SPECTRAL PHENOMENA IN SPARK DISCHARGES

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Abstract

Two methods are described for measuring the differences in the time of appearance of the spectrum lines in sparks. The first is a refinement of the Kerr cell method previously used and a detailed description of its use is included. The criticisms of Gaviola of the method are shown not to apply. The second method makes use of a rapidly rotating mirror which either reflects the dispersed light of the spark to a photographic plate or the undispersed light to the slit of a spectrograph. In either case the position of the beginning of a line on the photographic plate gives its time of appearance. The method of Henriot and Hunguenard was used to rotate the mirror. Photographs of sparks are shown with the mirror rotating 1830 r. p. s. However, higher rotational speeds have been used. It is concluded that the Kerr cell method is superior for examining the air lines in the initial stages of the spark; while the rotating mirror method is better in studying the appearance and duration of the metallic lines which are not present in the very first stages of the spark discharge.

Although the electric spark in air has been the subject of a very large number of careful investigations, most of the mechanisms in the various stages of the discharge still remain obscure. This state of affairs probably results from the fact that the essential phenomena of the spark occur in such a short interval of time that the apparatus used in most cases failed to separate them into their component parts. However, during the last few years considerable progress has been made in the study of the various stages of the spark, due largely to the development of several methods of investigation that make it possible to study processes occurring in from 10^{-6} to 10^{-9} sec. It is the purpose of this paper to describe two independent methods of investigating the spark discharge and to record some of the results obtained.

When the sparking potential is first applied across a spark gap the discharge does not take place instantaneously, but a certain average time is required for the initiation of the discharge.[1] This time—usually called the time lag of the spark—is decreased by increasing the overvoltage and becomes in some cases of the order of magnitude of 10^{-8} sec.[2]

When once the discharge is initiated and the effective resistance across the gap starts falling, very little is definitely known of the process except

[1] Sir J. J. Thomson, Conduction of Electricity Through Gases, Cambridge University Press, 2nd Edition, p. 431.

[2] P. O. Pedersen, Ann. d. Physik **71**, 317 (1923); Rogowski, Archiv f. Electrotech. **16**, 496 (1926); Torok, Jour. A.I.E.E. **47**, 177 (1928); Beams, Jour. Franklin Inst. **206**, 809 (1928); L. B. Loeb, Science **59**, 509 (1929)—Suggests a possible explanation of these short time lags.

that the potential across the gap does not fall instantaneously to zero but decreases at a finite and measurable rate.[3]

If the light emanating from the spark in air during its initial stages is examined spectroscopically, it is found that all the spectrum lines do not appear simultaneously. In general the air lines appear first, followed by the spark lines of the metal with the metallic arc lines appearing last. Observations on these phenomena were first made by Schuster and Hemsalech,[4] while they were studying the duration of lines in metallic sparks. Their method consisted essentially in projecting the spectrum on a rapidly moving photographic film and measuring the relative positions of the various parts of the lines. Other workers[5] have observed the spark in a rotating mirror with similar results. The time resolving power of their methods, however, was not sufficient to give anything but rough qualitative results. Recently[6] a method based upon the findings of Abraham and Lemoine[7] that the Kerr effect in some liquids disappears very quickly after the electric field producing it is relaxed, has been successfully used to measure the order of appearance of spectrum lines in condensed discharges. By this method the values for the differences in the time of appearance of the various air lines themselves as well as the lines of a few metals were measured directly in terms of the velocity of light.[8] Since that time the method has been considerably refined and the observations on the air lines repeated. These values have also been confirmed by a rotating mirror method within the limits of precision of the latter method.

The experimental arrangement, except for refinements and details, is essentially the same as that previously described. The method, however, has been recently questioned[9] on the basis that oscillations of large amplitude should exist that would complicate the results.* Since in the work care was taken to investigate experimentally the magnitude of the oscillations present and, since the writer believes the method might find applications to other experiments, it will be described somewhat more in detail.

In Fig. 1 light from the spark A, made parallel by a lens L, plane polarized by a Nicol prism N_1, passes through a Kerr cell K, made by immersing two parallel metallic plates in CS_2, into a second Nicol prism N_2 crossed with

[3] Lawrence and Beams, Phys. Rev. **32,** 483 (1929).

[4] Schuster and Hemsalech, Phil. Trans. **193A,** 212 (1900).

[5] E. C. C. Baly, Spectroscopy **2,** 153 Longmans (1927).

[6] Brown and Beams, J.O.S.A. **11,** 11 (1925).

[7] Abraham and Lemoine, Comptes Rendus **129,** 206 (1899).

[8] Beams, Phys. Rev. **28,** 475 (1926).

[9] Gaviola, Phys. Rev. **33,** 1023 (1929).

* Note: In the writer's opinion the questions raised by Gaviola (loc. cit.) and by L. V. Hamos [Zeits. f. Physik **52,** 549 (1928)] concerning the "electro-optical shutter" have been adequately investigated and reported [Beams and Lawrence, Jour. Franklin Inst. **206,** 169, (1928)]. The cause of the discrepancy in the values in the difference in the average lags of the Faraday effect as observed by Beams and Allison, [Phys. Rev. **29,** 161 (1927)] and Allison, [Phys. Rev. **30,** 66 (1927)], which Dr. Gaviola claims no attempt was made to explain, was investigated and discussed by Allison in the paper referred to and shown to be due to the effect of wave-length upon the lag.

respect to N_1. If a potential is applied across the plates of K and the plane of polarization of the light makes an angle (45° in these experiments) other than zero or 90° with the lines of force, light can pass N_2 because of the double refraction in K.[10] This double refraction produced in CS_2 by the electric field is called the Kerr effect. If μ_1 and μ_2 are the refractive indices for the

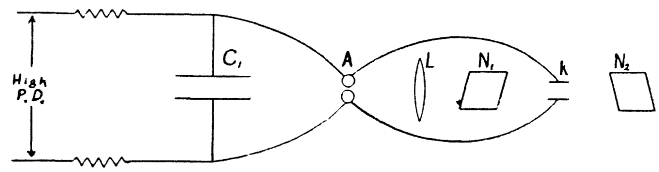


Fig. 1

two rays then their phase difference after passing through the Kerr cell K is $D = 2\pi l/\lambda(\mu_1 - \mu_2) = 2\pi BlE^2$, where λ is the wave-length of the light, B is a constant for a given substance, wave-length and temperature, l is the length of the light path through the liquid, and E is the electric field strength. The intensity of light passing N_2 is

$$I = A \sin^2 D/2 = A \sin^2 \pi BlE^2$$

where A is a constant. As a result, for comparatively small values of D (6° to 16°) as used in most of these experiments, the intensity of light passing N_2 varies approximately as the fourth power of the field strength.

If an electric potential is slowly applied across the spark gap A in air until the spark discharge takes place, it has been previously found that no light from the spark intense enough to be detected by the eye passes N_2, provided the lead wires are not too long and are approximately the same length as the light path. The Kerr effect in K therefore effectively vanishes by the time that the light reaches the cell, or the light from the spark is too faint to be observed for a certain time after the beginning of the discharge. If, however, the lead wires from A to K were lengthened, the light path remaining fixed, light passes N_2. When the light was examined spectroscopically it was found that the spectrum lines for any given substance appeared in a definite order which was not a function of their wave-length or of their intensity when measured over the entire duration of the spark.

Fig. 2 shows schematically the arrangement used to measure the time between the appearance of the lines directly in terms of the velocity of light. The arrangement in Fig. 1 is merely modified to allow the light to pass to a movable trihedral mirror system M_1 before entering the cell. The mirror system, designed by Professor L. G. Hoxton, returns a beam of light parallel but displaced. The three mirrors silvered on the front surface are mutually perpendicular and mounted on a steel frame which slides on a wooden track 23 meters in length. The optical system was adjusted (with Nicol prisms uncrossed) until the intensity of the light passing N_2 remained constant while the mirror system was moved throughout the length of its track.

[10] Kerr, Phil. Mag. **1**, 337 (1875); **8**, 85 (1879).

The lead wires from A to K were either symmetrical and equal in length or one of the leads was removed and one side each of A and K grounded with short wires to high capacity grounds as shown in Fig. 2. The lead can be lengthened or shortened over the ranges being investigated by a sliding copper bar T. The inductance and capacity of both the lead wires and K were made as small and uniformly distributed as conveniently possible. In some of the experiments a resistance $R=(L/C)^{\frac{1}{2}}$ (app. 500 ohms),

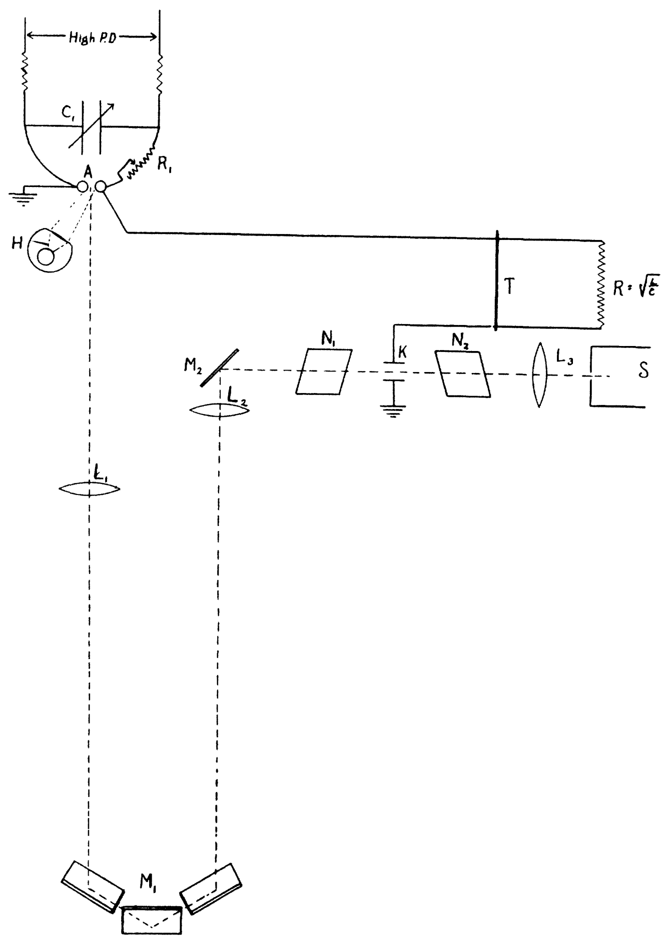


Fig. 2

where L and C are the inductances and capacities per unit length of the wire, is attached across the open ends to prevent possible reflections of the initial transients; while a variable capacity C_1(0.0005 to 0.005 microfarads) and variable resistance R_1 were used to change the conditions in the spark. The circuit containing C_1 is in a plane at right angles to the Kerr cell circuit to avoid unnecessary inductive coupling. The spark gap A was illuminated by a source of ultra-violet light H placed vertically over it and in a direction at right angles to the direction in which the light of the spark is observed. This reduces the time lag and causes the spark to jump at approximately the same potential each time.

When the spark at A takes place, the potential across it does not fall to its low later value instantaneously.[3] Some recent unpublished work done by Dr. L. B. Snoddy in this laboratory indicates that the exact rate of fall of potential is not completely independent of the circuital factors, as, for example, the rate at which energy is fed into the spark, but that under the conditions here used the potential probably falls to half value within the limits of 10^{-9} to 3×10^{-8} sec. Of the remainder of the potential-time curve very little is definitely known. The fall of potential travels along the lead wires at approximately the velocity of light and starts discharging K at a time equal to the length of lead wire divided by the velocity of light after the beginning of the fall of potential across A. Now since it is possible to reduce the capacity of K to a comparatively small value (4 cm) the rate of fall of potential across K follows roughly the rate of fall across A but at a definite time later.*

If the exact rate of fall of potential across K were definitely known, it would then be possible to compute the time of optical cut-off, since a possible lag in the Kerr effect of CS_2 is at least short enough to be here neglected.[11] Such computations show that the intensity of the light passing N_2 has dropped to $1/e$ of its value by the time that the potential across K falls to 0.77 of its original magnitude. The cell is therefore effectively closed before the potential across K drops to half value. If, then, the amplitude of oscillations in the Kerr cell does not exceed 1/2 the initial potential, when once the cell closes, it does not again effectively re-open.

The fact that the amount of light passing N_2 after the first optical cut-off was too small to effect the results obtained could easily be tested experimentally. The lead wire from A to K was lengthened until one or two lines appeared in the field of view. Then as the mirror system M_1 was slowly moved backward increasing the optical path, the intensity of the lines showed no rapid decreases and, when once they disappeared, did not reappear while the light path was lengthened over 30 meters. This shows that there are no effective short oscillations. Oscillations of longer period were also tested for by placing a mirror rotating at 2000 revolutions per second behind the cell and observing the light flashes passing N_2. The rotating mirror could easily resolve less than 10^{-7} sec, yet the spark appeared when reflected from the mirror as a single sharp image.

It was very easy, however, to introduce oscillations large enough to cause trouble by adding inductance and capacity or by sufficiently lengthening the lead wire from A to K. In fact, with a cell of 4 cm capacity and about 16 meters of lead wire the oscillations become very troublesome, although

* Note: By carefully purifying the CS_2 smaller cells than 4 cm can be used without sacrificing intensity of light passing N_2 for as is well known the dielectric strength of CS_2 can be considerably increased by careful purification.

[11] Beams and Lawrence, Jour. Franklin Inst. **206,** 169 (1928).

longer wires than this have been used successfully. When a low resistance (5.2 ohms) thermocouple galvanometer was placed in series with K and the lead wires lengthened, the readings of the galvanometer, which gave an indication of the magnitude of the oscillations present, increased relatively fast for the first 2 or 3 meters, then increased slowly as more wire was added. Similar observations were made with a wave meter having a vacuum tube voltmeter as an indicator, by means of which an estimate of the amplitude of the oscillations could be obtained. The frequency of course decreased with increase of wire path. A method making use of Lichtenberg figures[12] was also used to get the maximum potential that was applied across the cell after the initial field is relaxed. The method as used here is only approximate but it indicated that the potential never attained more than one half its original value over the wire path range used, at least in the investigation of the air lines.

The fact that the oscillations in K did not have an amplitude greater than one-half the initial potential of the spark might at first seem surprising, but when consideration is taken of the resistance in the spark in its initial stages, the high frequency resistance of the wires, corona losses, etc., this relatively large damping is to be expected. The resistance of the spark gap during its initial stages is not known, but it must fall from a very large value to a comparatively small one in less than the time required for the potential to drop to a low value. If then one-fourth the oscillation period of the Kerr cell circuit is of the same general order of magnitude as that of the time required for the resistance and potential to fall in the spark, the oscillation in the Kerr cell will be highly damped during a part of its first quarter of a period. As the lead wires are lengthened the inductance and capacity of the Kerr cell circuit are increased and hence the amplitude of oscillations, which occur after the initial transient has discharged the Kerr cell, is increased. An increase of lead wire also increases the period of the oscillations as was observed. If, therefore, very long leads are used, it is necessary to introduce resistance. The addition of resistance lengthens the time of optical cut-off, but in most of the work, especially when long leads are used, the cut-off can be slowed down considerably without the introduction of serious complications. The oscillating circuit containing C_1 and A can be changed over a fairly wide range without producing undesirable oscillations in K. This results from the fact that when once the potential across A falls to a low value and the air in the gap is ionized, it does not again rise to a value that, when applied across K, will cause an appreciable amount of light to pass N_2. This condition holds, of course, only when the oscillations in C_1, as in all these experiments, are rapid enough to prevent complete deionization in the gap between half oscillations. Also, since the circuit containing C_1 is not coupled to the circuit containing K except through the spark gap A, oscillations of amplitude large enough to give trouble should not be induced in K even for narrow bands of harmonics, as these, under the given conditions, have too little energy to be effective.

[12] P. O. Pedersen, K. Danske Vidensk. Selkab. **1**, 11 (1919); **4**, 7 (1922); **8**, 10 (1929).

The light after leaving N_2 either is focused on the slit of a spectroscope so that the length of the spark is parallel to the slit, or else the image is examined by means of a direct vision prism. The direct vision prism resolves most of the lines without a slit because of the fact that the spark starts as a narrow thread and expands radially. The air lines appear the full length of the gap. Table I gives the time of appearance of the strong air lines (since it was necessary to use a spectrograph of large light-gathering power and

TABLE I.

Wave-length	Classification[13]		Intensity	Interval (sec. $\times 10^8$)
5011	$1^3P_1'-1^3S_1'$	N II	3	
5007	$1^3S_1'-1^3P_2'''$	N II	4	
5005	$1^3D_3'-1^3F_4'$	N II	10	
5001	$\begin{cases} 1^3D_2'-1^3F_3' \\ 1^3D_1'-1^3F_2' \end{cases}$	N II N II	10	
				0.8
4643	$1^3P_2'-2^3P_1$	N II	8	
4631	$1^3P_2'-2^3P_2$	N II	10	
				1.4
5680	$1^3P_2'-1^3D_3'$	N II	10	
5676	$1^3P_0'-1^3D_1'$	N II	6	
5667	$1^3P_1'-1^3D_2'$	N II	8	

fairly wide slit, the members of the above groups of lines were not clearly resolved.) with respect to the first line that appears. The observations could be repeated with a precision of 3×10^{-9} sec. It will be noted that the order of appearance is not a function of intensity or of wave-length and therefore not the result of the electro-optical dispersion in K. This dispersion in double refraction should make the lines seem to appear in the order of increasing wave-length, but as previously pointed out, is too small to produce serious error under the experimental conditions. When the lead wires were lengthened, the spark lines of the metal appeared as points on the electrodes, followed in turn by the metallic arc lines. The fact that the metallic lines appear in the field of view as points introduces the greatest difficulty in determining the time of their appearance; in fact, some of the previous values for the metallic lines are perhaps somewhat in error due to this cause. Photometric measurements on the rate of increase of intensity of these metallic lines have been attempted but without much success. The rate of evaporation of the metal is apparently variable but a more serious difficulty arises because of the uncertainties of the photographic plate when illuminated with light flashes of short duration.[14] The Clayden effect and other effects that are probably related to it make practically all photographic measurements of light intensities with flashes as short as 5×10^{-8} sec. very unreliable. For example, if a photographic plate is slightly fogged by a weak light as is sometimes done to photograph faint sources of light[15]

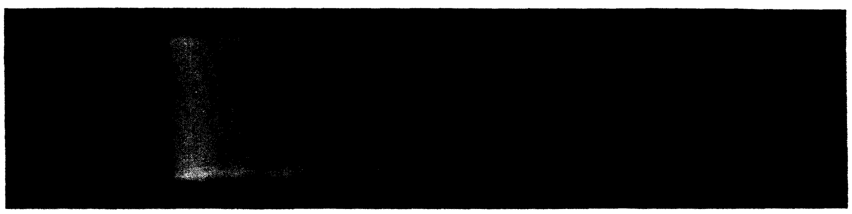
[13] Fowler and Freeman, Proc. Roy. Soc. **A114,** 662 (1927).

[14] R. W. Wood, Astrophys. J. **17,** 361 (1903). Lüppo-Cramer Grundlagen d. Photographischen Negativverfahren Halle **1,** 608 (1927).

[15] R. W. Wood, Astrophys. J. **27,** 379 (1908).

and then illuminated with a short flash, the image of the flash on the plate is usually reversed. Even when the plate is exposed to the flash alone and care is taken to prevent, as far as possible, fogging by other light, any developer fog is reversed. The intensity of the light is always a factor; a

A. Mg gap. = 7 mm



B. Bi gap = 8mm

C. Bi gap = 8 mm

D. Bi

Fig. 3

faint flash produces a reversal, while a more intense flash gives the ordinary image with usually a reversal around its edges. Attempts have been made to eliminate these troubles but, in the case of flashes less than 5×10^{-8} sec. in duration without much success.

Because of these difficulties with the Kerr cell method when used for observing the metallic lines, as well as the fact that its precision decreases in the later stages of the spark, a search has been recently made for an independent and complementary method of study. The method finally adopted has been made possible by the development by Henriot and Hunguenard[16] of a means of obtaining high rotational speeds. A mirror 12×12 mm is mounted on a cone shaped piece of metal which rides on a whirling cushion of air. With this arrangement the angular speed is in general limited only by the viscosity of the gas, its molecular velocity and the strength of the rotating parts.

The light from the spark passes through a lens, is reflected by a rotating mirror and falls upon a photographic plate placed at the focus of the lens. Fig. 3, A. B. C. give traces of the image of a spark between magnesium electrodes and bismuth electrodes, each moving 1,300,000 cm/sec. perpendicular to its length. In each case the constants of the circuit are the same. It will be specially noted that the spark first appears as a bright streak completely across the gap. This bright streak fades out very quickly, but the luminosity persists near the electrodes and gradually moves toward the center of the gap. The visible spectrum of the bright streak is composed of air lines and that of the luminous streamers emanating from the electrodes, metallic lines. In the bismuth spark the curved metallic streamers which start from the cathode each half oscillation and move with diminishing velocity until they reach the moving vapor front are very distinct on the original plate. These streamers have been previously observed by several experimenters,[5] but whether they are jets of luminous vapor or pulses of luminosity in the vapor has not yet been completely settled.

Fig. 3 D shows the image of the spark moving parallel to its length. A narrow portion is isolated by a slit perpendicular to the spark to prevent overlapping errors. It will be noted that the spark starts as a thread and expands radially. When the slit was removed or moved to allow only the light from near and including that on the surface of the electrode to reach the plate, and the light dispersed by a prism just before reaching the rotating mirror, the time of appearance of the various spectrum lines could be observed. Similar observations were made when the moving image of the spark fell upon the slit of a spectrograph. The photographs show plainly that the air lines appear first, followed by the spark and later by the arc lines. The technique, however, is not yet developed to a stage where the members of the metallic arc triplets can be distinctly separated, due probably to the photographic errors previously discussed. The limiting factor here seems to be intensity and not angular speed because it is not especially difficult to obtain rotational speeds of 4000 r. p. s. and this can be multiplied several times by simply allowing the light to be reflected from stationary mirrors back to the rotating mirror again. The work, however, is being continued with a better arrangement than that previously used.

The above experiments together with those performed by other investigators[5,17] show definitely that the various spectrum lines in the spark appear

[16] Henriot and Hunguenard, Jour. d. Phys. et Ra. **8**, 443 (1927).

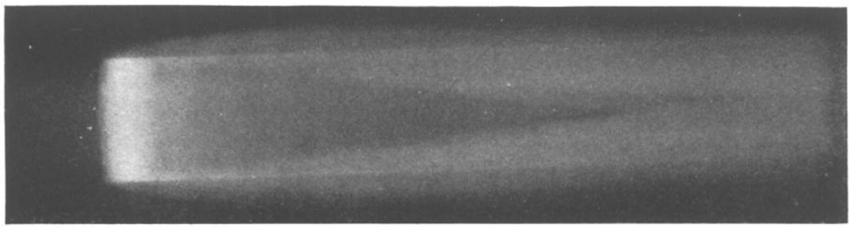
[17] Locher, J.O.S.A. **17**, 91 (1928).

at different times after the beginning of the discharge where by the appearance of a line is meant the time required for the line to become visible through the observing apparatus. However, there is a disagreement in the values obtained by Locher and the writer using similar methods. The difference perhaps lies partly in the larger Kerr cell used by Locher, which would lengthen the time for his cell to cut off. This probably explains, in part at least, why he could not completely extinguish the air lines with lead wires of the same length as his light path, for the intensity of the light passing his cell at maximum voltage was considerably less than that used by the writer so that any errors due to light intensity are in the wrong direction to explain the difference. He also had no way of slowly varying his light path which has been found essential in the above work in testing for troublesome oscillations, or of measuring his time directly in terms of the velocity of light.

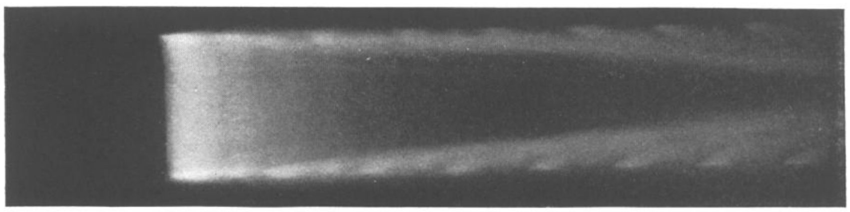
The principal factors that determine the appearance of a spectrum line during the initial stages of a spark discharge through a gas must be the average time required to put the atom in the properly excited state by the discharge, the average time it remains excited, and the rate with which it radiates energy when once it starts radiating. In the case of the air lines the sum of the last two factors would be expected from the general results of canal ray experiments[18] to be of the right order of magnitude to explain the observed time between the appearance of the groups of nitrogen lines. This then suggests that in the first stages of the discharge through air where a large number of atoms must be ionized before the potential can fall to a value which will effectively close the cell, that there is a correspondingly large number of atoms multiply ionized and excited to the upper energy levels of the strong air lines. Also, the distribution of excited atoms among the various upper levels of the strong lines probably does not change during the initial stages of the spark. It is possible to study the effect that the average time an atom holds its energy has upon the appearance of spectrum lines in the case of the arc triplets of zinc and cadmium. These triplets have the same upper energy level and therefore should be independent of the conditions of excitation in the discharge. In previous work[7] these lines were found to appear at different times but it has not yet been possible to increase the time-resolving power of the rotating mirror method to a point where a difference in the time of appearance of the lines can be observed. This is necessary before definite conclusions should be drawn because it will then be possible to change the excitation conditions over a very much wider range than was possible with the Kerr cell method and thus make certain any possible effect of the discharge.

The writer is indebted to Professors L. G. Hoxton and C. M. Sparrow of this Laboratory and to Professor E. O. Lawrence of the University of California for many valuable criticisms of part of the work. He is also very grateful to Mr. A. J. Weed, instrument maker, for help in the construction of apparatus.

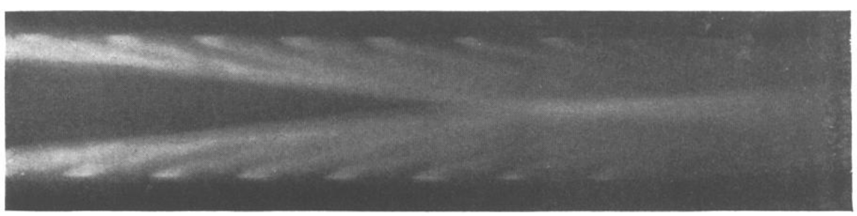
[18] Wien, Ann. d Physik **66**, 229 (1921); **73**, 483 (1924). McPetrie, Phil. Mag. Series **7**, **1**, 1082 (1926).



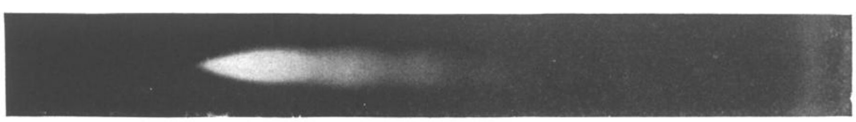
A. Mg gap. = 7 mm



B. Bi gap = 8mm



C. Bi gap = 8 mm



D. Bi

Fig. 3