the coils of an electro-magnet, thereby increasing the self-induction.

Hemsalech[4] has also investigated some of the general effects produced in spark spectra by inserting a self-induction in the discharge circuit from a condenser. He has not investigated the ultra-violet region, however, and has confined his attention to the statement of certain general effects observed. He has

[1] *Phil. Mag.* (5) 30, 1890.

[2] *Abhandlungen der K. Acad. Berlin*, 1861, p. 73.

[3] *Annuaire*, Upsala, 1866.

[4] *Jour. de Phys.*, December 1899.

also recently proposed[1] a division of the lines of spark spectra into groups, which does not quite agree, however, with the classification proposed in this paper, as it does not include any of the lines of Group C, mentioned below.

The division of the lines of the cadmium spark spectrum into three groups followed from a detailed study of the changes produced in the spectrum when the period of the condenser was varied by increasing the self-induction.

APPARATUS.

The spark was produced by a 110-volt alternating current, frequency 133 complete periods per second, which was stepped up to about 600 volts and put through the primary of a large induction coil, the potential of whose secondary was raised sufficiently to give a spark one centimeter long. The capacity consisted of six gallon jars connected in parallel, with a total measured capacity of 0.016 microfarads. The 110-volt current was regulated by a suitable resistance so as to give the best spark conditions for the given capacity, *i. e.*, a very noisy spark which should not heat the terminals to incandescence. If the current was too large the poles became very hot, the spark was less noisy, and, as was found later, the spectrum was not the same as with a noisy spark. The best spark was obtained when the 110-volt current was about twelve amperes, and the 600-volt current which passed through the primary of the induction coil was then about one ampere. The spark length varied from 6 to 8 millimeters. With the first-named length, the sparks followed one another with considerable regularity at the rate of 266 per second, and produced a fairly good musical tone, whose pitch was nearly that of middle C. When the terminals were pulled farther apart the regularity ceased, but again appeared at a spark length of about 8 millimeters, when the tone was an octave lower than the first.

The period of the condenser, when the wires connecting it to the spark gap were as short as possible, was found later by photographing the image of the spark by means of a revolving

[1] *Comptes Rendus*, April 22, 1901, p. 959.

mirror and measuring the separation of the oscillations on the photographic plate. Its value was 1.3×10^{-6} seconds. It should be added that each spark consisted of about ten or twelve complete oscillations.

The spectrum was photographed with the large concave grating of 21 feet radius. Some photographs were also taken by means of a small concave grating of 6 feet radius. Some plates of zinc and magnesium were taken for purposes of comparison.

RESULTS.

An examination of the cadmium plates showed the existence of about 143 lines in the ultra-violet, extending from λ 2100 to λ 3700, which have the following characteristic properties:

1. They have a breadth of ⅓ Ångström unit and their edges are hazy. They resemble air-lines somewhat, but they are not air-lines, being absent from the spark spectra of zinc, magnesium, and iron.

2. They extend only about 2 mm out from the poles toward the center of the spark, while the rest of the lines extend clear across the spark gap, with a spark 8 mm long.

3. When the spark length was 5 mm, and the period of the condenser was increased 13 times, *i. e.*, to 17×10^{-6} seconds, by throwing in self-induction, they disappeared from the spectrum, while the other metallic lines were practically unaffected. The period of the condenser was found by the rotating mirror as before, and the number of oscillations for each spark was nearly the same as before, *i. e.*, about 12.

4. They are absent from the arc spectrum, as given by Kayser and Runge and as photographed in this laboratory.

5. None of them are reversed.

These lines constitute the first group (C). Thirty-eight of them situated toward the red end are more hazy than the others, some of them being more than twice as broad, although in all other respects they are similar. Hence I have put them into a sub-group by themselves.

It is interesting to note here that the spark spectrum of zinc has a similar group of lines, while that of magnesium has not.

The second group of lines, (B), includes most of the remainder of the lines known as "spark lines," that is, lines either absent from or else very weak in the spectrum of the arc in air, but prominent in the spark. They have the following characteristics:

1. None of them are reversed.

2. When the period of the condenser was increased about 58 times, *i. e.*, to 75×10^{-6} seconds, some of them disappear and the others shorten up close to the poles, while the rest of the metallic lines extend uniformly across the spark gap. A few of the lines of Group B do extend clear across the spark gap, but they are strong close to the poles only and very weak throughout the center of the spark.

Under these conditions the number of oscillations of the condenser was 16 or 18, somewhat greater than before. The period was obtained in two ways: by photographing the spark with the rotating mirror, and by measuring approximately the self-induction of the coil, *i. e.*, 0.0093 henries and using the formula $T = 2\pi \sqrt{LC}$. The two values agreed to within 3 per cent.

The lines of the third group, (A), are the so-called arc lines. They include most of the lines common to both spark and arc. Some of them, as λ 4413, are extremely weak or absent altogether in the spark and strong in the arc. They form thus a spectrum simpler than that of the arc, and the effect of a self-induction is to make the spectrum of this group more complicated, and approach that of the arc. An examination of my plates showed that the scale of relative intensities among these lines is much closer to that of the same lines in the arc, when the period of the condenser is 75×10^{-6} than when it is 1.3×10^{-6}. In fact, with the period 75×10^{-6}, judging from the relative intensities of the lines, it might be said, figuratively, that I had gotten about "half-way" from the spark to the arc.

These lines possess the characteristic that they extend clear across the spark gap when the period of the condenser is great enough (75×10^{-6}) to cause the lines of Group B to shorten up close to the poles. There is scarcely any doubt that they are due to luminous metallic vapors which fill up the entire spark gap, while the lines of Group B are due to a different phenomenon which will be brought out in the second part of this paper.

Now, since this spectrum (Group A) becomes more complicated, especially in the ultra-violet, as we pass from the spark spectrum toward the arc spectrum by increasing the period of the condenser, it seems probable that the temperature of the metallic vapors in the arc is higher than the average temperature of the vapors in the spark, and that one effect of self-induction is to raise the average temperature of the metallic vapors in the spark. By average temperature I mean a time average, taken throughout the interval during which the metallic vapors remain luminous in the spark. There are other reasons for this conjecture. When the duration of the entire discharge is increased 50 to 60 times, there is more time for the vapors to become heated. Again, it is well known that rapidly oscillating currents produce less heating effect than slowly oscillating ones. Moreover, the poles are intensely hot in the arc and comparatively cool in the spark.

But it is apparent that the effect of self-induction is clearly a double action, a repressive effect upon the lines of Groups C and B, and an enhancing effect upon those of Group A. Its whole effect cannot be explained by saying merely that there is a gradual fall in temperature in passing from the spark to the arc; for the spark is a complicated mechanism, and its temperature varies from point to point, and is also a rapidly varying function of the time.

The following table gives a list of the lines belonging to the three groups in the region from λ 2100 to λ 5379 Å. U. No attempt was made to measure them accurately, no more so than was necessary simply to indicate them. Most of the lines occur in Eder and Valenta's table of the cadmium spark spectrum, and these observers have a few lines toward the red end which I do not find, owing possibly to the fact that in this region they photographed the spectrum of the spark in an atmosphere of hydrogen. Some lines have been omitted, a few of which do not fit in well with any of these groups, while the others are so faint that it was impossible to tell much about them. A list of them is given below.

The following abbreviations are used in the tables:

h —hazy.	½ —barely visible.
vh—very hazy.	*hR*—hazy on red side.
s —sharp.	*hV*—hazy on violet side.
b —broad.	*bR*—broadened toward the red.
r —reversed.	*bV*—broadened toward the violet.
10—very strong.	*2b* —two Ångström units broad.
1 —very weak.	

Lines marked with an asterisk * are given by Eder and Valenta. Pairs of lines marked]* are given by Eder and Valenta as single lines.

GROUP C.

Intensity	Wave-length	Intensity	Wave-length	Intensity	Wave-length
2	2111.7 *	5	3017.4 *	1	3153.4]
Fairly *s* 3	2224.5 *	3	25.4 *	2	54.2]*
vh 1	2350.4 *	1	27.3	5	57.3 *
2	2426.5 *	1	30.4	3	60.9]
2	2499.9 *	3	35.9 *	6	61.9]*
2	2618.9 *	2	44.2	4	73.6]
s 2	2668.2 *	6	49.0 *	4	74.5]*
Fairly *s* 3	2706.9 *	6	53.3 *	3	76.9 *
2	26.9 *	6	59.5 *	3	78.6 *
s 2	67.0 *	7	65.2 *	2	83.0 *
s 3	2805.5 *	4	69.0]	6	85.6 *
1	2808.8	3	69.4]*	2	95.9]
5	2910.9 *	2	74.0	2	96.5]*
2	26.9 *	4	77.3 *	3	97.9 *
5	48.4 *	7	85.2 *	2	3201.8 *
3	52.1 *	3	88.6]	5	10.2 *
1	53.2	3	89.3]*	2	12.7 *
1	54.6	1	91.0	2	13.8 *
2	64.5 *	3	92.5 *	1	15.5 *
1	65.2	5	95.7]	5	17.8 *
1	70.1	4	96.1]*	3	21.6 *
4	71.4 *	4	3113.2 *	2	24.3
4	87.4 *	5	19.1 *	3	36.7 *
4	96.2]	5	22.0 *	4	64.5 *
3	96.6]*	5	24.7 *	3	77.0 *
1	3003.2	1	28.0	4	83.9 *
2	04.0 *	6	29.5 *	3	86.0 *
3	09.0 *	2	41.7 *	2	3389.8
1	11.3]	1	45.1	2	3423.5
1	11.8]*	2	47.0	2	3486.0
3	14.4 *	1	49.0	1	3695.4

GROUP C.—*Continued.*

SUB-GROUP.

Intensity	Wave-length	Intensity	Wave-length	Intensity	Wave-length
2b, hR 3	3809. *	5	3977.8 *	2	4131.0 *
3	27.	0.8b 2	84.8 *	3	39. *
4	37.9 *	1b 4	88.3 *	3	42.0 *
3	40.6 *	1b 3	91.8 *	1b 4	58.1 *
0.8b 3	52.4 *	1	4009. *	2	63.8 *
1.2b 3	65.4 *	1b 2	18.5 *	1	71.6 *
1	89.9 *	2b 4	29.2 *	1b 2	92.0 *
1b 2	99.4 *	1b 1	49.4 *	0.7b 3	4216.9 *
1b 2	3935.7 *	1	54. *	1b 3	45.7 *
1.3b 6	40.5 *	0.9b 5	94.9 *	3	71.2 *
2	50.9 *	1b 4	4114.6 *	3	72.9 *
1b 6	59.0 *	0.7b 2	16.8 *	1b 1	94.3 *
5	76.8 *	1b 3	27.1 *		

GROUP B.

Intensity	Wave-length	Intensity	Wave-length	Intensity	Wave-length
Trifle hazy 2	2168.8 *	4	2418.8 *	9	3250.5 *
6	2194.7 *	5	69.9 *	3b 4	3497.5 *
2	2248.9 *	3	87.9 *	7	3535.7 *
b 9	2312.9 *	1	95.5 *	7	4415.9 *
7	1.2 *	b 4	2552.2 *	2b 10	5338.6 *
2	75.0 *	vb 4	2573.1 *	2b 10	5379.3 *
3	77.0 *	10	2748.6 *		

GROUP A.

Intensity	Wave-length	Intensity	Wave-length	Intensity	Wave-length
r 5	2144.5 *	bR 6	2677.7 *	9	3261.2 *
5	2239.9 *	3	2712.6	10	3403.7 *
1	62.4	bR 4	34.0 *	10	66.3 *
r 8	65.1 *	bR 5	64.0 *	9	67.8 *
4	67.5 *	bR 4	75.1 *	3	3500.1
br 7	88.1 *	7	2837.0 *	10	3610.7 *
5	2306.7 *	bV 1	62.4 *	8	13.0 *
6	2329.4 *	bR 5	68.4 *	4	14.6 *
½	2525.6	7	80.8]	s 2	49.7
vh 1	44.9 *	4	81.3] *	hR 3	3729.2
½	80.3	bV 3	2961.7 *	hR 4	4307.0
½	92.1 *	8	80.7]	1	4413.2 *
h ½	2602.0 *	5	81.5] *	bR 4	4662.7 *
2	29.1 *	½	3005.5	hR 10	4678.4 *
1	32.3	hR 6	81.0 *	hR 10	4800.1 *
4	39.6 *	hR 8	3133.3 *	hR 10	5086.1 *
h 2	60.4 *	hR 8	3252.7 *	hR 2	5154.9
h 1	70.7 *				

LINES OMITTED.

Intensity	Wave-length	Intensity	Wave-length	Intensity	Wave length
1	2004.2	vh 1	2411.2 *	½	3156.0
1	2055.5	½	2591.1	1	63.2
½	2148.3	½	93.0	h ½	87.5
½	51.6	½	96.0	½	90.5
½	55.5	½	2599.3	½	3219.5
1	88.0 *	½	2780.1 *	½	42.9
½	2325.8	h ½	2967.5	½	43.9
½	33.3 *	h ½	2968.5	b 5	3385.3
½	43.0	½	3032.8	h 1	4006.0 *
vh 1	55.2 *	½	41.		

II.

The second part of the investigation is a study of some of the properties of the spark and its spectrum by means of photographs taken with a revolving mirror, and an attempt to trace the connection between lines of different groups and also certain characteristic lines in the spectra of magnesium and zinc, and certain phenomena in the spark itself.

The appearance of the spark when viewed in a rotating mirror turning with sufficient velocity to separate out the oscillations of the condenser is well known. Feddersen studied its appearance in 1862,[1] and Schuster[2] has also photographed it by using, instead of a revolving mirror, a rapidly revolving disk to which was attached a sensitive film upon which the image was focused. Its appearance is shown in Plate III, Fig. 1, which was taken by placing a narrow vertical slit in front of and very close to the spark, and allowing the light to fall upon a rotating mirror with vertical axis and thence through the lens of a camera. Its appearance presents three general features.

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.

2. Curved lines of light which shoot out from the poles toward the center of the spark gap with a velocity constantly diminishing

[1] *Pogg. Ann.*, **116**, 1862. [2] *Phil. Trans.*, **193**, p. 209.

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. In a cadmium spark these lines of light are greenish-yellow and in magnesium they are purple.

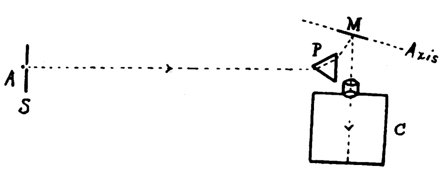
3. A rather faint light, generally of a different color from the curved lines of light, which fills up the spark gap and persists for a certain length of time, especially in the center of the spark gap, after the oscillations die out.

If the slit is very narrow, this light is not apt to come out on the photograph, owing to under-exposure, but by widening the slit or removing it altogether it is easy to get it, at the expense, however, of blurring the oscillations.

Schuster, by photographing the spectrum on the rotating disk, has shown that it is the first brilliant discharge to which the air-lines in the spark spectrum are due.

APPARATUS.

In order to get a connection between the different metallic lines and the phenomena in the spark, I arranged an apparatus, a section of which by a horizontal plane is shown in the diagram.



A is the spark, which is vertical. *S* is a vertical slit very close to it. At a considerable distance away, 231 centimeters, was placed a 60° prism, *P*, of flint glass, with its edge vertical. It was set at an angle of minimum deviation for a wave-length about 4500. At *M* was a rotating mirror with its axis horizontal. The mirror was driven by an air blast and its period measured by a speed wheel attached to the axis of the mirror by a worm gearing. The highest speed obtainable was 65 revolutions per second. The light reflected from the mirror passed through a lens and was focused on the ground glass of a camera, *C*. In this way a horizontal spectrum was obtained whose height, *i. e.*, the length of whose lines, was very small (0.7 mm).

By the rotation of the mirror the lines of the spectrum were pulled out in the direction of their length, by an amount depending upon their duration and upon the speed of the mirror. The time of exposure was found by trial, and was taken so that four or five flashes of the spectrum were thrown upon the plate, as a rule in different places. Photographs were taken using pairs of cadmium, zinc, and magnesium electrodes, and also by using one electrode of cadmium and one of magnesium, etc. By measuring the length d, of any line on the plate as pulled out by the mirror, and knowing the period of the mirror, T, the optical distance from the slit to the mirror, r, the small angle, 2θ, between the incident and reflected light at the surface of the mirror when the normal to its surface lay in a horizontal plane, and the magnification, f, of the image of the slit in the camera, it was easy to calculate the duration, t, of the different lines by the formula,

$$t = \frac{Td}{4\pi f r \cos\theta} .$$

With this apparatus,

$$r = 230.9 \text{ cm}$$
$$f = \tfrac{6}{55}$$
$$\frac{1}{\cos\theta} = 1.043 .$$

The first striking characteristic of the lines was that the principal arc lines (Group A) were at least twice as persistent as the strongest spark lines (Group B).

The following table gives an example of the duration of some of the principal lines of magnesium, zinc, and cadmium.

	Line		Duration
Magnesium	4481	strong spark line	24×10^{-6} seconds
	3838, 3832, 3830	strong arc triplet	45×10^{-6}
Zinc	4925	strong spark lines	14×10^{-6}
	4912		14×10^{-6}
	4811	strong arc lines	24×10^{-6}
	4722		24×10^{-6}

	Line		Duration
Cadmium	4800 4678	strong arc lines	36×10^{-6}
	4416	strong in spark, extremely weak in arc	18×10^{-6}

It was determined by eye observations that the duration of the principle arc lines was even greater than is indicated in the above table, the extreme end of the lines not appearing on the photograph owing to under-exposure.

The period of the condenser was 1.3×10^{-6} seconds. The duration of the continuous spectrum, which appeared quite strong by using such a small dispersion, was exceedingly short; *i. e.*, less than the period of the condenser. The air lines also, as might have been expected from Schuster's results, persisted for a length of time equal to one or two periods only.

Now, owing to the fact that the height of the spectrum is not small enough, and also that the mirror could not be run faster than 65 revolutions per second, it was impossible to show oscillations in the lines by this arrangement, but by increasing the period of the condenser to 5×10^{-6}, by a small self-induction, and by using poles of unlike metals, say zinc and cadmium, the oscillations were brought out very clearly.

A second characteristic of the lines was that the spark lines (Group B), appeared sharply beaded clear out to their ends, as a result of the oscillations, while the arc lines (Group A) showed only indistinct traces of beading, which did not extend all the way out to the ends of the lines. In other words, the spark lines are due entirely to the oscillations, and the arc lines are due partly to the oscillations and partly to something else which retains its luminosity after the oscillations cease. On some of the photographs the magnesium arc triplet at λ 3830 began a trifle later than the spark line λ 4481. This fact will be referred to later.

This seemed to point to a connection between the spark lines and the curved streams of light seen in the spark itself when viewed in a revolving mirror. To show this clearly, the mirror was turned over in order that its axis might be vertical, and the front half of the camera lens was removed so as to get a higher spectrum, *i. e.*, one whose lines should be longer, and also to spread out the oscillations. The period of the condenser was again reduced to 1.3×10^{-6}, by removing the self-induction, and magnesium poles were used on account of the extreme brilliancy of the spark line λ 4481. In the photograph, this line appeared broken up into a beautiful series of curved lines similar to the curved streamers in the spark itself.

In order to see if there were an exact similarity between the streamers in the spark and those into which this magnesium line was broken, the apparatus was arranged as follows: An image of the spark was focused on a vertical slit by means of a lens. The light then passed through a collimating lens, was transmitted through the prism in a parallel beam and fell upon the revolving mirror (with vertical axis), from which it was reflected into the camera, and the spectrum brought to a focus on the ground glass. The prism was mounted upon a sliding block, and a plane vertical silvered mirror was placed near its refracting edge upon the same block, so that, by sliding the block, a part only of the light passed through the prism, while the rest struck the silvered mirror from which it was reflected to the revolving mirror and thence into the camera, forming an undispersed image of the slit alongside of the spectral image. By tilting the silvered mirror very slightly out of the vertical, the undispersed image was thrown on the plate slightly above and one or two centimeters to one side of the spectral image. By this means it was possible to get a plain and a dispersed image of the *same* spark which did not overlap when the mirror was spinning. But no difference was found on the photograph, between the appearance of the streamers in the plain spark and those in the line λ 4481, every slight irregularity in the one appearing also in the other.

It was not found possible, on account of lack of light, to photograph the arc lines by any of these methods with the axis of the mirror vertical, without cutting down the speed of the mirror so much as to run the oscillations together. But even under these conditions the arc lines showed certain interesting features. The light from the magnesium triplet λ 3830 advanced from the poles toward the center of the spark gap with substantially the same velocity as that from the line λ 4481, but with feeble intensity, and burst out in the center of the gap with increased brilliancy an instant later, where it remained until some time after the spark line λ 4481 had ceased. This agrees with the fact, mentioned on page 126, that this arc triplet began a trifle later than the spark line λ 4481, its feeble intensity at the start not appearing on the photograph referred to on that page.

But in order to establish the exact connection between the principal arc lines and the curved streamers in the plain spark, it was necessary to resort to eye observations. The following apparatus was set up: The image of the spark was thrown on the slit of a Steinheil spectroscope containing two flint-glass prisms, and the eyepiece of the observing telescope was removed so that the spectrum was brought to a focus in the focal plane of the telescopic objective. A vertical slit was placed at the spectrum so as to transmit the light of any particular line desired. The light then fell upon the rotating mirror (with vertical axis) about 16 inches away, and was reflected into the camera and brought to a second focus on the ground glass. By spreading out the oscillations with a small self induction the following phenomena could be clearly seen by careful observation.

For cadmium.—The strong spark lines λ 5339 and λ 5379 appeared as a beautiful series of curved streamers sharply defined and separated clearly by dark spaces. The last two or three streamers did not proceed very far from the electrodes and the center of the spark gap at this instant was dark.

The line λ 4416 (strong in spark and very weak in arc) also showed oscillations, but its total duration was only about half that of λ 5339 and λ 5379.

The strong arc line λ 5086 also appeared as a series of curved streamers which were *not* clearly separated by dark spaces, and the center of the spark gap remained filled with light after the streamers ceased. Its total duration exceeded that of λ 5339 and λ 5379.

For magnesium.—The strong spark line λ 4481 appeared (as had been previously proved by the photographs) as a series of clearly defined curved streamers.

The strong arc triplet at λλ 5184, 5173, 5168 (*b* lines) also appeared in the form of curved streamers, but there was, besides, a luminosity which persisted long after the streamers ceased, so that the total duration of these lines was about four times that of λ 4481. The luminosity lasted longest in the center of the spark gap.

The oscillatory character of these lines was also verified visually by Mr. L. A. Parsons, Fellow in this University.

RESULTS.

It follows from these observations and the photographs, that the strong spark lines λ 5339 and λ 5379 of cadmium (Group B), and λ 4481 of magnesium are due entirely to the curved streamers in the spark; also that the spectrum of the last few streamers in the cadmium spark does not contain so many lines as that of the first few, *i. e.*, the line λ 4416.

The principal arc lines λλ 5086, 4800, 4678 of cadmium (Group A), and the triplets at λ 5170 and λ 3830 in magnesium are also due partly to the streamers, but a large part of their luminosity is due to something else which appears in the center of the spark gap a trifle later than the first discharge, spreads throughout the gap and retains its luminosity after the streamers cease, retaining it longest in the center of the gap.

This latter luminosity is without doubt due to the metallic vapors.

The fact that the arc lines are due in part to something else besides the streamers was rather strikingly shown by inserting a considerable self induction (0.0093 henries) in the spark circuit. As stated above, the principal spark lines show a tendency to shorten up close to the poles while the arc lines go clear across the spark gap. Now when the spark itself is viewed in a rotating mirror under these conditions, the streamers do not advance so far from the poles as with the ordinary spark, while the center of the spark gap is filled with a pale light whose color and intensity are quite different from those of the streamers.

Fig. 2 is a photograph of the spark under these conditions using cadmium electrodes. The streamers come out on the photograph, but the faint light in the center of the spark, while clearly visible to the eye, was too faint to appear on the negative. The period of the condenser was in this case about fifty-eight times as great as with the ordinary spark. It will be noticed that the initial straight discharge has disappeared. This was to be expected, since Schuster showed that a self induction cuts out the air lines, and that the air lines are due to the initial discharge.

The streamers emanate from the kathode.—It is known already that the streamers proceed from a pole of the same nature. Feddersen's results were somewhat irregular so that he was unable to lay down any general law as to which pole emitted the stronger luminosity. In order to determine whether this were kathode or anode, I charged the condenser by an electric machine and carefully tested the electrification of its terminals with a gold leaf electroscope just before the spark passed. Two or three photographs of the spark were taken under these conditions using magnesium electrodes. Knowing the electrification of the poles at the first discharge, it was comparatively easy to tell from the photographs whether the streamers proceeded from a positively or a negatively electrified electrode. In each photograph they proceeded from the negatively charged pole.

The streamers do not carry the current.— It is easy to see by an inspection of the plates that the streamers shoot out from the poles with gradually diminishing velocity, and that before they get more than half way across the spark gap, the entire charge has passed across and the return oscillation is beginning.

Spark with very hot poles.—It must be remembered that the results of this investigation hold only for comparatively cool electrodes. With magnesium poles, by inserting a small self induction and increasing the primary current from 12 to 25 ampères, small white-hot globules formed on the electrodes. When this occurred, the noise of the spark greatly diminished, the spectrum showed marked changes, and the appearance of the spark in the rotating mirror was quite different. The strong spark line $\lambda 4481$ shrunk down close to the electrodes, while the arc triplet at $\lambda 5170$ did not. The spark when viewed in the mirror showed a luminosity advancing from the poles to the center of the spark with far less velocity than that of the customary streamers. As far as could be made out, there were also feeble streamers present which advanced only a short distance out from the poles. Every now and then the little globules would fly off the poles, the loud noise would return, and the ordinary streamers would instantly reappear in the spark. The spark line $\lambda 4481$ then stretched clear across from pole to pole.

The result of this investigation may be expressed briefly by saying that the chief cause of the complexity of the spark spectrum is the presence of the luminous streamers in the spark.

As to their nature, they may be luminous pulses, something like those that occur in a Geissler tube discharge. Or they may be metallic vapors, the peculiar vibration of whose atoms is set up by the act of tearing them off the electrodes; as they moved off from the electrodes, the abnormal vibrations would die out, while the more fundamental vibrations, principal arc lines, would persist—would indeed be augmented by the passage of the to-and-fro currents through the vapors.

In conclusion, the author wishes to express his thanks to Professor Ames for his kindness and for the many fruitful suggestions made during the course of this work.

ADDENDA.

EFFECT OF A STRONG MAGNETIC FIELD.

Some experiments were also made upon the effect produced by placing the spark in a strong magnetic field. The spark terminals were placed between the poles of a large electro-magnet, and a mirror was arranged so that light from the spark which was propagated along the lines of magnetic force was reflected to a lens, thence to a slit upon which the image of the spark was focused. The light then passed along to a collimating lens, to the revolving mirror with vertical axis, from which it was reflected through the lens of a camera and brought to a focus on the ground glass, the lens being adjusted for parallel rays. By a variation in the above arrangement, the light from the collimating lens could be made to pass through a couple of prisms, then through another lens, then, at a distance away sixteen inches greater than the focal length of the last lens, upon the revolving mirror, and into the camera. By the latter arrangement, the behavior of the separate lines of the spectrum could be studied when subjected to a strong magnetic force.

Perhaps the most interesting feature of the change produced is that the spark lines (Group B) and the arc lines (Group A) behaved quite differently. With no magnetic field they were both long lines, *i. e.*, extended clear across the spark gap. With the magnetic field, the magnesium spark line λ 4481 extended outward from each pole only about a quarter of the way across the gap, leaving 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, where it remained luminous for about 160×10^{-6} seconds, the luminosity as it moved from the poles to the center of the gap being crossed by a series of streamers. The noise of the spark was increased by the magnetic field.

In these experiments the period of the condenser was 5.5×10^{-6} seconds, the strength of the field about 10000. The velocity and duration of the luminosity were measured by a series of careful visual observations.

Velocity of the streamers.—As there are two distinct phenomena in the spark that might indicate the velocity with which the metallic vapors advance from the poles toward the center of the spark gap, a few plates were measured up in order to distinguish between them,

1. By measuring the slope of the streamers in the magnesium line λ 4481 on a photograph of the spectrum taken with the revolving mirror, it is possible to determine the velocity with which the streamers shoot out from the poles. The value of the velocity obtained in this way was not far from 25×10^4 cms. per second. About a millimeter out from the pole the velocity falls to 16 or 18×10^4.

2. Now the appearance of the line λ 4481 in the rotating mirror often shows a peculiarity which would seem to indicate a second velocity. The first streamer shoots out only a little way, the next one a little farther, and the third still farther, so that the locus of the extremities of successive streamers, when viewed in the rotating mirror, forms an inclined line which is sometimes fairly straight but which is sometimes irregular, owing to the fact that the distances to which successive streamers advance do not increase strictly in arithmetical progression. If the slope of this line be regarded as indicating a velocity it gives a value less than one fifth of the maximum velocity of the streamers, *i. e.*, about 4×10^4. Now, this is not far from some of the values found by Schuster[1] and Hemsalech in their work on the spark, and interpreted by these observers as the velocity of the metallic vapors. But the appearance of my negatives points to the conclusion that the slope of this line does not indicate a velocity, but is in most cases a sort of envelope of successive streamers, and that this is probably what Schuster and Hemsalech have measured in many cases. As pointed out by Schuster, this apparent velocity is not far from that of a sound wave, and if we assume that the violent sound emitted by a spark is produced by the expansion of a column of air raised to high temperature and therefore to high

[1] *Phil. Trans.*, 193, pp. 189–213.

PLATE III.

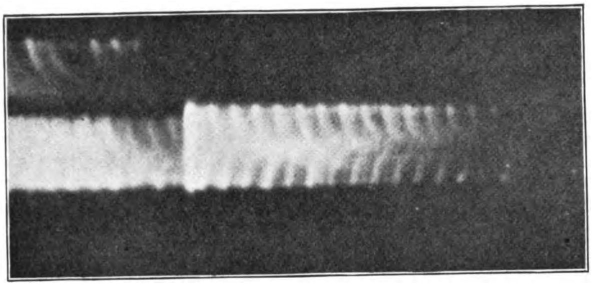


FIG. 1.

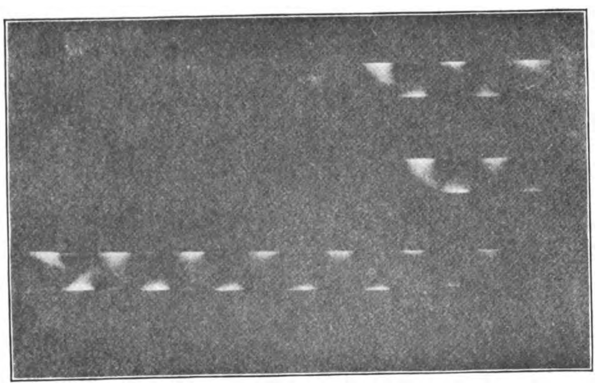


FIG. 2.

PLATE IV

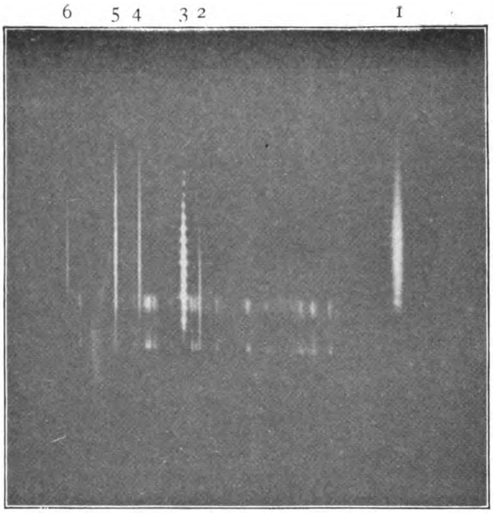


FIG. 3.

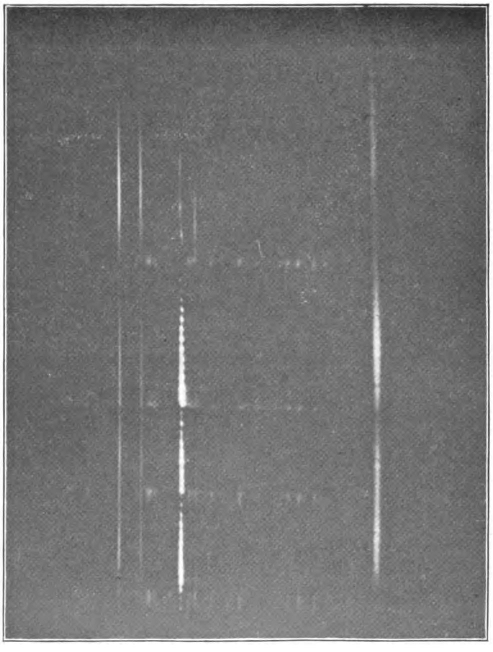


FIG. 4.

PLATE V.

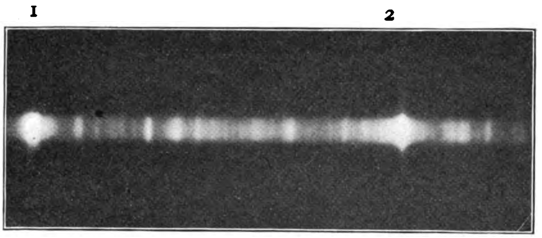


FIG. 5.

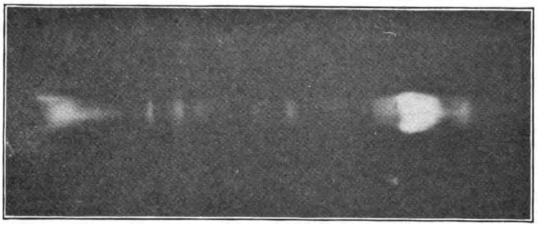


FIG. 6.

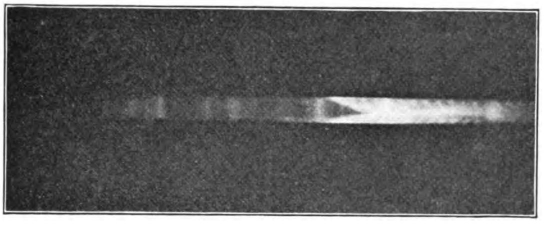


FIG. 7.

PLATE VI.

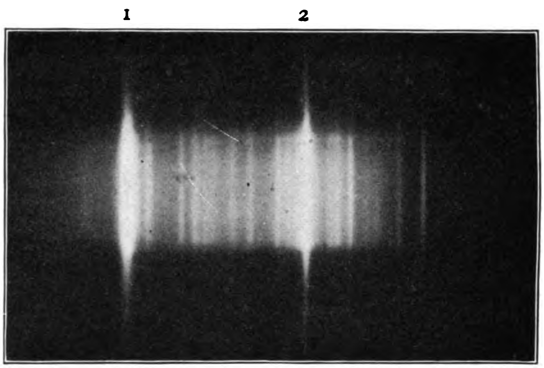


FIG. 8.

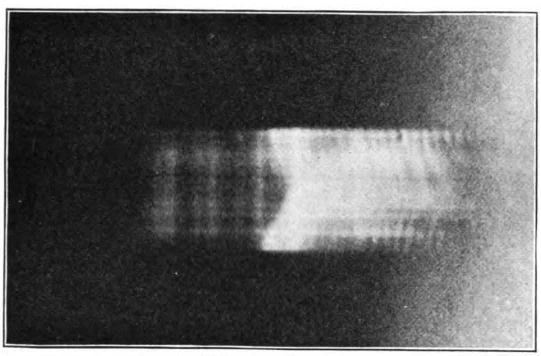


FIG. 9.

pressure by the first discharge (for if the temperature of a gas is raised, the density remaining constant, the pressure is raised also), it is rational to suppose that the distances to which successive streamers advance would increase as the pressure of the air which opposes their motion becomes less and less.

JOHNS HOPKINS UNIVERSITY,
Baltimore, Md., June 1901.

DESCRIPTION OF THE PHOTOGRAPHS.

Plate III, Fig. 1. Spark, cadmium electrodes. Period of the condenser, 5×10^{-6}. Mirror is turning in such a direction that light appears at the left of the image first. In this photograph the exposure was so long that another spark happens to have struck the plate just to the left of the principal one. A fragment of a third spark appears above the latter, which was gotten by raising the lens of the camera. There is also a luminosity which persists after the oscillations die out, which fails to appear on the photograph, owing to under-exposure.

Plate III, Fig. 2. Spark, cadmium electrodes. Period of condenser, 75×10^{-6}. Three images appear upon the plate. In the upper two, the plate was not long enough to catch more than two or three oscillations.

Plate IV, Fig. 3. Spark spectrum photographed with rotating mirror whose axis of rotation is horizontal. The lines are thus pulled out vertically upwards. The upper pole is magnesium and the lower, cadmium. One notices the distinct beading in the magnesium spark line λ 4481, (3), and the indistinct beading in the arc triplet λ 3830, (1). The greater duration of the latter is also apparent, though not very clearly so on this particular photograph. The oscillations in the cadmium spark line λ 4415, Fig. 2, also appear, but those in the arc lines $\lambda\lambda$ 4678, (4), 4800, (5), and 5086, (6), do not. This is because the mirror is turning in the most favorable direction for bringing out the oscillations in the magnesium, and not in the cadmium lines. The magnesium line λ 4481, (3), being due to puffs that shoot downwards from the poles, the action of the mirror is to diminish or to arrest their apparent motion, thus separating them into a series of distinct beads. With the cadmium lines the puffs shoot upwards, and the mirror prolongs each into a line of light thus rendering the oscillatory effect less clearly visible. I have another negative taken with the cadmium pole on top in which the oscillations of the cadmium lines are clearly shown, to the detriment, however, of those of the magnesium lines. It will be noticed that two separate sparks appear on this negative, shown by the two sets of air lines. The lower part of the magnesium line λ 4481 belongs to the lower spectrum. With the mirror at rest the length of all the lines would be about the same as that of the upper set of air lines.

Plate IV, Fig. 4. Same as Fig. 3 except that four flashes of the spark appear. The air lines also are somewhat weak on the enlarged print. It will be remembered that these impressions are not made by four *consecutive* sparks, as the interval between consecutive sparks was 100 times as great as the entire duration of a single spark. In Figs. 3 and 4 the period of the condenser was 5×10^{-6}.

Plate V, Figs. 5, 6, and 7 show the magnesium spectrum with the axis of the mirror vertical. In Fig. 5 the mirror is at rest, in Fig. 6 it is making 11¼ revolutions per second, and in Fig. 7, 65½ turns per second. In Fig. 6 we notice the tendency of the arc triplet at λ 3830, (1), to appear most brilliant in the center of the spark gap; also its greater persistence compared with the spark line λ 4481, (2). In Fig. 7 the spark line 4481, (2), appears broken up into a regular series of twelve or more streamers. We also see the two *less* steeply inclined lines of light advancing from the poles to the center of the spark gap, where the line λ 4481 starts out. The arc triplet at λ 3830, (1), does not appear, owing to lack of light, while the air lines are scarcely changed by the rotation of the mirror.

Plate VI, Figs. 8 and 9 show also the separation of the same line, λ 4481 magnesium, (2), into a succession of about eighteen curved streamers, the air lines being straight and hazy. The arc triplet at λ 3830, (1), again disappears for lack of light. The horizontal lines of light in Fig. 9 are due to inequalities in the width of the slit. The spark length was the same, seven millimeters, in Figs. 5, 6, 7, and in Figs. 8 and 9, but Figs. 5, 6, and 7 were taken with the objective prism, and Figs. 8 and 9 with a collimating lens which produced a wider spectrum. In Figs. 5, 6, 7, 8, and 9 the period of the condenser was 1.3×10^{-6}.

Charles Carroll Schenck was born in Baltimore, October 10, 1871. His elementary education was obtained in the public schools, and in 1890 he entered the Johns Hopkins University, following the studies of the Mathematical-Physical Group. He received the degree of Bachelor of Arts in 1893, having held for three years either an ordinary or an honorary Hopkins Scholarship.

He then followed advanced courses in Physics and Mathematics, pursuing such subjects as Theory of Heat Conduction, Thermodynamics, Hydrodynamics, Electricity and Magnetism, and Light in Physics, and Theory of Functions, Elliptic Functions and Higher Plane Curves in Mathematics. In 1899 he undertook an investigation of the Electric Spark and its Spectrum by means of a Revolving Mirror, which was published in the Astrophysical Journal for September, 1901. This was submitted to the Board of University Studies as a thesis for the degree of Doctor of Philosophy in June of that year. During his advanced studies he was twice appointed to a University Scholarship.