ON THE EARLY STAGES OF ELECTRIC SPARKS

BY ERNEST O. LAWRENCE AND FRANK G. DUNNINGTON
UNIVERSITY OF CALIFORNIA

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ABSTRACT

With the Kerr-cell electro-optical shutter of Abraham-Lemoine and Beams, phenomena in the early stages of sparks between electrodes of Zn, Cd and Mg have been studied. It was found that, during $50(10^{-8})$ sec after beginning of the sparks, the spark doublet lines $3d_{1,2}-4f_{1,2}$ of Zn have widths of 45A, while the corresponding lines of Cd and Mg are about 30A in width. The luminosity of the metallic vapors of Zn, Cd and Mg was observed to spread from the electrodes with speeds of $2.1(10^5)$ cms/sec, $1.5(10^5)$ cms/sec, and $1.2(10^5)$ cms/sec, respectively. Photographs of the early stages of single sparks with exposure times as short as $4(10^{-8})$ sec were obtained. The snapshots showed that during these short intervals of time after beginning of a spark the discharge is confined to a filament having a cross-section at the anode of $5(10^{-4})$ cm^2 which broadens out to four times this size at the cathode. From the circuit constants and these dimensions of the discharge it was accordingly estimated that the discharge current density attained the magnitude of $1.7(10^6)$ amps/cm^2. The asymmetry of the photographed images of the sparks disappeared when the exposure times were extended to include a complete cycle of the discharge, thereby proving the satisfactory operation of the shutter.

Assuming that the broadening of the lines to be due to the Stark effect of inter-ionic fields and with the aid of existing data on the Stark effect behavior of the lines, it was calculated that the average inter-ionic field was 10^6 volts/cm. This result in turn implies that the average separation of the ions was $3.8(10^{-7})$ cm and therefore that 1/3 of the molecules in the path of the discharge were ionized. Approximately the same degree of ionization follows from the assumption that 1/2 of the discharge current is carried by the positive ions moving towards the cathode with the observed velocity of $2.1(10^5)$ cms/sec.

Four more or less independent methods of estimating the temperature of the early periods of the spark from the present observations lead to values of the order of magnitude of 10,000°K which point to thermal ionization as a prominent feature of such discharges.

INTRODUCTION

ELECTRIC sparks have been studied extensively for a long time and yet much remains to be understood concerning the physical process involved. One of the great remaining mysteries[1] centers around the observations of Pedersen,[2] Rogowoski,[3] Torok,[4] Beams,[5] Peek,[6] Burawoy[7] and others that sparks sometimes break down in time intervals of about 10^{-8} sec after ap-

[1] Loeb has proposed a solution of the difficulty, Science **69,** 509 (1929).
[2] Pedersen, Ann. d. Physik **71,** 317 (1923).
[3] Rogowski, Archiv. f. Electrotech. **16,** 496 (1926).
[4] Torok, Jour. A. I. E. E. **47,** 177 (1928).
[5] Beams, Jour. Frank. Inst. **216,** 809 (1928).
[6] Peek, A. I. E. E. Trans. **34,** 2, 1857 (1915).
[7] Burawoy, Archiv. f. Electrotech. **26,** 14 (1926).

plication of electric fields. Their work and the work of Lawrence and Beams[8] made it clear, moreover, that during such short time intervals the voltage across a spark gap drops from its initial high value to low values characteristic of arcs. Thus, the interesting high voltage processes which distinguish a spark from an arc occur during such short intervals of time that they are not easily susceptible to experimental observation.

However, several experimental methods have been developed which have contributed valuable information of the above mentioned sort. Pedersen[2] used Lichtenberg figures to measure spark lags, Rogowski[3] developed a high speed cathode ray oscillograph and studied time variations of potential across spark gaps, Torok,[4] Peek[6] and others used surge or transient voltages of very short duration in their studies of sparks, and Anderson and Smith[9] devised a revolving mirror camera and obtained interesting information on the early phenomena occurring during the "explosion" of wires. The adaptation by Beams[10] of the electro-optical shutter of Abraham and Lemoine[11] to the studies of the relative time of appearance of spectrum lines in spark discharges has perhaps pointed to one of the best ways to the attack of the problem of the early stages of sparks, because the Kerr cell optical shutter makes it possible to view sparks during the desired short intervals of time.

The present paper is concerned with such an experimental study in which, for example, snapshots of single sparks with exposure times as short as $4(10^{-8})$ sec. have been obtained, which show interesting features of the early state of affairs in the discharge.

Apparatus

The apparatus (Fig. 1) consisted essentially of a spark gap *SG*, with condenser *C* in parallel, connected across a source of high voltage *T*, and an electro-optical shutter placed in the optical path between the spark gap and the light recording device at *P*. The latter was either a spectrograph or a camera. When the spectrograph was used, the source of high voltage was

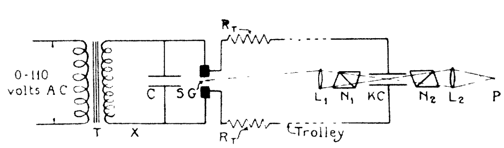

Fig. 1. Experimental arrangement.

simply a 25,000 volt 1 KW transformer which supplied a 60 cycle voltage of any value up to its maximum. When the camera was used a high voltage kenotron (KM−1) rectifying tube was inserted at *X* together with a resistance of about 500,000 ohms. The electrodes of the spark gap made of Zn, Cd or Mg were shaped so that the spark jumped between two parallel faces

[8] Lawrence and Beams, Phys. Rev. **32,** 478 (1928).

[9] Anderson and Smith, Astrophys. J. **64,** 295 (1926).

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

[11] Abraham and Lemoine, Comp. Rend. **130,** 245 (1900).

6 mm apart. The dimensions of these faces were, when using the spectrograph 3×6 mm (the short dimension being perpendicular to the optical path), and when using the camera, 3×3 mm. The spectrograph was a Hilger constant deviation type having a dispersion of about 36A per millimeter at 4900A. The camera consisted of a plate holder and bellows to exclude light, no lenses other than L_1 and L_2 being necessary.

The electro-optical shutter which was the heart of the apparatus was essentially the same as that described by Beams,[10] but with certain minor though important modifications. A Kerr cell consisting of parallel plates 9.5 cm long, 1.2 cm wide and 0.5 cm apart immersed in carbon bisulphide and situated between crossed Nicol prisms N_1 and N_2 was attached to the terminals of the spark gap by wires of variable length. This system operated as an optical shutter controlled by electrical means in the following manner. With no voltage on the Kerr cell, the carbon bisulphide was not doubly refracting and hence light could not pass through the crossed Nicols. Upon application of a potential across the cell the liquid became doubly refracting and a fraction of the light was passed, within a limited range of voltages the amount of light passed being proportional to the fourth power of the voltage. Now since the voltage which was impressed across the gap and condenser was also impressed across the Kerr cell, by the time the voltage had built up to a value sufficient to cause a breakdown of the gap the shutter was open. When the gap broke down the voltage across it dropped to a relatively small value in a time interval at least not greater than 10^{-8} sec. A resulting discharge wave was propagated along the wires to the Kerr cell causing a lowering of the voltage across the plates at a time after the spark breakdown approximately equal to the length of wire in one lead from SG to KC divided by the velocity of light. At about the same time that this discharge wave started from the gap, light from the spark began to be emitted and traveled towards the Kerr cell system. A part of the light which reached the cell before the wave was transmitted, while all of the light reaching the shutter thereafter was rejected. Thus it was possible to observe the light from the spark from its beginning up to any desired time of cut off determined by the lengths of the trolley leads. The times of cut off in the present experiments ranged from practically zero to 50 (10^{-8}) sec. after beginning of the spark.

The modifications in the electro-optical shutter had to do with the control of oscillations. It is obvious that if oscillations should exist in the Kerr cell circuit after the voltage is supposedly reduced to a low value, light from later periods of the spark would be transmitted, thereby producing spurious results. Because previous work has been questioned[12] on this basis, it is believed worthwhile to give some of the details and show proof that the shutter operated in the manner outlined above. The methods used to control the oscillations in the trolley circuit were as follows

(1) *Reduction of coupling between the condenser-spark gap circuit and the trolley-Kerr cell circuit to a minimum.* Upon breakdown of the gap, the dis-

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

charge of the condenser C through the gap is oscillatory. If the coupling between this condenser-spark gap circuit (hereinafter referred to as the condenser circuit) and the spark-gap-trolley-Kerr cell circuit (hereinafter referred to as the trolley circuit) were appreciable, forced oscillations would be produced in the latter. With this in mind the length of path in common between the two circuits was reduced to a minimum by taking off the leads to the trolley circuit by taps in the electrodes about a millimeter back from the sparking surfaces. The coupling was further reduced by taking off these leads to the trolley in a plane at right angles to the condenser circuit.

(2) *Maintaining the fundamental wave-length of the condenser circuit always considerably under that of the trolley circuit.* The trolley circuit consisting of distributed inductance and capacity has a fundamental oscillatory period of its own. It is obvious that even though the coupling were small, the effect in the trolley circuit of oscillations in the condenser circuit would be much greater at or near resonance. To avoid the effect of harmonics as well as that of the fundamental oscillations of the condenser circuit, its wave-length was adjusted so as to be considerably less than that of the trolley circuit. The wave-length of the condenser circuit was calculated and checked by a wavemeter. That of the trolley circuit was obtained by comparison with the condenser circuit by resonance in the following manner. The trolley leads to the gap were disconnected and joined together and the plane of the leads was turned so as to increase the mutual inductance of the circuits. For every set of condenser circuit constants that gave a wave-length within the range of that of the trolley circuit, a position of the trolley could be found that allowed light to pass. Approximate calculations showed that such resonance between the circuits involved fundamentals and not harmonics of the condenser circuit.

(3) *Damping of the oscillations in the trolley circuit.* Even though the trolley circuit were free of all outside disturbances, the charge stored by its distributed capacity previous to a breakdown of the spark would oscillate upon the shorting of the gap by the spark. If these oscillations were critically damped by the insertion of sufficient resistance R_t, the rate of fall of voltage across the Kerr cell would thereby be greatly diminished. However, this impasse to arranging the circuit so that the shutter closes with great rapidity free of appreciable oscillations is only apparent. The intensity of the light passed by the shutter is proportional to the fourth power of the voltage. Hence were the amplitude of the voltage on the first reversal only damped to a value one half the original voltage, the light passed per unit time would be only a sixteenth that at the original voltage. Thus, since the delay in the voltage-drop caused by damping is small until the region of critical resistance is reached, it is possible to damp the oscillations sufficiently without appreciably delaying the closing-time of the shutter. Exact calculations being difficult, the best value for the damping resistance was found experimentally by finding the value which gave the smallest observed distance of migration of the metallic vapor out from the electrodes (see results). The value found was 500 ohms (250 ohms distributed over each lead from spark gap to Kerr cell).

Oscillations were apparent when using resistances considerably below this value. Increasing the damping resistance produced little effect until values of over 1000 ohms were reached when the slowing down of the rate of closing of the shutter became observable

That the shutter was effectively closing at times close to those calculated from the wire path was definitely proved by the direct photographs of the spark (see results). When the time of cut off was made equal to or less than that of a half cycle of the condenser circuit, the pictures obtained were assymmetric relative to the cathode and anode, the images of the discharge being narrower and more intense near the latter electrode. This experimental observation constitutes indisputable evidence that the shutter operated in the manner outlined above.

The Experiments

The initial experiments were concerned with observations of spectra emitted during early stages of the spark. An image of a portion of the spark near one electrode was projected through the optical shutter and was focused lengthwise on the slit of the spectrograph and photographs of the spark spectra of Zn, Cd and Mg were obtained with the shutter closing at various times after the beginning of the sparks. In order to obtain sufficient blackening of the photographic plates it was necessary to expose for from 3 to 10 minutes. Since 120 sparks occurred per sec. the photographs represent the integrated spectra of the beginning of a large number of sparks. The general features of the results were the same for the three metals studied and therefore only the data on Zn are here exhibited. Fig. 2h shows the spectrum of the Zn spark obtained with the Nicol prisms uncrossed, being consequently the ordinarily observed spark spectrum. The Zn spark doublet 4912–24A and the arc lines 4680A, 4722A and 4811A together with several air lines are prominent. 2a exhibits the spectrum observed with the shutter closing 19 (10^{-8}) sec after the beginning of the spark—a spectrum which bears little resemblance to 2h. As the experiments of Schuster-Hemsalech[13], Beams[10] and others have shown, the metallic lines of the spark are absent in its early stages, the spectrum being that of air with a strong continuous background. Taking into account the dependence on wave-length of the photographic sensitivity of the plate and the absorption in the optical system it is estimated that the maximum intensity of the continuous spectrum occurred well below 4600A. It is of particular significance to note the extreme diffuseness of the air lines during this early period of the spark which is attributed to the Stark effect of the inter-ionic fields

Fig. 2b shows the spectrum photographed with the shutter closing 27 (10^{-8}) sec after the beginning of the spark. In this photograph, as in all the others, light which produced the lower ends of the spectrum lines came from the region of the spark adjacent to one of the electrodes and the length of the lines represents about 2 mm of the gap. The continuous background at this later time appears definitely to be most intense near the electrodes.

[13] Schuster and Hemsalech, Phil. Trans. **193A,** 189 (1900).

This photograph indicates also that the position of maximum intensity of the continuous spectrum shifts to a slightly longer wave-length at this later time. This photograph also shows the first appearance of the Zn metallic spark doublet 4912–24A as a very diffuse region of luminosity near the electrodes. The broadening of the lines is more easily seen in 3g which is

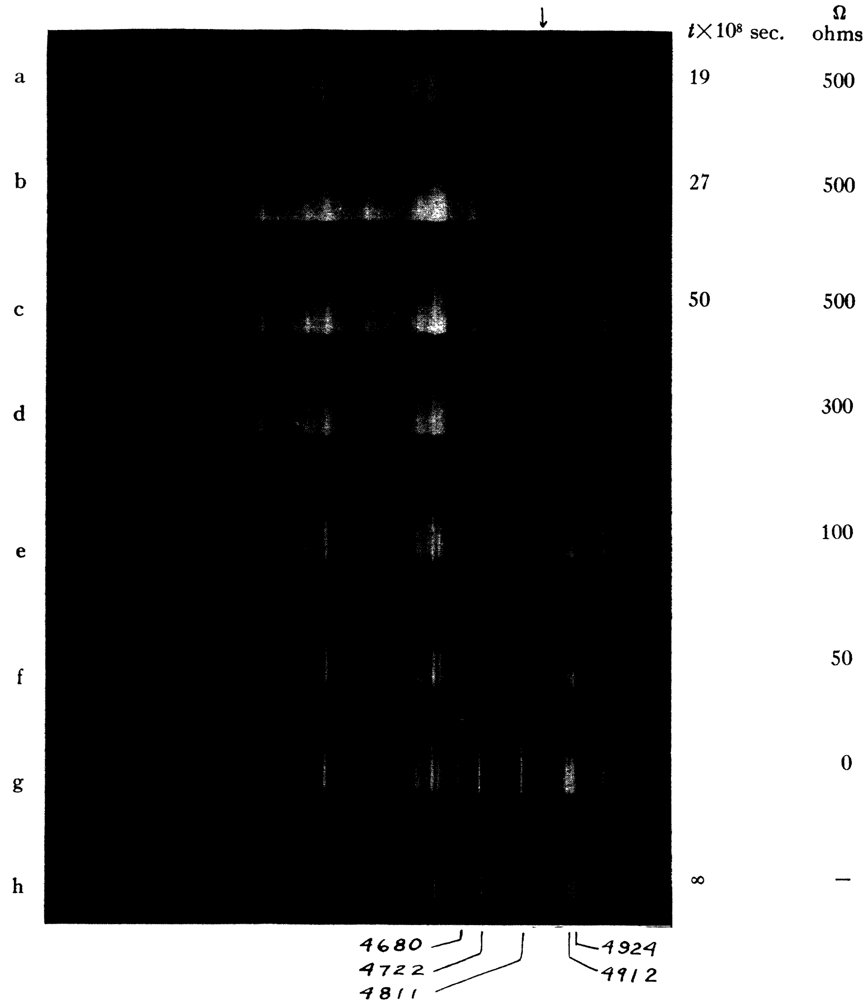

Fig. 2. Photographs of spectra emitted during various intervals of time after beginning of sparks between Zn electrodes in air.

a magnified section of 2c. It was estimated from these observations that each of *the spark lines during this early period of the discharge were broadened symmetrically to a total width of 45A*. The widths of the corresponding lines of Cd and Mg were observed to be somewhat less—approximately 30A.

Fig. 2c shows that at the later time of 50 (10^{-8}) sec after the beginning of the spark, the metallic spark lines were emitted at a greater distance from the electrodes. This observation gives at once a measure of the average velocity of migration of the metallic ions away from the electrode surfaces. From several such observations it is found that *during the first 27 (10^{-8}) sec the average velocity of migration of the metallic ions away from the electrode surface is 2.1 (10^5) cms per sec.* The corresponding observed velocities for Cd and Mg ions were 1.2×10^5 cm/sec and 1.5×10^5 cm/sec respectively. Due to photographic difficulties, these values however are much less accurate than that for Zn.

The above mentioned spectra were taken with a distributed resistance in series with the Kerr cell of 500 ohms. Reducing this resistance to 300 ohms produced no perceptible change—as shown by the spectrum 2d which was taken under the same conditions as 2c excepting that the resistance was reduced to the lower value. On reducing the resistance to 100 ohms, 50 ohms and practically zero, however, a marked effect resulted as shown by Fig. 2e, f and g. From the fact that the luminosity of the spark lines extended further from the electrodes in the latter cases and that even the arc lines were in evidence, it is concluded that the oscillations were of sufficient magnitude to reopen the shutter at a later time. Careful examination showed that the operation of the shutter was sensibly independent of the damping resistance over the range 300 to 1000 ohms. Inserting resistance in excess of 1000 ohms over damped the discharge of the Kerr cell to such an extent that its effective time of closing was perceptibly delayed. Though it was not possible to make an accurate estimate, a calculation from the dimensions of the circuit agreed with the above values as being the right order of magnitude to damp the oscillations to the extent desired.

Our photographs fail to show the metallic arc lines at all, during 50 (10^{-8}) sec after beginning of the spark, a result not in agreement with the observations of Beams[10] and Locher.[14] A faint haze of luminosity near the electrode of wave-length near 4811A shown in 2c might easily have been thought to be due to the Zn arc line 4811A. However, measurements show that it is nearer 4817.5A. The origin of this line is uncertain at the present time as there are no well known Zn or air lines of this wave-length.

The photographs 2a, b, c, show a diffuse air line near 4865A (indicated by arrow) which occurs only in these very early periods of the discharge. 2a shows it extending practically across the spectrogram while in 2b and 2c it is confined successively nearer the lower edge. As will be evident in the discussion, very intense ionization and accompanying high temperature exists in the early period of the spark and it is probable that this line therefore is due to an ionized constituent of the air. There are many examples in the literature of lines which appear only under such conditions.[15]

For the purpose of measuring the cross-section of the discharge during its early development in order to obtain an estimate of the current density, direct snapshots of the spark of the requisite short exposures were attempted. A kenotron and a one-half megohm resistance inserted in series with the

[14] Locher, J.O.S.A. and R.S.I. **17**, 91 (1928).
[15] Handbuch der Physik **21**, p. 434.

condenser made it possible to apply known differences of potential across the spark gap resulting in single sparks. Images of the spark projected through the Kerr cell and focused on a photographic plate are shown in Fig. 3. The polarity indicated in all the photographs is that of the first half cycle. 3a is a series of single sparks taken with the Nicol prisms uncrossed (with the

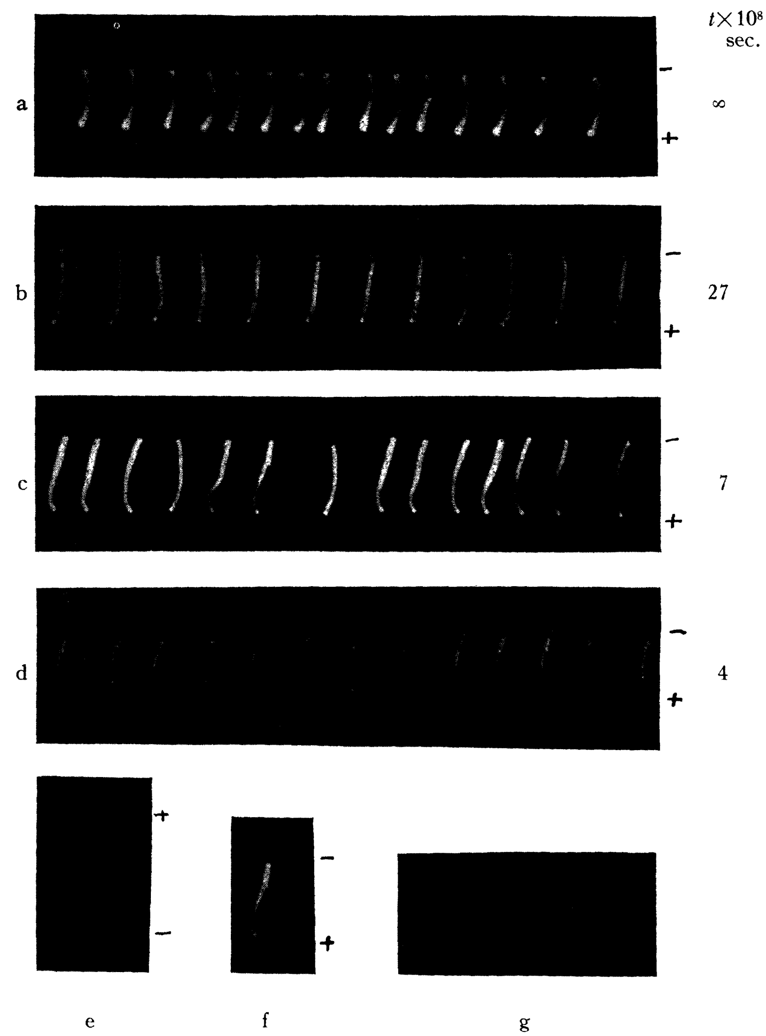

Fig. 3. Photographs of the early stages of sparks between Zn electrodes.

shutter continuously open) and therefore represent images of completed sparks. 3d shows the spark during the first 4 (10^{-8}) sec of its existence. To obtain these photographs it was necessary to have a condenser capacity of 0.004 mf in order to maintain the oscillations in the spark circuit out of resonance with the Kerr cell circuit. It is seen that *the discharge is confined* *to a very narrow filament near the anode which widens out towards the cathode.* Measurement of the plates showed that *the average diameter of the discharge at the anode was 0.25 mm and at the cathode 0.5 mm.* Since the period of oscillation of the spark was 26 (10^{-8}) sec, these photographs represent the form of the discharge during the earlier part of the first half cycle. Changing the condenser capacity to 0.008 mf, the photographs of 3c were obtained with the shutter closing 7 (10^{-8}) sec after the breakdown of the potential across the gap. In this instance the period of oscillation was 36 (10^{-8}) cm and consequently these are pictures of approximately the first quarter cycle of the discharge. The dissymmetry of the discharge is still evident, though not as marked as in the shorter exposures,—the average diameter of the discharge at the anode being 0.45 mm and at the cathode 0.5 mm. Another interesting feature of these photographs is the presence of *a very bright spot of luminosity close to the anode,* indicating an intensity of light there greatly in excess of that of the central section of the filament. 3b was obtained with the shutter closing at 27 (10^{-8}) sec. In this instance the shutter closed after the setting in of the second half cycle, as the period of oscillation remained at 36 (10^{-8}) sec. As was to be expected, this photograph shows a more nearly symmetrical filament with minute intense spots of light as both electrodes, that at the cathode being less intense than the one at the anode because the cut off occurred at about the middle of the second half cycle. The average diameter of the filaments is 0.5 mm. It is perhaps not amiss to emphasize again that *these observations of the asymmetry of the discharge during the first half cycle are indisputable evidences that the electro-optical shutter functioned in the manner outlined above and that oscillations were of inappreciable magnitudes.*

Thus during the period of 23 (10^{-8}) sec between the closing of the shutter for groups d and b, the cross-section of the discharge at the anode was observed to vary from 4.9 $(10^{-4},)$ sq cms to 1.9 (10^{-3}) cm^2 and since during these periods the average discharge currents (estimated from the circuit constants) were 800 and 1100 amps respectively, *the average current density varied from 1.7* (10^6) *amps per* cm^2 *to* $5.8(10^5)$ *amps per* $cm.^2$ These enormous current densities produced the great brilliance of the spark which made possible the short exposure photographs of the present experiments.

The path of breakdown of the sparks usually were along the lines of force. When the electrode surfaces were flat with sharp edges the sparks jumped from edge to edge along the curved lines shown in many of the photographs. When the edges were rounded off the sparks jumped between the middle of the electrode surfaces along the straighter lines of force in that region. However, interesting exceptions have been observed during the first 30 (10^{-8}) sec of the spark as shown in Fig. 3, e and f. 3f shows a sharp spur protruding from the main filament of the discharge of the sort that might arise from an ion path initiated by a high velocity particle. The spur is bent away from the anode and luminosity is seen to extend outside the main discharge from the spur to the cathode, as though positive ions formed along the path of the spur produced additional luminosity during their passage to the cathode. 3e shows a case where the spark took two simultaneous paths, the bifurcation suggesting that the spark breakdown was initiated at the cathode. Examples of bifurcation at the anode and also in the middle of the gap, however, have been observed.

Discussion

There can be little doubt that large broadening of spectrum lines produced by high current densities is due to the Stark effect of inter-ionic fields.[16] The width of the spark doublets of Mg, Cd and Zn observed in the early stages of the spark therefore can serve as a measure of the average ionic fields, and in turn, the average number of ions per cc in the discharge. Such an estimate requires an independent knowledge of the Stark effect behavior of the lines. Now the spark lines in question result from transitions between the hydrogen like energy levels $3d_{1,2}$ and $4f_{1,2}$ and indeed are very similar to the corresponding line 4686A of ionized helium. It is therefore to be expected that the metallic spark lines should exhibit a Stark effect closely resembling the observed Stark effect of the corresponding He line. Several experimental measures of the Stark effect of the He line in question have been made, the most recent being that of Foster[17] who finds that the maximum displacement of the components from the undisplaced position is about 2.4A per 100,000 volts/cm field. The results of Nagaoka and Sugiura[18] show that the corresponding line 4811A of Mg is broadened to a width of about 2A on each side of the undisplaced position in an average field of 116,000 volts/cm, a fact which supports the expectation that the corresponding lines of He, Zn, Cd and Mg should exhibit nearly the same Stark effect. From the total width of 45A observed in the present experiments then it can be concluded with considerable confidence that *the average ionic field during the early stage of the Zn sparks here studied was approximately 10^6 volts per cm.*

From this value for the average ionic field and the inverse square law it follows that the average separation of the ions was approximately 3.8 (10^{-7}) cm and therefore that the total number of ions and electrons was about 1.8 (10^{19}) per cc. *Thus, about 33 percent of the molecules in the path of the discharge were ionized.* Anderson and Smith[9] have found an equally great degree of ionization during the early stages of the "explosion" of wires.

The present experimental data lead to a second and independent estimate of the ionic density. The average velocity of migration of the metallic spark luminosity, and therefore presumably of the positive ions away from the anode was observed. Assuming that the positive ions moved towards the cathode with this speed and carried one-half the discharge current, it follows that there were necessarily present about 0.82 (10^{19}) positive ions per cc. Thus, this second estimate indicating 30 percent ionization is in excellent agreement with the first.

[16] An excellent resume of the subject of the broadening of spectrum lines is to be found in volume 21 of the "Handbuch der Physik."

[17] Foster, Astrophys. Jour. **62,** 229 (1925).

[18] Nagaoka and Sugiura, Jap. Jour. of Phys. **3,** 46 (1924).

The objection might be raised perhaps that, because of the far greater mobility of the electrons, they carry most of the current of the discharge and consequently it is not valid to assume that half the current is carried by the positive ions. Loeb[1] states, for example, that the electrons have about 1000 times the mobility of the positive ions. However, such estimates are made with the assumption that the density of the ions is small compared to the density of the neutral molecules, a state of affairs existing in low current-density discharges. The above results make it clear that in the early stages of sparks because of the high degree of ionization a pumping action of the ions produces a general flow of both ions and neutral molecules resulting thereby in a greater mobility of the ions than calculated in the usual manner. Moreover, a simple calculation shows that the high current density of the discharge produced a magnetic field as great as 20,000 Gauss which exerted a great influence on the trajectories of the electrons. Thus, if the velocity of the electrons were 10^8 cms/sec perpendicular to the magnetic field, it is calculated that the magnetic field caused them to travel in curved paths with radii of curvature 3 (10^{-4}) cm. The effect of the magnetic field was consequently to increase greatly the paths traversed by the electrons in passing from cathode to anode, thereby producing a great reduction of their general drift velocity (mobility). Space charge effects played an unknown though probably important part also in keeping the electron current and the positive ion current at the same order of magnitude.

Several independent estimates of the temperature may be made as follows.

(1). From the degree of ionization the effective temperature of the discharge can be calculated after the manner of Saha.[19] We have the reaction-isochore

$$\log \frac{x^2}{1-x^2}P = -\frac{5050V_i}{T}+2.5\log T-6.69.$$

where x is the fractional number of the atoms ionized, P is the pressure in atmospheres, V_i is the ionization potential in volts and T is the absolute temperature. Taking for x the here-observed value 1/3, for V_i 9.3 volts, the ionization potential of Zn, and for P, 10 atmospheres, there results for the temperature of the discharge the value of 13,500°K. A higher assumed value for V_i corresponding to ionization of O or N would lead to a correspondingly higher estimate of the temperature. However, the observations were taken in the proximity of the electrode where the metallic vapor predominated. From the observed spreading of the filament of the discharge during the course of time, from the work of Anderson and Smith on exploded wires, and from other considerations, it appears that the assumed pressure is right in order of magnitude.

(2). It is also possible to make a rough estimate of the temperature of the discharge from knowledge of the rate of dissipation of energy in the spark. Professor J. W. Beams has kindly let us see some of his revolving mirror

[19] Saha, Proc. Roy. Soc. **A99**, 135 (1921).

photographs of sparks in advance of publication from which we deduce that the sparks we worked with had a duration of the order of magnitude of 10^{-5} sec, and therefore that about one one-hundredth of the energy of the discharge was dissipated in the spark during the first 10^{-7} sec. Knowing in addition the capacity of the condenser, the voltage at breakdown, the specific heat of the, and the volume of the gas heated, an elementary calculation leads to 5000°K as the temperature of the discharge. This estimate is somewhat lower than that resulting from Saha's equation, a fact that is to be accounted for by the assumption that only 1/100 of the energy stored in the condenser is dissipated in 10^{-7} sec. Beams has shown in his revolving mirror photographs that the first cycle of the spark discharge has a period about 1.5 times longer than the period of later oscillations and therefore that the resistance and rate of energy dissipation is greater at the beginning of the spark. This fact was also taken into account in estimating the current density in the above calculations.

(3). As has been pointed out above, the high degree of ionization produced a general flow of ions and neutral molecules to such an extent that the observed velocity of migrations of the ions probably also measured the average velocity of the molecules. An estimate of the temperature then follows from

$$(3/2)kT=(1/2)mv^2$$

where k is Boltzman's constant, T is the temperature, m is the mass of a Zn atom and v is the observed velocity. Such an estimate yields a temperature of 10,900°K.

(4). Finally, an estimate of the temperature may be made from the intensity distribution in the continuous spectrum of the discharge. From the observation that the intensity was a maximum well below 4600A, it is concluded that the discharge temperature was considerably above 6200°K. This value is least reliable of all because many sources of error in estimating light intensities were not carefully investigated.

Thus, four more or less independent estimates of the temperature of the sparks obtained from the data of the present experimental study agree in indicating that it is of the order of magnitude of 10,000°K. This result points to thermal ionization as the main process in the early stages of sparks as has been suggested by Slepian.[20]

[20] Slepian, Phys. Rev. **31,** 1123 (1928).

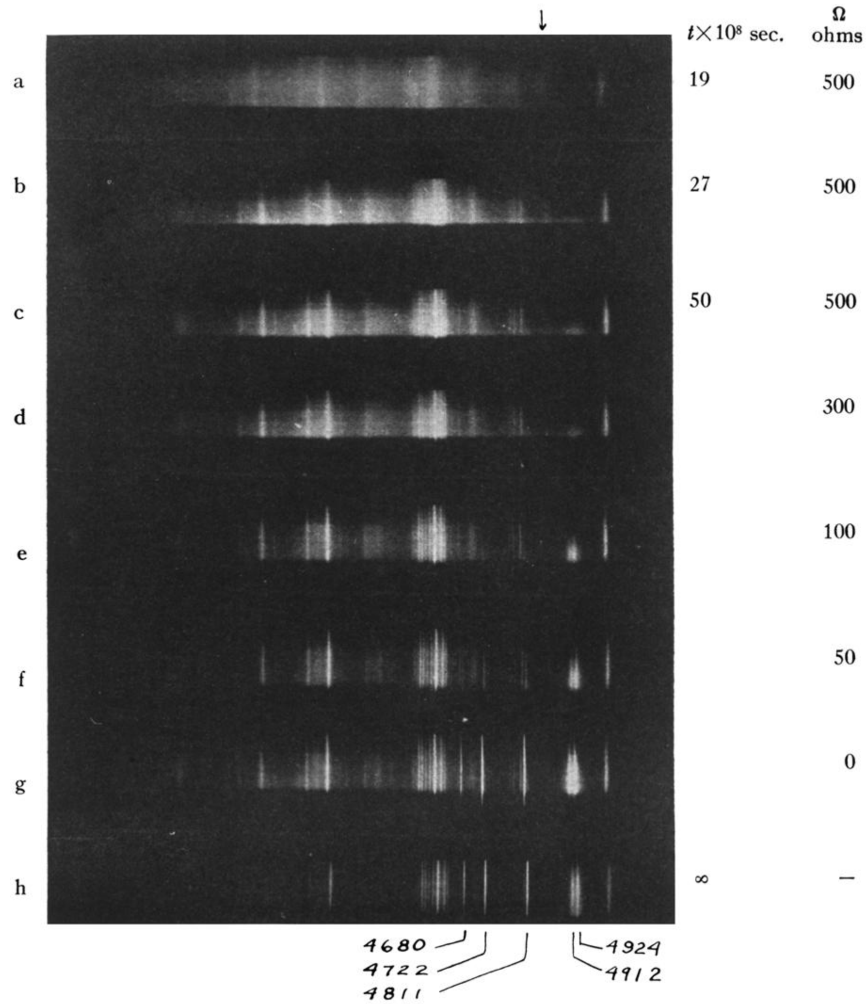

Fig. 2. Photographs of spectra emitted during various intervals of time after beginning of sparks between Zn electrodes in air.

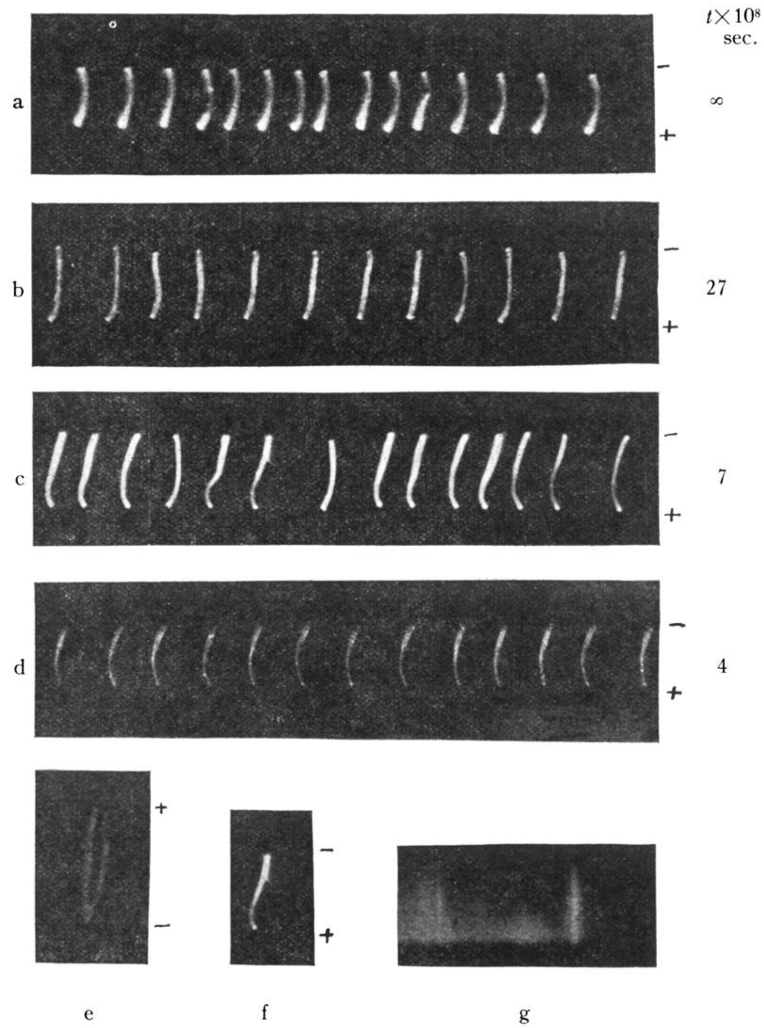

Fig. 3. Photographs of the early stages of sparks between Zn electrodes.