[1] Polanyi, M., *Zeits. Phys.*, **7**, 323, 1921.

[2] See for instance, Born, M., *Encyklopaedie Math. Wissenschaften*, V_3, Heft. 4.

[3] Zwicky, F., *Physik. Zeits.*, **24**, 131, 1923.

[4] Joffe, A., Kirpitschewa, M. W., and Lewistzky, M. A., *Zeits. Physik*, **22**, 286, 1924. Muller, H., *Physik. Zeits.*, **25**, 223, 1924. Ewald, W., and M. Polanyi, *Zeits. Physik*, **28**, 29, 1924.

[5] Griffith, A. A., *Proc. Int. Congr. Appl. Mechanics*, Delft, **1924**, 55.

[6] Smekal, A., *Zeits. techn. Physik*, **7**, 535, 1926; **8**, 561, 1927, and several other papers.

[7] See for instance, the article of P. P. Ewald in *Handbuch Physik*, **24**, 280 (Ed. J. Springer, Berlin).

[8] Lennard-Jones, J. E., and B. M. Dent, *Proc. Roy. Soc.*, **121**, 247, 1928. In this paper the authors also remark that the lateral contraction might cause cracking of the surface of crystals.

[9] Kapitza, P., *Proc. Roy. Soc.*, **119**, 358, 1928.

[10] Steacie, E. W. R., and F. M. G. Johnson, *Proc. Roy. Soc.*, **113**, 542, 1926.

THE MECHANISM OF SPARK DISCHARGE

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In attempting to account for the ionization required for the initiation of a self-sustained electrical discharge, J. S. Townsend[1] developed a theory of the electric spark. While the cumulative ionization of the gas at high fields by electrons constitutes part of the mechanism of the spark, Townsend has shown that for a self-sustained discharge it is essential that electrons be liberated in the neighborhood of the cathode. From his investigations on the ionization current between parallel plates produced by high electrical fields Townsend concluded that for sufficiently high values (X/p), (X = electric field strength, p = gas pressure) the positive ions could ionize the gas molecules by impact. As a result of these researches he developed his well-known equation for spark discharges. At that time experiment seemed to indicate that the sparking potential was a function of the gas and the electrical field strength and was practically independent of the electrode material, consequently Townsend's equation was quite generally accepted. Later Townsend[1] extended his theory to include ionization by positive ions at the surface of the cathode, an effect that could conceivably take place at low pressure when the positive ions had little chance to strike gas molecules near the cathode. In 1922 Holst and Oosterhuis[2] found that the sparking potential in neon (p of order of a few mm.) varied in the ratio of 1–3 when the cathode material was changed from carbon to rubidium or caesium. Assuming a uniform

field between the anode and cathode they showed that the probability of positive helium ions acquiring sufficient energy to ionize molecules by impact was less than 10^{-17}. They therefore concluded that the amount of ionization produced in the gas by positive ions was negligible and that the electrons were liberated from the cathode by some process which was not dependent on the energy of impact of the positive ions with the cathode; for liberation of electrons by positive ion bombardment of a surface requires energies of the same order of magnitude as does the ionization of the gas molecules. They accordingly set forth the hypothesis that these electrons were pulled out of the cathode surface by some mechanism dependent on the electrical image forces which exist between the approaching positive ions and the cathode surface. J. Taylor[3] repeated, extended and confirmed these experiments qualitatively and on the basis of his results postulated that electrons were liberated from the cathode photoelectrically, according to the suggestion of J. J. Thomson,[4] by the neutralization radiation produced *at* the cathode.

The results of Holst and Oosterhuis and J. Taylor, together with the apparently low ionizing efficiency of the positive ions in a gas for low fields assumed uniform and the low electron emission from an *out-gassed* metallic surface due to bombardment by positive ions, have led many workers in this field to question the validity of Townsend's theory. Granting that a source of electrons exists at or near the cathode surface we may classify the possible mechanisms of this source as follows:

(*A*) Ionization of the gas by impacts between positive ions and gas molecules. (Townsend.[1])

(*B*) Liberation of electrons from the cathode by positive ion bombardment. This effect depends on the energy of impact and the work function of the cathode. (Townsend[1] and J. J. Thomson.[5])

(*C*) Liberation of electrons from the cathode or the gas by methods which are independent of the energy of motion of the positive ions.

1. By the photoelectric action of the neutralization radiation on the cathode. This radiation is produced by the neutralization of positive ions at the cathode or in the body of the gas. (Taylor.[3])

2. By the electrical image forces exerted by the approaching positive ions on the cathode surface. (Holst and Oosterhuis.[2])

3. By the thermionic emission produced by the local heat of neutralization of the positive ions neutralized on the cathode surface. (von Hippel.[6])

4. Ionization of the gas by inelastic collisions of the second class or by radiation falling on the activated metastable atoms near the cathode as a result of electron impacts. (Brode.[7])

5. Ionization of the gas by the photoelectric action of the neutralization radiation on the gas. (Thomson.[4])

Now these types of mechanisms, (A), (B) and (C) are clearly distinguishable in terms of experimental facts. Type (A) depends on the value of X/p and the nature of the gas and is completely independent of the cathode surface. Class (B) is a function of the cathode material, the value of X/p and the gas used. This type of mechanism is dependent on the gas because both the work function and the formation of positive ions are functions of the chemical nature of the gas. Type (C) is dependent upon the cathode material and the ionization potential of the gas but is independent of the velocity of the positive ions. (C) depends upon the properties of the cathode surface with regards to its photoelectric characteristics, thermionic emissivity or work function. The mechanism is also dependent upon the gas in that electron emission from the cathode is influenced by the gas layers formed on the cathode surface, and by the ionization mechanism of the gas by electrons. These differences permit us clearly to distinguish between mechanisms (A), (B) and (C) as follows: (A) is independent of the cathode material and depends on the kinetic energy of the positive ions whereas (B) depends upon both the cathode material and the energy of the positive ions. (C) however is independent of the velocity or kinetic energy of the positive ions, but is a function of the gas and of the cathode material.

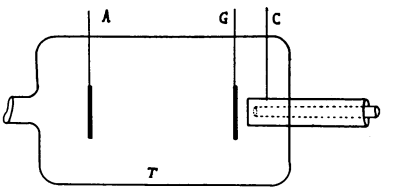

FIGURE I

It was suggested to the writer by A. Joffé and L. B. Loeb that the dependence of the mechanisms (A) and (B) on the velocity or energy of the positive ions together with the independence of (C) of this factor should lead to a critical experiment which could definitely decide which mechanism was the essential one in the spark discharge. The discharge tube shown in figure 1 was used to distinguish between the two mechanisms of ion production. A and G are nickel wire grid electrodes so constructed that they can be heated by means of an electrical current. G is placed a few mm. in front of the flat end of a glass tube C which can be cooled by a stream of water. A tungsten lead is sealed to C. The discharge tube T was placed in a furnace while being evacuated and baked at 600°C. Carefully prepared sodium was distilled into the hot discharge tube and condensed on the cooled tube C while the filaments were kept at dull red heat. A clean bright sodium cathode was thus secured. Carefully purified argon was then admitted at various pressures. When the sparking potential is placed across the two clean nickel electrodes A and G (A positive) and an auxiliary field of about 10% of the sparking potential is placed between the nickel electrode G and the sodium cathode C (G positive) the following results should be observed: positive ions generated

between A and G are accelerated toward G by a high electric field. Now most of these positive ions should pass through the nickel grid and be carried toward C by the weak field between G and C. However, in traveling this distance G–C they make many impacts with neutral molecules and thus loose most of their energy of motion gained in the field A–G before reaching C. Any electrons created between G and C or at or on C by mechanisms of the (C) class will, however, be carried toward G by the weak field between G and C. Now in pure argon (p = 0.1 to 0.3 mm.) the sparking potential for a sodium cathode is from 30 to 50 volts less than the sparking potential for a clean nickel cathode (see Fig. II). If we assume that processes (A) or (B) determine the mechanism of sparking we would expect to find the high value of the sparking potential characteristic of nickel, since the positive ions of high energy are only found near G, and as there is no sodium on G. If, however, processes (C) constitute

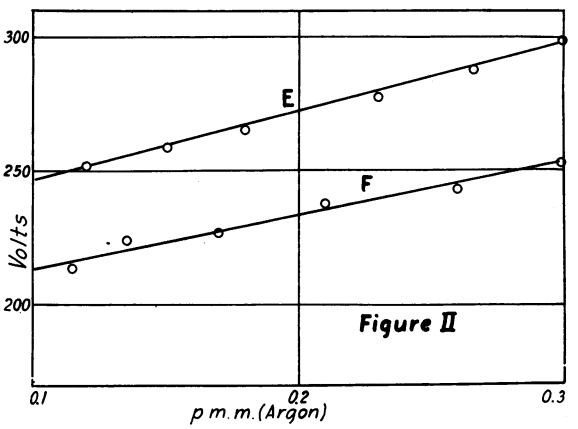

Figure II

the mechanism of sparking, then, since it is probable that a large portion of the positive ions reach C with only a low energy, and are neutralized there, electrons liberated by (C) class mechanism will be carried by the weak field, between G and C, into A–G with relatively little loss. We should thus expect the sparking potential to be characteristic of a sodium cathode, for it is immaterial where the electrons come from as long as they are present in the neighborhood of G.

It was found when the grid G was cooled soon after the sodium had been deposited on C that the sparking potential was characteristic of sodium. (Curve F, Fig. II). However, if the grid G was heated to dull red heat the sparking potential jumped up to the characteristic value for nickel. (Curve E, Fig. II). These readings were reversible and could be reproduced at will by condensing sodium on the grid and then vaporizing the sodium by heating the nickel electrode.

Upon extending these experiments to higher pressures (about 10 mm.) it was observed that the sparking potentials for nickel and sodium cathodes were practically the same (i.e., they differed by less than 5 volts which is the limit of experimental accuracy) and that the change could be observed in a reversible fashion indefinitely by changing the pressure. This fact is exceedingly instructive in that it clearly shows that mechanism (*A*) plays a more and more important part in the spark discharge as the pressure increases, a fact in complete accord with the observations of previous experimenters.[1,8,9] Figure III gives a schematic picture of the sparking potentials for nickel (curve *M*) and sodium (curve *N*) cathodes as a function of the pressure in argon.* Whether the gas is ionized by positive

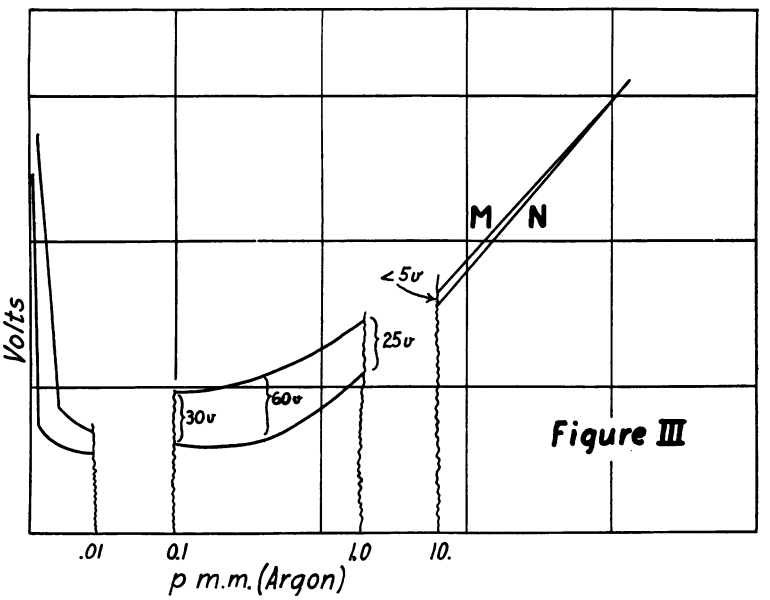

Figure III

ions or whether electrons are liberated from the cathode depends upon the relative probability of ionization by these two processes under any given set of conditions. The probabilities are a function of the nature of the gas and the cathode surface as well as the field strength and pressure of the gas. As the pressure increases even with a low probability of gaseous ionization by positive ion impact, the increase in the number of molecules struck increases the number of electrons from this source relative to the number from the cathode which must be decreased by a greater pressure and a consequent decrease of high energy positive ions striking the cathode. Consequently the ionization of the gas by positive ions becomes more important than the liberation of electrons from the cathode. This is clearly shown by the curves in figure III.

From these experimental results one is led to the following conclusions:

(1) In argon at low pressures the cathode material plays an important part in the mechanism of the spark discharge as was previously observed by Holst and Oosterhuis, and J. Taylor.

(2) Under these conditions the principal mechanism by which positive ions liberate electrons from the cathode depends upon the velocity or energy of impact of the positive ions with the cathode.

(3) The liberation of electrons from the cathode by the photoelectric action of the radiation produced by the neutralization of slowly moving positive ions near, at or on the cathode is not the primary mechanism of electron production in the spark discharge in argon. This photoelectric action may play a minor part.

(4) Very thin sodium films which distill over from the sodium cathode to the grid at room temperature (p = 0.1–0.3 mm.) suffice to reduce the sparking potential to the value characteristic of sodium. The formation of such alkali films has already been studied by Ives and Johnsrud.[10] Dull red heat is sufficient to drive the sodium from the nickel grid and change the sparking potential to the higher value characteristic of nickel.

(5) As the pressure increases the predominating mechanisms of electron production in the spark discharge change from type (B) to type (A), i.e., those in which electrons are liberated from the cathode by the bombardment of swiftly moving positive ions to those in which electrons are generated in the gas by collisions between swiftly moving positive ions and neutral molecules. This is in accord with experimental fact, observed by many experimenters, that at atmospheric pressure the sparking potential is practically independent of the cathode material.

These results are in conformity with the recent advances in our knowledge of positive ions. It is true that Jackson[11] and others have shown that the probability of secondary emission from a *gas denuded* surface due to bombardment by positive ions is very low; however, nickel and sodium surfaces in argon are not gas denuded. Baerwald[12] has found that even 20-volt positive rays can liberate electrons from metallic surfaces which are not out-gassed. Under these conditions the secondary emission is a function of the energy of the positive ions and the metallic surface.

Ionization of gas molecules by positive ions has been a point of much controversy.[9] The recent experiments of R. M. Sutton,[13] however, indicate very definitely that 100-volt potassium ions can ionize helium and argon in appreciable amounts. In hydrogen this ionization is much less.

The serious criticisms raised about the mechanisms of the (A) and (B) type which these experiments seem to uphold merit some discussion. They arise from the fact that to gain enough energy from the field the positive ions must fall through potentials of from ten to fifty or more volts over relatively short mean free paths (of the order of 10^{-1} to 10^{-2} cm.).

If we make the usual assumption that the fields existing at spark over are uniform, the acquisition is highly improbable as Holst, Oosterhuis, Taylor and Loeb[14] have shown. This together with the facts detailed above in which it is shown that the mechanisms (*A*) and (*B*) are the probable mechanisms lead one to conclude that the fields existing under conditions of breakdown are far from uniform before the spark passes. If, then, the gratuitous assumption as to uniformity of fields be discarded, the question presents no serious discrepancy. The recent measurements of time lag in spark discharge observed by Rogowski,[15] Torok[16] and Beams,[17] where intervals of the order of 10^{-7} seconds are observed with considerable overvoltages lead one to the conclusion that their fields are built up in very short periods of time. Since the mobilities of the electrons and ions will under these conditions barely permit space charges to build up in intervals of this order of magnitude, the problem still requires study from the point of view of space-charge conditions at the time of passage of the spark, and the mechanism of their formation.

The writer wishes to acknowledge his indebtedness to Professors A. Joffé and L. B. Loeb for valuable suggestions and to especially express his appreciation to Professor Loeb for assistance and his constant encouragement and inspiration.

* The curves indicated schematically have been observed by the writer. A more complete set of data is needed before giving actual results. These are now being obtained. This work was delayed by lack of argon but it was felt advisable to publish the results to date in the interim. The curve is represented in sections because of the enormous range of pressures covered and is typical of curves passing through the minimum sparking potential upwards, except for the fact previously unknown that the differences in sparking potential for different cathodes vanished above 20 mm. pressure.

[1] Townsend, J. S., "Electricity in Gases," p. 322 and p. 330, Oxford Press, 1914; *Phil. Mag.*, **45**, 444, 1923.

[2] Holst and Oosterhuis, *C. R. Paris Acad.*, **175**, 577, 1922; *Phil. Mag.*, **46**, 1117, 1923.

[3] Taylor, J., *Phil. Mag.*, **3**, 753, 1927; *Proc. Royal Soc.*, **114A**, 73, 1927.

[4] Thomson, J. J., *Phil. Mag.*, **2**, 675, 1926.

[5] Thomson, J. J., *Conduction of Electricity through Gases*, 2d edition, p. 490, Cambridge Press, 1906.

[6] von Hippel, A., Physics Seminar, Univ. Calif., 1927; *Ann. Physik*, **81**, 1053, 1926.

[7] Brode, R. B., Physics Seminar, Univ. Calif., 1927; *J. Frank. Inst.*, **205**, 312, 1928.

[8] Hooper, W. J., *J. Frank. Inst.*, **201**, 311, 1926.

[9] Loeb, L. B., *Science*, **66**, 627, 1927.

[10] Johnsrud and Ives, *Astrophys. J.*, **60**, 231, 1924.

[11] Jackson, W. J., *Phys. Rev.*, **28**, 524, 1926, and **30**, 473, 1927.

[12] Baerwald, H., *Ann. Physik*, **41**, 643, 1913.

[13] Sutton, R. M., *Phys. Rev.*, **33**, 3, 364, 1929.

[14] Loeb, L. B., *J. Frank. Inst.*, **205**, 305, 1928.

[15] Rogowski, *Arch. Elekt.*, **16**, 496, 1926; also Schumann, *Zeit. Tech. Phys.*, **7**, 618, 1926.

[16] Torok, J. J., *J. A. I. E. E.*, **47**, 177–181, 1928.

[17] Beams, J. W., *J. Frank. Inst.*, **206**, 809, 1928.