remove an $M_{II, III}$ electron of atom $Z=21$ (scandium) is approximately 37 volts. Then the energy requisite to producing a state of KM ionization in the calcium atom is 4067 volts, in excellent agreement with the experimental value.

III. Conclusions

From the excitation potential measurement we conclude that the initial state of the atom emitting the $K\alpha''$ satellite is one of KM ionization, a conclusion which is in agreement with the Wentzel-Druyvesteyn theory and also with the Richtmyer theory for the origin of this satellite.

From the wave-length positions there is no choice between the theories. Druyvesteyn, using Dolejšek's wave-length measurements, has shown[14] that the $\Delta\nu$ interval between α'' and α_1 is of the same order of magnitude as the interval between the frequencies of the M levels of atom $Z+1$ and of atom Z. On the basis of this evidence, Druyvesteyn ascribed, in accord with the Wentzel-Druyvesteyn theory, the origin of the α'' line as due to the transition $KM \rightarrow LM$. In this region of atomic numbers the energy values of the M shells are rather indefinite[18] and by "order of magnitude" must be meant a factor of possibly several-fold. Agreement of about the same order of magnitude is also obtained with Richtmyer's theory.

From the relative intensities, so far as theoretical predictions can be or have been made,[19, 20] there is likewise, as yet, no choice between the two theories.

Acknowledgments

The author is indebted to Professor F. K. Richtmyer for his criticisms of the manuscript and to the University of Chicago for the loan of the double spectrometer with which the data of the present experiments were obtained.

[19] R. D. Richtmyer, Phys. Rev. **49**, 1 (1936).
[20] F. Block, Phys. Rev. **48**, 187 (1935).

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Effect of Intense Illumination on Time Lag in Static Spark Breakdown

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The time lag of spark breakdown in static uniform fields and with *intense* illumination of the cathode has been studied in air, helium and carbon dioxide. An electro-optical shutter was used to observe the time lag, while an auxiliary spark gap supplied the intense cathode illumination. In air, the time lag was about 10^{-7} second for overvoltages of a few percent and increased very rapidly with decreasing overvoltage. Increasing the overvoltage to above 30 or 40 percent reduced the time lag to a more or less constant value of 2 or 3×10^{-8} second. This, in part, is shown to be due to the nature of the initiatory spark. The position of the midgap streamer observed in previous experiments has been found to depend on both the overvoltage and intensity of illumination. An explanation of these observations is advanced on the basis of space charge effects. The results in carbon dioxide were quite similar to those in air. In helium a much higher overvoltage was found necessary to produce a given time lag than in air. This is explained by considerations of the relative rates of gain of energy by electrons in the two gases.

Introduction

The time lag of spark breakdown in static fields has been studied in a thorough and systematic manner by Zuber[1] and Tilles[2] for lags from about 1 second to below 10^{-5} second. The effects of overvoltage and intensity of illumination of the cathode on the time lag were investigated. Time lags down to about 2×10^{-7} second with low overvoltage and high illumination intensity have been observed by Snoddy.[3] Very short time lags of the order of magnitude of

* Now with Research Corporation, New York.
[1] K. Zuber, Ann. d. Physik **76**, 231 (1925).
[2] A. Tilles, Phys. Rev. **46**, 1015 (1934).
[3] L. Snoddy, Phys. Rev. **40**, 409 (1932).

10^{-8} second have been observed by Pederson,[4] Tam,[5] Beams[6] and others, by using large overvoltages. None of the investigations of the very short lags has been quantitative, correlating the effects of overvoltage and intensity of illumination on the time lag. To this end the Kerr cell electro-optical shutter has been used to study these short lags and the results are being reported in this paper.

Method and Apparatus

In the method used, the time lag of breakdown of a given gap is determined by measuring the time interval between the impulse which sets off the spark and the appearance of luminosity in the gap. The starting impulse is provided by a flash of ultraviolet radiation focused on the cathode of the gap and coming from a spark in an auxiliary gap. The elapsed time between the starting impulse and the appearance of luminosity is determined by using an electro-optical shutter which is focused on the gap being studied, but controlled by the potential across the auxiliary gap. Thus, the shutter closes at a definite time after a spark occurs in the auxiliary gap, and, by varying this open time until luminosity is just observed to appear, the time lag is determined.[7, 8, 9, 10]

A schematic diagram of the apparatus is shown in Fig. 1. G_2 is the gap for which the time lag is to be determined and G_1 is the auxiliary gap which illuminates G_2 and controls the closing time of the electro-optical shutter. The high voltage direct potentials are supplied by transformers with thermionic tube rectifiers and smoothing condensers of sufficient capacity to reduce the a.c. ripple voltages to negligible values. The electro-optical shutter is designated by E.O.S. and involves no unusual features.

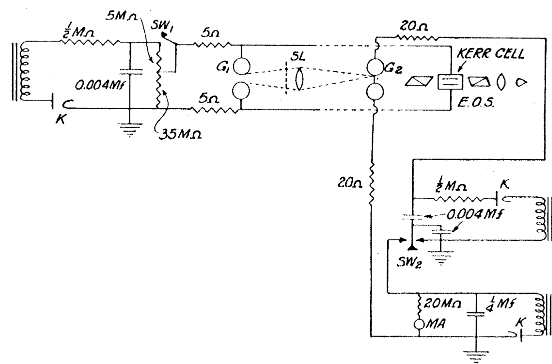

Fig. 1. Schematic diagram of apparatus.

The voltage supply for gap G_2 is divided into two sections for the purpose of applying an overvoltage of a definite and easily variable value. The upper section supplies a voltage approximately equal to the static sparking voltage of G_2, while the lower section supplies the overvoltage. The magnitude of the overvoltage is measured by means of a voltmeter consisting of an accurate 20 megohm-resistor and a milliammeter. The overvoltage is applied to G_2 by moving the switch SW2 from the right to the left contact. Gap G_1 is fired by closing switch SW1 which raises the voltage to a few percent above the sparking value. A quartz mercury arc is used to illuminate the cathode of G_1 in order to reduce the time lag to a small value. The switches are synchronized so that SW2 closes a few hundredths of a second ahead of SW1, thus enabling an essentially static voltage to be applied to gap G_2 without its sparking before being set off by gap G_1. To be sure that the switching operation did not affect the voltage supplied to G_2, tests were made for its sparking with zero overvoltage.

The procedure followed in making the measurements is as follows. The length of the leads to the Kerr cell is adjusted to a definite value and the voltage of the upper section of the supply for G_2 set at just the minimum sparking potential. Then gap G_1 is fired at intervals of about 10 seconds and the overvoltage on G_2 raised until luminosity is just seen to appear. Using this procedure the time lag was measured as a function of the overvoltage and intensity of illumination for

[4] P. O. Pedersen, Ann. d. Physik **71**, 317 (1923).
[5] R. Tam, Archiv. f. Elektrotechnik **19**, 235 (1928).
[6] J. W. Beams, J. Frank. Inst. **206**, 809 (1928).
[7] This assumes that the photoelectrons from the cathode are released instantaneously, and that the appearance of luminosity is simultaneous with the breakdown of the gap as marked by the rapid fall of the potential difference across it. The photoelectric effect has been shown to be instantaneous to within 3×10^{-9} second by the work of Lawrence and Beams,[8] while observations by Dunnington[9] and the writer[10] show that luminosity first appears within about 2×10^{-9} second after the beginning of breakdown.
[8] E. O. Lawrence and J. W. Beams, Phys. Rev. **32**, 478 (1928).
[9] F. G. Dunnington, Phys. Rev. **38**, 1535 (1931).
[10] H. J. White, Phys. Rev. **46**, 99 (1934).

several gap lengths in air at atmospheric pressure and also for helium and carbon dioxide.

Data

The results obtained for air at atmospheric pressure and for gap lengths of 1 mm, 3 mm and 5 mm are shown in Fig. 2. The results for helium at a gap of 10 mm and for carbon dioxide at a gap of 5 mm are shown in Figs. 3 and 4, respectively. The curves for the three gap lengths in air are very similar. At overvoltages of several percent the time lags are of the order of magnitude of 10^{-7} second. Increasing the overvoltage causes the time lags to decrease rapidly at first, but to finally turn up sharply and approach a nearly constant value of 2 or 3×10^{-8} second.

The effect of varying the cathode illumination intensity was noted by interposing wire screens between the two gaps which reduces the effective aperture of the quartz lens L (Fig. 1). Decreasing the intensity resulted in increasing the time lag, the effect being much larger at low overvoltages. Thus, referring to Fig. 2 and the 3-mm gap, decreasing the intensity from 1 to 0.002 at 10 percent overvoltage increased the time lag from 68×10^{-9} second to 130×10^{-9} second, while at 30 percent overvoltage the corresponding increase was from 37×10^{-9} second to 53×10^{-9} second. Experimental difficulties prevented measurements being taken at higher values of overvoltage. However, from the trend of the curves it appears that decreasing the intensity at high overvoltages increases the time lag by a more or less constant amount.

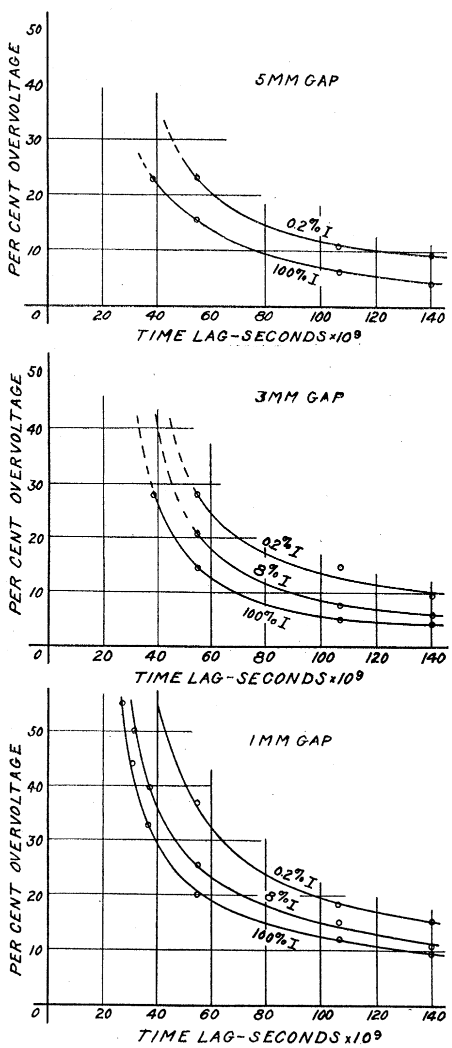

FIG. 2. Time lag curves for air.

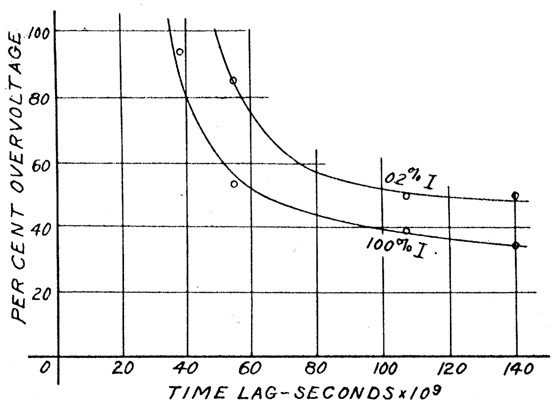

FIG. 3. Time lag curves for helium, 5-mm gap.

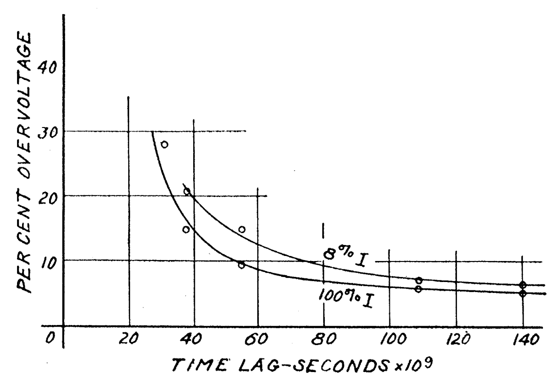

FIG. 4. Time lag curves for carbon dioxide, 5-mm gap.

The measurements show that the time lag is a function of overvoltage and intensity of illumination; also that time lags of the order of magnitude of 10^{-7} second occur in gaps of a few mm at low overvoltages but only provided very intense cathode illumination is used. Limitations of the apparatus prevented time lags of longer than 1.5×10^{-7} second being measured, so that the curves could not be traced down to very small overvoltages. However, from the trends of the curves at low overvoltages, the time lag for voltages just above the minimum sparking potential[11] must be orders of magnitude larger than 10^{-7} second, and may possibly run continuously into the formative lags observed by Tilles.[2] It is of interest to extend the present measurements into the region of time lags observed by Tilles, and work in this direction is being undertaken by R. R. Wilson at the University of California.

From Fig. 3 it is seen that much higher overvoltages are required in helium than in air or carbon dioxide to produce approximately the same time lags. The significance of the curves for helium will be discussed in the theoretical interpretation of the results. No particular significance can be attached to the curves for carbon dioxide which are more or less analogous to those for air.

In the course of the present study it was found that the position of the midgap streamer[9, 10] which appears for long gaps is affected by both the overvoltage and the intensity of illumination of the cathode. Fig. 5 shows approximately how the location of this streamer varies with overvoltage for a 5-mm gap. As the gap voltage is raised above the minimum sparking potential, the streamer moves toward the anode and reaches the latter at an overvoltage of about 10 percent. Further increases in overvoltage cause the streamer to move back toward the midgap region. The position of the streamer for this latter range of overvoltage tended to be quite variable and at times even two parallel streamers would appear in the same breakdown. Increasing the intensity of illumination had the same effect on the position of the streamer as would be caused by increasing the overvoltage and *vice versa*.

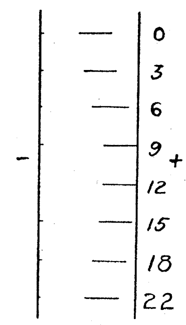

Fig. 5. Variation of the midgap streamer position with overvoltage. Percent overvoltage indicated at the right.

Discussion of Results

The short time lags observed can be explained on the basis of the theories proposed by Loeb[12] and by von Hippel and Franck[13] which were also developed by Schumann.[14, 15] According to these ideas the breakdown is precipitated by high fields being built up by space charge formation in the gap. The space charge is generated by electrons crossing the gap and producing by impact electrons, positive ions and also radiating molecules. The electrons, because of their relatively large drift velocity in the electric field, are removed from the gap before the positive ions move an appreciable distance. Thus a net positive charge is left in the gap, which, under favorable conditions, may give rise to fields large enough for positive ions to produce a sufficient number of secondary electrons at the cathode to cause breakdown to occur. The radiation from molecules excited by electron impact may also be important in releasing electrons from the cathode. In any event the elapsed time is about that required for an electron or perhaps several electrons to cross the gap, and is of the order of magnitude of 10^{-8} to 10^{-7} second for gaps of a few mm in air at atmospheric pressure.

[11] The overvoltages are calculated relative to the static sparking potential obtained with low intensity illumination, i.e., in terms of the ratio of the observed potential to the so-called normal sparking potential of the gap. Actually the real minimum sparking potential for a gap with this illumination is several percent lower than the normal sparking potential with weak light sources.

[12] L. B. Loeb, Science **69**, 509 (1929).

[13] A. von Hippel and J. Franck, Zeits. f. Physik **57**, 696 (1929).

[14] W. O. Schumann, Zeits. f. tech. Physik **11**, 131 (1930).

[15] J. J. Sämmer, Zeits. f. Physik **81**, 490 (1933).

In interpreting the results obtained, account must be taken of the nature of the flash of illumination which was used to illuminate the cathode. The distribution of its intensity with time is not definitely known. Photographs of sparks taken by Snoddy[3] with a rotating mirror under somewhat similar conditions show that the intensity rises to a large value in a few times 10^{-7} second and then dies out after several microseconds. Observations by Dunnington[9] and the writer[10] show that an appreciable fraction of the maximum intensity is attained in a few times 10^{-8} second. The photo-charge released from the cathode by a single flash of the illuminating spark at maximum intensity was measured and found to be about 10^7 electrons. This is sufficiently large to make it probable that at least several photoelectrons were emitted during the first 10^{-8} second, a time equal to about 1/500 of the total duration of the flash.

The time lags measured lie in the period during which the illuminating spark intensity was rapidly increasing. Hence one must consider the rapid variation of photoemission with time in discussing the significance of the time lag-overvoltage curves. The rapidly increasing intensity of the illumination probably had a large effect on the shapes of the time lag curves. Thus, if the breakdown is due to the formation of space charge in the gap, and if the distribution of the space charge does not change appreciably, the condition for a spark to occur in a given gap is that a certain amount of charge, say q, be generated. Then

$$q/e = \text{No. of positive ions or electrons produced} = \sum_{0}^{N_0} \epsilon^{\int_0^d \alpha dx} \Delta N_0,$$

where α = Townsend coefficient for impact ionization by electrons,
d = Gap length,
N_0 = No. of photoelectrons effective in producing the spark.

The integral $\int_0^d \alpha dx$ is a function of the amount of space charge already generated and hence must be evaluated for each photoelectron, the latter being designated as ΔN_0 in the above sum.

The space charge generated in a given gap thus depends essentially on α and N_0. Decreasing the time lag also decreases N_0 because of the smaller integrated light intensity of the initiatory spark. To compensate for this decrease, the value of α, and therefore the gap voltage, must be increased somewhat. At least a part of the gap voltage increment required to reduce the time lag by a given amount is needed to compensate for the correspondingly smaller number of photoelectrons. Hence the rapidly increasing intensity of the illuminating spark doubtless accounts in a large measure for the rapid decrease in overvoltage at the longer intervals. The shortest time lags observed of 2 or 3×10^{-8} second may be due to entirely inadequate illumination intensities produced by shortening the initiating spark. They may also be caused by the fact that at these time intervals the electrons are unable to cross the whole gap and therefore, in view of the shortened distance taken, the overvoltage must be increased to make the ionization more effective. The mobility of electrons in these high fields is uncertain by a factor of 3 or 4, but at least in order of magnitude the transit time of electrons across gaps of a few mm corresponds to the shortest time lags observed of 2 or 3×10^{-8} second.

The space charge generated by a single electron crossing a gap under the high fields corresponding to the shortest time lags observed is significant in this connection for if, under these gap conditions, the breakdown is initiated by the first few photoelectrons, the space charge field generated by them must be large enough to cause the spark to occur. As an example consider the 3-mm gap at 50 percent overvoltage for which $X/p=73$. The value of α for $X/p=73$ is from Sanders'[16] data 200, and neglecting space charge distortion, $\int_0^d \alpha dx = \alpha d = 200\times0.3=60$. From this, the number of positive ions generated by one photoelectron in crossing the gap would be $\epsilon^{\alpha d}=\epsilon^{60}$, and the corresponding charge expressed in e.s.u., is

$$q=4.8\times10^{-10}\times e^{60}=4.8\times10^{-10}\times10^{26}\cong5\times10^{16}.$$

Such an enormous space charge could not be generated under the existing conditions and this must mean that the photoelectron traverses only a fraction of the gap before building up a large space charge. Thus, assuming that the spark is initiated by space charge effects, the breakdown

[16] F. Sanders, Phys. Rev. 44, 1020 (1933).

under these conditions probably will start before the first photoelectron has crossed the gap. Increasing the gap voltage will reduce the time lag somewhat, but the limiting lag will be determined by the initiatory photoelectric emission.

The space charge hypothesis provides a plausible explanation for the appearance and changes in position of the central streamer as observed in Fig. 5. The point or points at which the breakdown begins in a gap will be determined by the location of the space charge in the gap. For gaps with relatively weak fields it is possible that the space charge is set up through the migration of positive ions or the passage of successive electron avalanches in such a way as to concentrate the field at the cathode for short gaps and out in the gap itself for longer gaps. As the field is increased, fewer photoelectrons will be needed to produce the intense field and the field produced becomes more a field due to the ionization by a single electron avalanche. As this process takes place with increasing field strength, the enormously enhanced ionization along a single electron path as the electron approaches the anode will tend to concentrate the positive space charge at first near the anode, and, with increased field strength, back toward the midgap region. With an intense positive space charge in the midgap region the gradient which will be most effective will be located there and while some gradient exists at the cathode, the gradient in the midgap region is sufficient to produce a beginning spark there. When visible streamers appear, they appear simultaneously at the cathode and midgap for long gaps, and within 2 or 3×10^{-9} second. In short gaps the midgap streamer probably cannot be formed because the breakdown gradient will always occur first at the cathode.[17]

From the variation of overvoltage and time lag with illumination over the whole range investigated the following may be said. For time lags in the neighborhood of 10^{-7} second, the illuminating spark has had time to become rather bright, so that the number of photoelectrons released is large. Referring to our previous equation a very approximate condition for breakdown in a given gap is that q be constant. Decreasing the illumination intensity means that the value of α, and therefore the gap voltage, must be increased in order to keep the time lag constant. On the other hand, for very large overvoltages, the time lag is very small and only a few photoelectrons or even one are necessary to produce a breakdown. The illuminating spark intensity increases from zero at zero time lag, and an average time of several billionths of a second elapses before the several photoelectrons necessary to produce breakdown are emitted. Now decreasing the intensity will result in increasing this average time, and the time lag will be increased by just this amount. Increasing the overvoltage cannot compensate for decreasing the intensity in this region, for the condition for breakdown is that only a few, possibly one, photoelectrons appear in the gap. This is in contrast to the situation existing for the longer time lags where a decrease in the intensity can be compensated for by increasing the overvoltage.

The curves for helium are similar to those for air except that a much higher overvoltage is necessary to produce a given time lag of breakdown. The relatively large overvoltage necessary can be explained on the basis that ionization by electron impact occurs at low field strengths in helium, and at these field strengths is so inefficient that it is necessary in relatively shorter gaps to increase α materially in order to produce the ionization necessary for a spark. Thus, for example, Werner[18] finds that the ionizing zone in the positive corona discharge in helium comprises at least 500 free paths with a potential drop of about 200 volts, while in nitrogen about 460 volts are required and only 70 free paths. This means that the rate of gain of energy is relatively small in the low fields in helium, while in the relatively large fields in nitrogen it is large.

The writer is very much indebted to Professor L. B. Loeb for his interest in the writing of this paper and for his help in interpreting the experimental results. He also wishes to thank Dr. R. N. Varney for valuable criticism of the manuscript.

[17] The field in the neighborhood of the cathode surface is enhanced by the image of the positive space charge in the cathode. This will have a large effect in increasing the field there only if the space charge is relatively close to the cathode, as it must be in the shorter gaps.

[18] S. Werner, Zeits. f. Physik **90**, 384 (1934).