OSCILLATORY SPARK DISCHARGES BETWEEN UNLIKE METALS.

BY D. L. RICH.

INTRODUCTION.

IT is known by physicists that there are some twenty factors affecting the production of an oscillatory spark discharge; furthermore, with a few exceptions, there is general agreement as to the part each one of these factors plays. One of the exceptions noted is the effect of the electrode material itself, and that particular phase of the subject forms the basis of this paper.

In view of the very great amount of work that has been done in connection with the electric spark, the effect of the electrode material is very rarely mentioned. In practically all research work on spark discharges the spark has been formed between electrodes of like material, so that opportunities for observing the effect of dissimilar materials have been in general absent. Considering the extensive literature on the oscillatory spark discharge, the lack of experimental data for sparks between electrodes of unlike material is surprising. On the other hand, the effect of the electrode material on the electric arc, both D.C. and A.C., and the behavior of what are known as crystal rectifiers, have been subjects of wide investigation in recent years, and the well-known results therein determined would naturally lead one to believe that the electrode material is not a negligible factor in any electric discharge.

PREVIOUS WORK ON THIS PROBLEM.

One of the earliest investigators of the effect of the electrode material was Righi.[1] He found no difference in the sparking potential in the case of C, Bi, Zn, Sn, Pb and Cu. In 1878, De La Rue and Muller,[2] in addition to their work on the effect of the shape of the electrodes, used their 10,000-cell silver chloride battery to produce sparks between similarly shaped electrodes of unlike material, Cu, Ag, Pt, Mg, Zn, Al, brass and steel. They also found no difference, except in the case of aluminum, from which sparks could be drawn apparently a little more easily. In 1892, Peace[3]

[1] Righi, Nuovo Cimento, 16, p. 97, 1876.
[2] De La Rue and Muller, Phil. Trans., Part 1, p. 55, 1878.
[3] Peace, Proc. Soc. Lond., 52, p. 109, 1892.

worked with Cu, Zn and brass electrodes. His method was to apply a storage battery to two spark gaps connected in parallel. These spark gaps were set at unequal lengths, and enclosed in separate receivers from which the air could be exhausted; then by changing the gas pressure the sparks were shifted from one gap to the other. No variation produced by interchanging the electrode materials was observed. In 1903, Carr[1] measured the breakdown potential difference for brass, Fe, Zn and Al. He likewise found no difference.

When the spark gap is exceedingly short, as in the case of the coherer, the material undoubtedly affects the discharge. Guthe[2] was the first to point this out, showing in 1901 that the cohering effect between electrodes of unlike material takes place at a lower voltage in one direction than in the reverse direction. Hobbs,[3] using like electrodes and very short spark-lengths (two to six wave-lengths of light) claims that the metallic ions take part in the discharge, with the result that the material of which the electrode is composed exerts an important influence on the spark potential. Almy[4] attempts to connect cathode fall with spark potential. To quote him, "The fact that different metals show marked difference in the so-called cathode fall obviously leads to the inference that spark potentials must to a certain extent depend on the material of the electrode used." Later he says, "In air the cathode fall of the different metals differs so little that it hardly seemed probable a difference in spark potentials would be detected." His experimental work was done almost entirely with hydrogen as the gas in which the electrodes were immersed. He used a storage battery to furnish the voltage, and a Weston voltmeter to measure it. In hydrogen he finds fairly consistent differences due solely to the material of the electrodes. In air the only variation in sparking potential that he mentions is in the case of Pt-Al electrodes, the $Pt^{-}Al^{+}$ discharge requiring eight volts more than the $Pt^{+}Al^{-}$ discharge.

The work of Schuster and Hemsalech,[5] followed by that of Milner[6] and of Royds,[7] throws much light on the behavior of metallic ions in the spark gap. These men photographed the spark on a rapidly revolving film, allowing the light to pass through a spectroscope placed between the spark gap and the film. The appearance of the photographed lines enabled

[1] Carr, Phil. Trans., A, 201, p. 419, 1903.

[2] Guthe, Annalen der Physik, 4, p. 762, 1901.

[3] Hobbs, Phil. Mag., 10, p. 619, 1905.

[4] Almy, Univ. of Nebraska Studies, Vol. 6, No. 4, 1910.

[5] Schuster and Hemsalech, Phil. Trans., A, 193, p. 189, 1899.

[6] Milner, Phil. Trans., A, 209, p. 71, 1909.

[7] Royds, Phil. Mag., 19, p. 285, 1910.

them not only to identify the metallic vapors present in the spark, but also to compute the velocities with which these vapors traveled out into the spark gap from each electrode. Their results show that the different metal vapors travel with unequal velocities. Since their work was mainly the determination of ionic velocities they were not concerned with the critical sparking potential, nor with rectification effects. It is however only a logical probability that if the metal ions travel with unequal velocities these same ions are liberated from the electrodes with unequal facility, and therefore the spark might start more readily from some metals than from others; in other words, the measurements of Schuster and Hemsalech rather support the idea that rectification effects due to electrode material do exist.

The Problem.

If there is a rectification effect of this nature, it should manifest itself when an alternating electromotive force of sufficient magnitude is applied to unlike electrodes. And the behavior of the spark discharge is probably best studied by photographing the spark gap while the discharge is taking place.

Our problem then is really this: *Apply an alternating electromotive force to an oscillatory circuit containing a spark gap made of electrodes mechanically alike but chemically different and determine by photographing the spark whether or not the oscillatory discharge starts as readily when one electrode is anode as when the other is anode.* During one of the series of half-cycles, say that series consisting of the first, third, fifth, seventh, etc., half-cycles, one of the electrodes will be initially an anode; while in the other alternate series, consisting of the second, fourth, sixth, etc., half-cycles, this same electrode will be initially the cathode.

To photograph the spark gap in air at ordinary atmospheric pressure, three principal methods are available: (*a*) To insert either a rotating mirror or a rotating lens between the spark gap and the stationary sensitized surface of the camera. Feddersen, and Trowbridge, for example, used the rotating mirror, while Boyd used a series of rotating lenses. (*b*) To separate the otherwise superimposed oscillations by blowing the sparks from the narrow to the wide end of a V-shaped spark gap by means of a powerful blast of air. Klingelfuss was the first to use this method. (*c*) To receive the image of the spark on a rapidly revolving plate or film. Pierce, and Lodge and Glazebrook used a revolving plate, while Schuster and Hemsalech used a revolving film.

The second method was discarded as undesirable, and throughout this work there has been used a combination of the first and the third methods

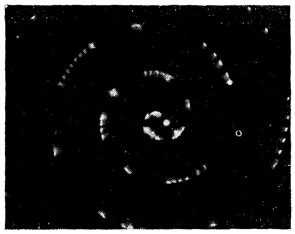

Fig. 1.

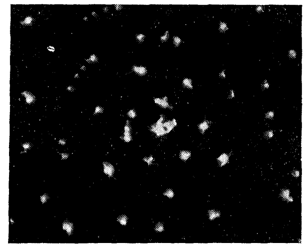

Fig. 2.

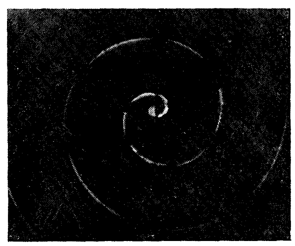

Fig. 3.

Fig. 5.

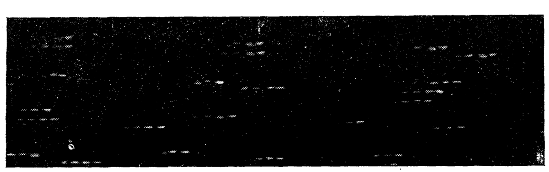

Fig. 6.

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outlined above, the photographic lens being moved with rather slow velocity, and the photographic film or plate with a much higher velocity.

First Method Used—Plate Camera.

In order to observe the relative number of spark trains per half-cycle no excessive speed of the photographic surface is necessary. For this the following method was found satisfactory. An ordinary glass plate negative, held in its customary plate holder which in turn was clamped centrally on the end of the shaft of a small motor, and at right angles to the shaft, so that the plate could be turned at a fairly high speed in its own plane, was the arrangement used for moving the photographic surface. In order to prevent the superposition of images the lens of the camera was swung slowly across in front of the plate and parallel to it, so that the successive spark trains traced out a spiral on the plate.

To produce these sparks a spark gap, an inductive resistance, and a condenser were connected in series, and then the condenser put directly across the secondary of a rather leaky high voltage transformer whose primary was connected to 110-volt 60-cycle mains.

Figs. 1, 2 and 3 are reproductions of photos secured in this way. Each spot represents not a single spark but a complete train of sparks, the speed of rotation not being sufficiently great to separate the individual oscillations. The groups of spark trains correspond to the half-cycles of the exciting primary current. The asymmetry of the spark trains per half-cycle is very plainly evident, every second half-cycle containing many trains, and the alternate half-cycles fewer trains. In Fig. 1 is a half-cycle (marked "0") that produced no spark trains whatsoever. In Fig. 2 several alternate half-cycles trail off into a tail, indicating that the oscillatory discharge degenerated into an ordinary arc discharge. To test this, the capacity and the inductance were disconnected, and Fig. 3 is the appearance of the resulting arc.

Interpretation and Predictions.

Figs. 1, 2 and 3 are photographs taken when the electrode materials were copper and iron. The asymmetry of the spark trains per half-cycle indicates that there is a rectification effect present in the oscillatory discharge between two electrodes of dissimilar material. Probably if the critical voltage were secured (a difficult task, but not impossible) spark trains would be produced only on alternate half-cycles, the others being entirely suppressed. Even if this critical voltage were not used, but instead a voltage somewhat higher than the critical, rectification effects when present would manifest themselves in at least three ways:

1. *In the Relative Number of Spark Trains per Half-cycle.*—If we assume that the sparks start more easily at one electrode than at the other, we are led immediately to the conclusion that the sparks must start more readily on one half-cycle than on another; that one set of alternate half-cycles will produce more spark trains than the other alternate set. The following diagram (Fig. 4), it is reasonable to suppose, might represent what our assumption leads us to expect. Suppose the electrodes are Cu and Fe, and that the first half-cycle occurs when Fe is initially positive, and the second half-cycle when the electrode Fe is initially negative; and suppose further that we assume that the spark starts the more readily when Fe is negative than it does when Cu is negative. This amounts to the same as assuming that the sparking potential, or the difference of potential necessary to initiate a spark, is relatively high on the Cu^-Fe^+ half-cycles and relatively low on the Cu^+Fe^- half-cycles. The potential builds up along the curve *AB* until it reaches the sparking potential *CD* at the point *E*. Then a discharge takes place, either unidirectional or oscillatory as the case may be, with the result that the potential difference is reduced to a magnitude less than that necessary to maintain the discharge (not necessarily reduced to zero, however). The voltage then builds up again, let us say along some such line as *FG*, and the process repeats itself until finally the curve reaches *H* and no further discharge takes place until the potential difference builds up in the opposite sense in the next half-cycle, with Fe initially negative. Owing to the relatively high potential necessary to initiate a spark, only a relatively small number of trains will be produced in this Cu^-Fe^+ half-cycle.

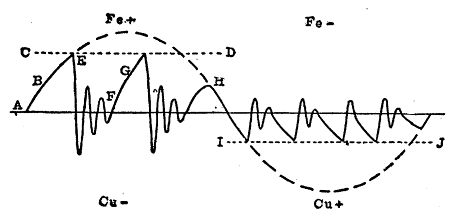

Fig. 4.

During the next half-cycle, if the sparking potential *IJ* is small, the discharges will have a chance to begin *earlier* in the half-cycle; after the falling off of the potential due to the discharge, the potential can build up again to the necessary sparking magnitude *more quickly*; and the sparks can start and last *later* in the half-cycle; *all three* of these factors tend to produce *more discharges* in this Cu^+Fe^- half-cycle than in the preceding Cu^-Fe^+ half-cycle.

2. *In the Relative Number of Individual Oscillation Sparks per Train.*—When a spark does occur at the higher sparking potential, this spark might reasonably be expected to be of a more violent nature than a spark produced at a lower sparking potential. If more violent, not only would

the condenser be more strongly charged in the opposite sense, but there would also be more ions produced in the spark gap, with the result that the spark gap resistance would be decreased. Both the stronger charge and the lowered resistance would lead one to expect that the oscillations following the initial spark would be more numerous. The large initial charge and the smaller damping decrement would each tend to prolong the duration of the wave train.

3. *In the Relative Number of Spark Trains Containing an Even Number, or an Odd Number, of Individual Oscillation Sparks.*—So far as the material affects matters, if the initial spark in any train starts with ease, the third, fifth, etc. (the *odd* sparks), in that same train, since they start from the same electrode, should also start with ease, with greater ease than the second, fourth, etc. (the *even* sparks), which originate at the other electrode, from which the spark starts with difficulty. It would naturally be expected that any spark train would stop with an easy spark, *i. e.*, at the beginning of a spark difficult to start. That is, if the initial spark of any train starts easily, that particular spark train might be expected to contain an *odd* number of sparks. Likewise, the train whose first spark originates at an electrode from which the spark starts with difficulty should in general contain an *even* number of individual sparks.

But in addition to the material of the electrodes there are at least two other factors (even with the electrodes mechanically and chemically alike) that probably have an influence on the oddness or evenness of the number of sparks per train. The primary current is changing while the secondary discharge is taking place. The flux change in the secondary due to this slowly changing low frequency primary current, combined with the flux change in the secondary due to the rapidly changing high frequency secondary current, since these two changes are in the same sense during half the sparks and in opposite sense during the other half, would probably produce an asymmetry that would favor one set of sparks always whether the electrodes were of the same material or not.

Also, the ionization produced in the spark gap is a function of the velocity of the ions, which velocity is in turn dependent on the potential at which the ions were emitted,—a high potential difference producing a high velocity and therefore a low capacity for ionization. So considering the three factors, and not knowing their relative magnitudes it is impossible to predict which spark trains will contain an even number of individual oscillation sparks, and which an odd number.

Reasons for Changing to a Film Camera.

To investigate the above matters it became necessary to rearrange both the camera and the oscillatory circuit. The first method used, and the photographs secured, samples of which are shown above, are satisfactory to determine the relative number of spark trains per half-cycle; but to obtain photographs showing individual oscillation sparks the photographic surface must be made to move at a very much higher rate, and the period of the oscillatory discharge must be lengthened to secure a much lower frequency.

To lower the frequency a larger inductance coil and a larger condenser were built. The inductive resistance was a circular coil a meter in diameter and a meter high, and consisted of about a hundred turns of no. 12 coppered iron wire wound on a rough wooden frame. Its low frequency resistance was 6.5 ohms, and its low frequency inductance 25 millihenrys. The condenser was made of 48 large panes of ordinary window glass, each pane shellacked, coated on both sides to within five centimeters of the edge with tin foil, then given two more coats of shellac. The panes were mounted in a wooden frame with air insulation. When thoroughly dry the leakage was not excessive, but the absorption was very bad. The low frequency capacity ranged from an eighth to a half microfarad, depending on the duration of the charge and of the discharge.

To increase the speed of the camera the glass plate was abandoned and a film used instead (Eastman extra rapid speed film, about 55 inches long and $2\frac{1}{2}$ inches wide). The film was wrapped around the flat outside rim of a wheel 40 cm. in diameter. This made the total exposed length of the film about 1,260 mm. The wheel was mounted on a motor running 2,000 revolutions per minute, giving a linear velocity to the film of about 42,000 mm. per second. In order to hold the film in position at this rather high speed it was found necessary to bolt the film to the wheel with twelve bolts arranged zigzag around the circumference. By actual measurement of the developed films it was found that this inductance, capacity and film speed resulted in a separation of the individual oscillation sparks to distance of 4.1 mm., a distance amply sufficient for all present purposes.

As before, exposure was made by swinging the lens across the film while the film was rotating at a high speed, so that the spots of light traced out a continuous spiral on the film. The lens was moved by a heavy weight which in falling from ceiling to floor picked up counterbalancing weights so that its speed was kept approximately constant. Further the weight in falling automatically operated a mercury switch so that the spark discharge took place only while the lens was passing in front of the film. By adjustment it was found possible to cause the spiral to trace out twenty complete turns on each film, thus *enabling the spark gap to be kept under continuous observation for over half a second at a time*, *showing the groups of spark trains in over sixty consecutive half-cycles all spread out in a single line photograph over twenty-five thousand millimeters long.*

Data Secured from a Typical CuFe Photo.

Half-cycles in Which Fe Was Initially *Negative.*				Half-cycles in Which Fe Was Initially *Positive.*			
Half-cycle.	Number of Spark Trains.	Number of Sparks in Each Train.	Total Number of Sparks.	Half-cycle.	Number of Spark Trains.	Number of Sparks in Each Train.	Total Number of Sparks.
1		Incomplete		2		Incomplete	
3		Incomplete		4		Incomplete	
5	4	5 2 2 2	11	6	3	5 3 3	11
7	7	4 2 2 2 2 2 2	16	8	2	5 3	8
9	2	5 3	8	10	4	4 2 3 3	12
11	6	4 2 2 2 2 2	14	12	2	5 3	8
13	6	4 2 2 2 2 2	14	14	2	5 3	8
15	5	4 2 2 2 3	13	16	3	4 3 3	10
17	5	5 2 2 2 3	14	18	3	5 3 3	11
19	9	4 2 2 2 2 2 2 2 2	20	20	2	5 3	8
21	8	4 2 2 2 2 2 2 2	18	22	4	5 3 3 3	14
23	7	4 2 2 2 2 2 2	16	24	3	5 3 3	11
25	5	4 2 2 2 2	12	26	3	4 3 3	10
27	5	4 1 2 3 2	12	28	3	4 3 3	10
29	4	4 3 2 3	12	30	3	4 3 3	10
31	8	4 2 2 2 2 2 2 2	18	32	4	4 3 2 3	12
33	6	4 2 2 2 2 2	14	34	3	5 3 3	11
35	9	4 2 2 2 2 2 2 2 2	20	36	2	5 3	8
37	8	4 2 2 2 2 2 2 2	18	38	3	5 3 3	11
39	7	4 2 2 2 2 2 2	16	40	3	3 3 3	9
41	5	3 3 2 2 2	12	42	5	3 2 2 2 3	12
43	9	4 2 2 2 2 2 2 2 2	20	44	2	3 3	6
45	7	4 1 2 2 2 2 2	15	46	4	3 3 3 3	12
47	7	3 2 2 2 2 2 2	15	48	3	3 3 3	9
49	7	4 2 2 2 2 2 2	16	50	4	3 3 3 3	12
51	7	4 2 2 2 2 2 2	16	52	2	5 3	8
53	9	4 2 2 2 2 2 2 2 2	20	54	4	4 2 2 3	11
55	8	4 2 2 1 2 2 2 2	17	56	3	3 3 3	9
57	8	4 2 2 2 2 2 2 2	18	58	4	4 2 2 3	11
59	11	2 2 2 2 2 2 2 2 2 2 2	22	60	3	3 3 3	9
61	8	3 2 2 2 2 2 2 2	17	62	4	3 3 3 3	12
63	8	4 2 2 2 2 2 2 2	18	64	4	3 3 3 4	13
65		Incomplete		66	4	3 3 3 3	12
67		Incomplete		68	3	3 3 3	9

To show relative number of spark trains per half-cycle, and also to show relative number of oscillation sparks per train, it is desirable to use a short spark gap, and highly damped oscillations. Fortunately these conditions are the very easiest possible.

A large number of photographs were taken, in an interval extending over two years. Most of the work was done on CuCu and CuFe electrodes in an attempt to settle definitely the point in question with these particular metals. Later electrodes of zinc and bismuth were used in various combinations with each other and with copper and iron. Many different specimens were used, and several different shapes. The sparks were always produced in air at atmospheric pressure. The spark gap was varied in length from 0.1 mm. to 3 or 4 mm., while the lens of the camera was so placed that the image of the spark gap was slightly longer than the spark gap itself.

Figs. 5 and 6 are sections of typical films showing the appearance of the sparks between CuFe electrodes and CuCu electrodes respectively. Owing to the fact that some of the beginning and the ending half-cycles are incomplete on the edges of the films, the number of half-cycles observable in the two series are in general unequal; however, no error is thus introduced as average values are desired, and any number of half-cycles may be averaged.

CuFe Summary.

	Cu^+Fe^-.	Cu^-Fe^+.
Total number of half-cycles observed	30	32
Total number of spark trains	205	101
Average number of spark trains per half-cycle	6.2	3.16
Total number of oscillation sparks	472	327
Average number of oscillation sparks per train	2.3	3.23
Number of trains consisting of 1 spark	3	0
Number of trains consisting of 2 sparks	166	9
Number of trains consisting of 3 sparks	10	71
Number of trains consisting of 4 sparks	23	9
Number of trains consisting of 5 sparks	3	12
Total number of spark trains consisting of an *even* number of sparks	189	18
Total number of trains consisting of an *odd* number of sparks	16	83
Per cent. even	92.2	17.7
Per cent. odd	7.8	82.3

An examination of the CuFe data summary shows that the spark trains on the Cu^+Fe^- half-cycles were almost double the number of trains on the Cu^-Fe^+ half-cycles (6.2 to 3.16); that the number of oscillation sparks per train was over a third larger (2.3 to 3.23) in the Cu^-Fe^+ half-cycles than in the Cu^+Fe^- half-cycles; and that in the Cu^-Fe^+ half-cycles 82 per cent. of the trains contained an *odd* number of sparks, while in the Cu^+Fe^- half-cycles 92 per cent. of the trains contained an *even* number of sparks.

Interpretation.

The relative number of spark trains per half-cycle, and the relative number of sparks per train indicate clearly that the Cu^+Fe^- discharge takes place more readily than the Cu^-Fe^+ discharge. The fact that an odd number of sparks per train predominates during the Cu^-Fe^+ half-cycles and an even number during the Cu^+Fe^- half-cycles indicates that the ionizing effect is the predominating influence in determining the evenness or oddness, as the sparks as a rule stop with the higher voltage, higher velocity, lower ionizing discharge.

In contrast with the preceding data, which was secured from a typical series of discharges between electrodes mechanically alike but chemically different, and which show rectification effects attributable solely to electrode material, compare the following set of data, from a characteristic series of discharges between CuCu electrodes.

Summary of Data Secured from a Typical CuCu Photo.

	Odd Half-cycles.	Even Half-cycles.
Total number of half-cycles observed	31	33
Total number of spark trains	63	74
Average number of spark trains per half-cycle	2.03	2.24
Total number of oscillation sparks	250	291
Average number of oscillation sparks per train	3.97	3.93
Number of trains consisting of 1 spark	0	0
Number of trains consisting of 2 sparks	0	0
Number of trains consisting of 3 sparks	10	7
Number of trains consisting of 4 sparks	45	64
Number of trains consisting of 5 sparks	8	3
Number of trains consisting of an *even* number of sparks	45	64
Number of trains consisting of an *odd* number of sparks	18	10
Per cent. even	71.5	86.5
Per cent. odd	28.5	13.5

An examination of the CuCu data summary preceding shows that the average number of spark trains per half-cycle is practically the same in the two series (2.03 to 2.24); that the average number of individual sparks per train is almost identically the same (3.97 to 3.93); and that in both series the spark trains are predominantly of four sparks each. In not one of these three respects is there even any hint of rectification effects. The irregularities which do occur in discharges of this nature are probably due to the conducting variations in the spark gap, possibly caused by air-currents, etc., variations which prevent the absolutely uniform charging of the condenser.

In every photograph, without a single exception, I have found the CuCu discharge to be symmetrical, and the Cu^+Fe^- discharge to be more easily produced than the Cu^-Fe^+ discharge.

DETERMINATION OF POLARITY.

In order to determine which particular kind of spark should be associated with the Cu^-Fe^+ discharge, and which with the Cu^+Fe^-, the A.C. primary circuit was disconnected and there was substituted a 220-volt D.C. source, through a suitable non-inductive high resistance and a knife switch. The fact that the primary E.M.F. was high, produced a rapid change of flux in the transformer when the switch was closed, and consequently a vivid spark in the secondary circuit; yet the resistance inserted in the primary circuit resulted in less than a volt across the primary coils, so that it was perfectly safe to put an ordinary 250-volt voltmeter directly across the secondary of the high potential transformer, and thus determine definitely and easily the polarity of the spark electrodes at make and at break. The voltmeter behaved as a ballistic galvanometer, and by the direction of its "kick" gave positive evidence concerning the polarity.

The camera film was set in motion, the camera shutter closed except at "make," and a series of make spark photos secured. Then the lens was displaced sideways slightly, the shutter closed except at "break," and a series of break spark photos obtained. The electrodes were then reversed, and the make and the break photos again taken, all on the same film, side by side.

When the primary circuit was closed, a single spark train was expected. As a matter of fact the photographs showed several spark trains for each make, the number varying from four to forty-two, depending on the length of the spark gap. This may be explained as follows:

Suppose the total quantity of electricity flowing into the condenser of the secondary circuit be plotted against time, giving the familiar curve of Fig. 7. A quantity q_1 might be sufficient to charge the condenser to

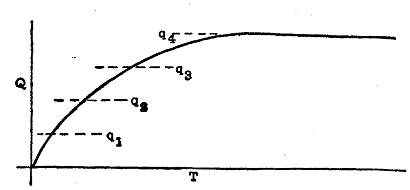

Fig. 7.

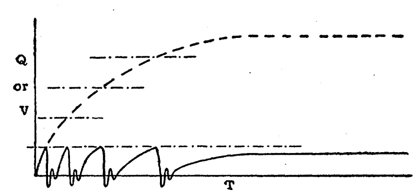

Fig. 8.

the sparking difference of potential, and an oscillatory discharge would then occur. A further quantity $q_2 - q_1$ might again charge the condenser, and another oscillatory discharge ensue; and again a quantity $q_3 - q_2$, and still further $q_4 - q_3$, and so on, might each cause a spark train. The fact that at each make the first spark trains were not only more intense but also made up of from five to eight oscillation sparks each, while the later spark trains were of less intensity and also of shorter length (2, 3, or 4 oscillation sparks each) supports the above explanation. The curve (Fig. 8) probably represents what took place:

Owing to the arcing effect at the knife switch when the primary circuit was opened, usually only one spark train was observed at "break," and it was usually much fainter than the sparks at "make."

Several films were used in this manner. In every case the photos of the Cu^-Fe^+ discharge consisted of light, narrow, faint spots alternating with heavy, broad, darker spots, and *always beginning with* the fainter spot, as shown in (*a*) Fig. 9; while the Cu^+Fe^- discharge photo was of similar alternations, but *always beginning with the broad dark spot*, as shown in (*b*), Fig. 9. The metallic vapor liberated in the spark gap when iron was anode always produced the much more intense light effect. On all the photos, whether produced by direct current or alternating current means, the polarity of the electrodes could be identified easily and positively. Furthermore, on the D.C. photos, the Cu^+Fe^- discharge without exception consisted of an even number of oscillation sparks; while the Cu^-Fe^+ generally, though not always, consisted of an odd number of sparks.

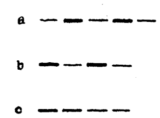

Fig. 9.

When the electrodes were of the same material, for example CuCu, the sparks were always of like character throughout, gradually growing fainter as the amplitude decreased, as shown in (*c*), Fig. 9. Furthermore the number of individual oscillation sparks when the electrodes were alike was predominantly even.

Further Results with Other Electrode Combinations.

It next seemed desirable to investigate the behavior of some other metals when used as electrodes, in order to see whether or not there exists a consistent rectification series among conductors in general. The same method was continued, and zinc, bismuth, copper and iron electrodes were used repeatedly in all possible combinations.

Iron-bismuth was one of the first combinations tried. Below is a summary secured from a typical Fe-Bi photo.

An examination of this summary, particularly the relative number of spark trains per half-cycle, and the relative number of oscillation sparks per train, indicates that the discharge can start more readily when iron is negative. Each of the other films of this particular electrode combination indicated the same rectification. Not much reliance, however, can be placed on the relative number of even and odd spark trains.

Iron-Bismuth Summary.

	$Fe^{-}Bi^{+}$.	$Fe^{+}Bi^{-}$.
Total number of half-cycles observed	28	29
Total number of spark trains	146	83
Average number of spark trains per half-cycle	5.21	2.86
Total number of oscillation sparks	218	184
Average number of oscillation sparks per train	1.49	2.21
Number of trains consisting of 1 spark	76	15
Number of trains consisting of 2 sparks	68	35
Number of trains consisting of 3 sparks	2	33
Number of trains consisting of an even number of individual sparks	68	35
Number of trains consisting of an odd number of individual sparks	78	48
Per cent. even	46.5	42.1
Per cent. odd	53.4	57.8

After finding that the spark discharge could be initiated more readily from iron that from either copper or bismuth (always assuming that the discharge is electronic in nature, so that the current flows from anode to cathode), the next step seemed to be the investigation of the copper-bismuth spark gap. Below is a copy of the data secured from a characteristic CuBi film. Note the 3's.

Copper-Bismuth Summary.

	$Cu^{+}Bi^{-}$.	$Cu^{-}Bi^{+}$.
Total number of half-cycles observed	32	32
Total number of spark trains	69	34
Average number of spark trains per half-cycle	2.16	1.06
Total number of oscillation sparks	201	101
Average number of oscillation sparks per train	2.91	2.97
Number of half-cycles producing no spark	1	5
Number of trains consisting of 1 spark	0	0
Number of trains consisting of 2 sparks	7	1
Number of trains consisting of 3 sparks	61	33
Number of trains consisting of 4 sparks	1	0
Number of trains consisting of an even number of individual sparks	8	1
Number of trains consisting of an odd number of individual sparks	61	33
Per cent. even	11.5	3
Per cent. odd	88.4	97

Here again, as in all of this work, the criterion as to rectification lies in the relative number of spark trains per half-cycle. After the spark is once started various extraneous and uncontrollable irregularities lessen the reliability that can be placed on the way in which that particular spark train continues. On the above film, twice as many spark trains originated from the bismuth anode as from the copper anode. And five times as many failures to produce any discharge whatsoever are charged to the copper anode.

Another combination tried was zinc and iron. The spark when iron is anode is always easily recognized, the light from the spark then apparently being exceedingly rich in actinic rays.

Iron-Zinc Summary.

	Fe^-Zn^+.	Fe^+Zn^-.
Total number of half-cycles observed	31	29
Total number of spark trains	96	41
Average number of spark trains per half-cycle	3.1	1.41
Total number of oscillation sparks	181	115
Average number of oscillation sparks per train	1.88	2.80
Number of trains consisting of 1 spark	46	4
Number of trains consisting of 2 sparks	17	1
Number of trains consisting of 3 sparks	31	35
Number of trains consisting of 4 sparks	2	1
Number of trains consisting of 5 sparks	0	0
Number of trains consisting of an even number of individual sparks	19	2
Number of trains consisting of an odd number of individual sparks	77	39
Per cent. even	19.8	4.9
Per cent. odd	80.1	95.0

Here again the half-cycles in which iron was initially the anode produced considerably more than twice as many spark trains as the other series. In fact, the discharge took place so readily from the iron anode that the condenser could receive only a very small quantity of electricity, so small that a return spark was very frequently impossible, as is shown by the fact that 46 of the trains (48 per cent. of them) were unidirectional, one spark discharges.

One of the most prominent cases of rectification which was observed occurred in connection with a copper-zinc spark gap. The data for this particular gap is inserted here not as a typical case, but as a special case, illustrating the fact that with proper adjustment it is possible to initiate spark trains from one electrode alone. The necessary adjustment probably would be difficult to make, and still more difficult to maintain, but the following data show that it can be done.

Other films in the CuZn spark gap, while not so prominently asymmetrical as this one, always showed a decided preponderance of spark trains initiated during the half-cycles when zinc was anode, indicating that a discharge could start from zinc much more readily than from copper.

An inspection of the foregoing summaries shows that rectification effects manifest themselves prominently in the relative number of trains per half-cycle, and generally in the relative number of sparks per train.

Copper-Zinc Summary.

	Cu^-Zn^+.	Cu^+Zn^-.
Total number of half-cycles observed	32	30
Total number of spark trains	14	143
Average number of spark trains per half-cycle	1.27[1]	4.77
Total number of oscillation sparks	38	253
Average number of oscillation sparks per train	2.71	1.77
Number of half-cycles producing 0 trains	21	0
Number of trains consisting of 1 spark	1	55
Number of trains consisting of 2 sparks	2	72
Number of trains consisting of 3 sparks	11	10
Number of trains consisting of 4 sparks	0	6
Number of trains consisting of an even number of individual sparks	2	78
Number of trains consisting of an odd number of individual sparks	12	65
Per cent. even	14.3	54.5
Per cent. odd	85.7	45.4

Since other factors enter into the cause of oddness or evenness of the number of sparks per train, not so much reliance can be placed on the relative number of odd and even trains.

As a result of the work discussed in this paper the conclusion is reached that rectification effects do exist in oscillatory discharges between the unlike metals used, the order being Fe, Bi, Zn, Cu, a spark being initiated with the greatest facility from iron, and with the greatest difficulty from copper.

More complete data of this nature, involving the various elements which may be used as electrodes, may throw light on the stability of ionic or electronic aggregations or orbits within the atom.

Comparison with a Former Result.

It has already been mentioned that Guthe was the first to suggest that the discharge in the case of the coherer is undoubtedly affected by the material of the electrodes. In an attempt to measure the smallest potential difference necessary to produce coherer action Guthe[2] experimented with many different metals, among which were the same four, Cu, Bi, Fe and Zn, mentioned in this paper. Since in the coherer the two electrodes are either in actual contact or else separated by an exceedingly thin layer or film, the conditions are somewhat different from the ordinary spark gap. Further, the potential difference applied to the coherer was a very slowly changing, and finally constant, statical, battery potential difference; whereas the voltage used in this work was always a rapidly changing, alternating, transformer potential difference. Nevertheless, if the discharge is electronic, either method should yield some

[1] 11 half-cycles only.

[2] Guthe, Ann. d. Physik, 4, p. 762, 1901.

information concerning the facility with which electrons are torn from the anode and fired across the spark gap or the coherer film. Guthe arranges the metals in the order Bi, Fe, Zn, Cu, the series beginning with the easiest and ending with the hardest; *i. e.*, ending with the metal requiring the highest potential difference to produce coherer action. His series differs from the series proposed in this paper only in the relative positions of bismuth and iron.

Summary.

Many photographs of the oscillatory spark discharge between electrodes mechanically alike, but chemically different, were taken, in an attempt to determine whether or not the material of the electrode has any influence on the initiation of the discharge.

Electrodes of copper, iron, zinc and bismuth were used; also both alternating currents and intermittent direct currents were used; in producing the required potential differences.

The interpretation of the relative number of spark trains per half-cycle, the relative number of individual oscillation sparks per train, and the relative number of trains containing odd numbers and even numbers of individual sparks, is given, with reasons for such interpretation.

When the electrodes were alike symmetrical discharges were always found.

When the electrodes were of two unlike metals decided rectification effects were always produced, being very pronounced when copper was one of the electrodes, and most prominent when iron was the other electrode. In other words, the material of the electrodes is not a negligible factor in the initiation of a spark discharge.

If the discharge is electronic, the electrons are emitted from iron more easily than from bismuth or zinc, and much more easily than from copper; they are emitted from bismuth more easily than from zinc or copper; and from zinc more easily than from copper. Arranged in a rectification series, these metals stand

Fe, Bi, Zn, Cu.

The rectification effects seemed marked and consistent throughout. Many and various specimens of metals in various shapes were used all in air at ordinary atmospheric pressure.

In conclusion, my thanks are due to Professor K. E. Guthe, under whose helpful supervision this work was done; and also to Professor N. H. Williams for much good advice during the progress of the work.

University of Michigan,
Ann Arbor, Michigan,
April 1, 1915.

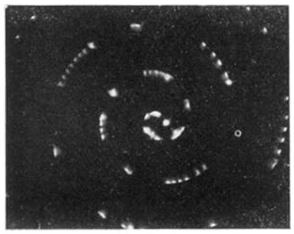

Fig. 1.

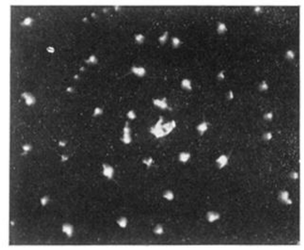

Fig. 2.

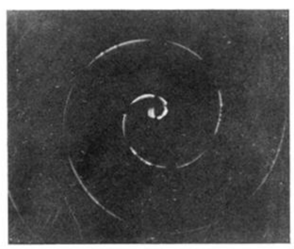

Fig. 3.

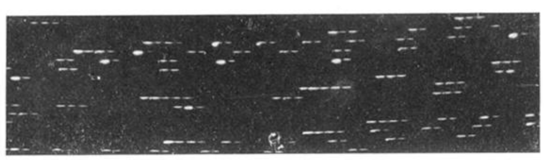

Fig. 5.

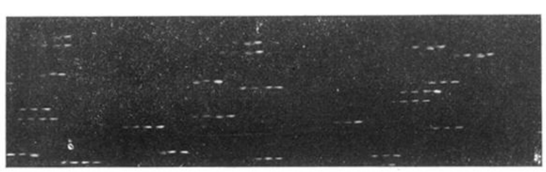

Fig. 6.