advanced courses, prerequisites for which are courses in mathematics which only a few premedical students elect.

To meet this need the speaker conducted for a number of years a course of lectures illustrated with experiments and presented in such a manner as to avoid the use of mathematics beyond algebra and trigonometry. These courses were well attended, and not infrequently in addition to the medical students, graduate physicians who were making use of X-rays in their practice requested permission to attend. It is conceivable that a professor of biophysics in a medical college might develop a much better course of this kind dealing with the biological effects of X-rays and perhaps including also the effects of other radiation and means for its production and measurement.

By far the most important need is for the close cooperation of the physicist, the chemist, the physiologist, pathologist and others in an attempt to evolve rational theories to coordinate and explain the immense amount of curious and interesting experimental data which workers in the various fields of biology have accumulated.

The medical sciences already owe a large debt to physics. They have had at various times the services of more than one eminent investigator in that field. There remains a wealth of problems still unsolved and with the powerful aids which recent advances in physics make available it should be possible to secure results with greater ease than ever before. May I leave with you first of all the suggestion that students about to enter upon their premedical work should be impressed with the importance of making the utmost use of the opportunity which is afforded them in their course in college physics. In addition may I suggest that occasionally an advanced student of physics who has developed an interest in its biological applications may find in biophysics a field of activity where there is an abundance of interesting problems to tax his ingenuity and where he may, if fortunate and industrious, achieve results whose importance can hardly be estimated.

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THE MECHANISM OF SPARK DISCHARGE IN AIR AT ATMOSPHERIC PRESSURE

SOME fifteen years ago the mechanism of the electric spark in air was considered as quite satisfactorily described by the classical theory of Townsend.[1] In recent years this theory has been seriously called into question by the researches of Holst and Oosterhuis,[2] and James Taylor.[3] As shown by the writer in a recent article[4] the serious difficulty with the original theory of Townsend lay in the fact that the mechanism of spark discharge proposed assumes ionization by the positive ions of the gas through collision with gas molecules in such a manner and measure as to produce enough electrons in the neighborhood of the cathode as to make the discharge self-maintaining. This means that the positive ions must gain enough energy in moving through several free paths in the field to enable them to ionize neutral gas molecules by impact. Now in recent years the ability of the positive ions to ionize molecules by impact has been seriously questioned.[5] Furthermore Taylor and Holst and Oosterhuis believed to have shown in inert gases at low pressures that the nature of the cathode surface plays an important rôle in the mechanism of the spark as the alkali metals like Na and K gave distinctly lower sparking potentials under these conditions than more inert metals. The possibility that at low pressures in spark discharge the generation of electrons from the electrode surface occurs through positive ion impact (an effect characteristic of the metal as their results indicate) was also scouted by these authors as unlikely for two reasons. The first one was that electron emission by positive ion bombardment on an outgassed surface is a phenomenon requiring high potentials as shown recently by Jackson.[6] The second reason is that in the fields assumed the positive ions could only extremely rarely (one in 10^{-17}) acquire the ionizing energy over a mean free path in the gas.

Now the writer[4] pointed out that metal surfaces even in inert gases were not "outgassed" so that positive ions of 20 or less volts equivalent energy could remove electrons.[7] He further stated that the assumptions as to the values of the fields occurring near the cathode just at sparking (which gave the low values for the energy of impact of positive ions) were both gratuitous and probably contrary to fact. In his original deductions Townsend assumed that the fields were uniform and that the sparking potential gradient was merely the sparking potential divided by the distance. This assumption was probably made for simplicity only, and Townsend[1] himself provided the possibility of non-uniform fields at breakdown in

[1] J. S. Townsend, "Electricity in Gases," Clarendon Press, Oxford, 1915. pp. 322, 330 and 429.

[2] *Phil. Mag.*, 46: 1117, 1923.

[3] *Phil. Mag.*, 3: 753, 1927; *Proc. Roy. Soc.*, 114A: 73, 1927.

[4] *Jour. Franklin Inst.*, 205: 305, 1928.

[5] L. B. Loeb, SCIENCE, 1928.

[6] W. I. Jackson, *Phys. Rev.*, 28: 524, 1926; 30: 473, 1927.

[7] H. Baerwald, *Ann. der Physik*, 41: 643, 1913.

his theoretical treatment. In the study of the values of the ionization functions $\frac{\alpha}{p}$ and $\frac{\beta}{p}$ for the electrons and positive ions in a gas, Townsend actually worked under conditions where the fields were sensibly uniform, but where the ratio $\frac{X}{p}$ (field strength in volts/cm divided by pressure in mm of mercury which was the important variable in the process) was very high (of the order of 100 to 1,000 as compared to the value of 39, $\frac{30,000}{760}$ for $\frac{X}{p}$ for sparking at atmospheric pressure assuming uniform fields). The ionization functions obtained by Townsend at these high values of $\frac{X}{p}$ satisfied the conditions for sparking but not under ordinary conditions of spark discharge in air at atmospheric pressure.

In his previous article the writer showed that it was only necessary to assume that before the spark discharge passed, through the medium of the dark current preceding breakdown, non-uniform fields of the order of magnitude of those investigated by Townsend should build up as a result of space charge effects. Such fields at atmospheric pressure would have to be fields of from 1×10^5 to 10^6 volts/cm. It was shown that such fields could be expected as a result of space charges due to the fact that electrons travel with velocities of 2,000 cm/sec in unit field compared to about 2 cm/sec for positive ions. The theory, however, required that time intervals of the order of 10^{-4} seconds should be involved in the building up of the space charges owing to the low velocity of the positive ions. The writer therefore stated that such time intervals must constitute the "time lag" of the spark under uniform conditions.

Since the writing of the above cited paper[4] many new developments have taken place. L. J. Neumann[8] in the writer's laboratory showed by experiment that it was probable that in argon and the inert gases the mechanism of breakdown did not consist of the mechanisms postulated by Holst and Oosterhuis and Taylor (action of electrical image forces and photoelectric effects on the metal); but that they consisted as had earlier been postulated by J. S. Townsend and J. J. Thomson[9] of the liberation of electrons from the cathode by positive ion bombardment. At higher pressures in argon (20 mm pressure), the phenomenon in Neumann's experiments went over to a phenomenon which was independent of the nature of the electrodes, indicating definitely that at higher pressures the ionization by positive ions was taking place in the gas itself as initially suggested by Townsend. This conclusion is in agreement with the fact that it is only by such a mechanism that the discharge from positively charged points in gases at higher pressures can be explained.[10] In the interim also the beautiful experiments of R. M. Sutton,[11] at California Institute of Technology, have beyond doubt proven the rather copious ionization of the gases O_2, N_2, Ne and Ar by positive ions of Na and K above 100 volts energy. The most significant discovery of all, however, was a discovery made independently and with different methods by Pedersen,[12] Rogowski,[13] Torok[14] and Beams[15] that for nearly plane parallel electrodes at potentials exceeding the normal breakdown potential by from 50 per cent. to several hundred per cent. the time lag of the spark was surprisingly short, *i.e.*, from 10^{-7} to 10^{-8} seconds. This value of 10^{-} seconds is so far smaller than the one demanded by the writer's original theory that some serious modification was needed. It is the purpose of this article to set forth the modified theory of the phenomenon which will account for such time intervals and the other effects observed, as well as some effects never accounted for in the theory of spark discharge. That a theory as obvious as this one to be described has not been proposed is quite surprising.

What is needed in a theory of spark discharge as it appears at this time is that (1) non-uniform potential gradients of high value can be generated in fields of the order of 30,000 volts between electrodes 1 cm apart, and (2) that such fields can be generated in 10^{-7} to 10^{-8} seconds.

For simplicity one may regard the conditions between plane parallel electrodes separated by 1 cm and over an electrode area of 1 cm^2 in air at atmospheric pressure. In such a volume of 1 cm^3 to which 30,000 volts potential difference have been applied there existed at the time of application some 1,000 pairs of ions due to the natural processes of ionization in the air. There are from 10 to 20 ions per cm^3 generated in air in a second due to radioactive and other causes and these are removed only by diffusion and recombination at such a rate that about 1,000 pairs of ions per cm^3 exist at any one time. Some of these ions are electrons, others are negative ions. The recent work of Cravath[16] has shown that in high fields negative ions lose their electrons by impact so that shortly after the appli-

[8] *Proc. Nat. Acad. Sci.*, 15: 259, 1929.

[9] J. J. Thomson, "Conduction of Electricity in Gases," Cambridge, 1906, p. 490 ff.

[10] L. B. Loeb, *Jour. Franklin Inst.*, 205: 308, 1928.

[11] *Phys. Rev.*, 33: 364, 1929.

[12] P. O. Pedersen, *Ann. der Phys.*, 71: 317, 1923.

[13] *Archiv. f. Electrotech.*, 16: 496, 1926.

[14] J. J. Torok, *Jour. A. I. E. E.*, 47: 177, 1928.

[15] J. W. Beams, *Jour. Franklin Inst.*, 206: 809, 1928.

[16] A. M. Cravath, *Phys. Rev.*, 33: 605, 1929.

cation of the field these negative ions are mostly in the electronic condition. Now these electrons are distributed at random in the cm^3 so that each electron is on the average 1 mm or less from its nearest neighbor. As soon as the field is applied the electrons begin to move towards the anode at a velocity in this field of some 10^7 cm/sec as shown by the experimental studies of electron mobilities in air. The positive ions which the electrons create move only some 6×10^4 cm/sec towards the cathode. Each electron in such a field from Townsend's experimental data produces some 400 new electrons and ions per cm path under the conditions above. Thus since the electrons generate new electrons according to the equation $n = n_0 e^{+\alpha x}$, where x is the distance covered in the gas and $\alpha = 400$, we see that the 1 initial electron in 1 mm path has resulted in the formation of e^{40} or 2.42×10^{17} new ions, provided it has traveled with undiminished velocity in this field. It is of course doubtful whether this magnitude will actually have been reached as the separation of the electrons from the slow positive ions will produce space charges that may act to retard or even stop the electronic motion. As the electrons advance towards the anode they spread apart owing to self-repulsion and diffusion so that the space charge on residual positive ions takes on a sort of wedge-shaped form with the broad end towards the anode. The pressure as well as the space charge determines the amount of spreading of the electron cloud, and the lower the pressure the wider the base of the wedge. The actual width of the spark discharge path must be an indication of this spreading, and it is well known how on reducing the pressure and increasing the diffusion the width of the spark path increases. Now if the initial electron were alone in the space between the electrodes the increase of ionization would probably largely cease as a result of the local annihilation of the field by the separation of space charges of electron and positive ion clouds. However, in moving this millimeter if the chance arrangement of initial electrons was propitious the negative cloud has approached the positive cloud of the next electron ahead. Thus the effects of the two positive space charges one behind and one ahead can offset each other somewhat, so that the electrons can continue to move and ionize and such an offsetting of the local field must occur from one electrode to the other before a spark can pass. When this fortuitous arrangement of initial electrons exists the conditions in the ion paths will be such that close to the cathode there will be a powerful positive space charge and close to the anode an approaching electron cloud with a succession of ion and electron clouds between. As a result of such actions the normal uniform fall of potential (shown as the straight line in Figure 1) will be replaced by some such a potential distribution as given by

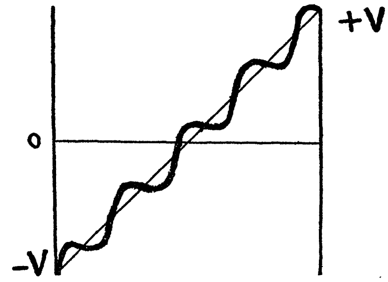

FIG. 1

the wavy line. It is seen that in this arrangement potential gradients many times steeper than the original line may result. In such fields $\frac{X}{p}$ may reach values ten to twenty times the value assumed from the uniform potential fall between the electrodes. Under such conditions positive ions can surely ionize by impact and furnish fresh electrons, especially near the cathode. Each such new electron generated by the positive ions can do much to improve the conducting path in the high fields obtained. From recent[17] experiments on recombinations of electrons with positive ions in gases at atmospheric pressure it appears that the phenomenon of recombination is so rare that the electron might easily move far into the positive cloud meanwhile ionizing without being neutralized. The calculation of electrical fields, such as described above, from theory is a well-nigh impossible task, but rough computations indicate that for space charges far smaller than those to be expected from the motions of electrons over 1 mm the volume charge of the positive ions alone could produce fields of the order hoped for. Until, however, such computations can be carried through the theory can only be considered as a promising suggestion.

The question of the time lag of the spark discharge is, however, nicely settled, for the initial electron can complete its path of 1 mm or probably less in 10^{-8} seconds since the electron velocity is easily of the order of 10^7 cm/sec. The theory also accounts in a simple fashion for the ordinary time lag of the spark. Recently Zuber and M. v. Laue[12] have investigated the time lag for the spark when *just* the minimum sparking potential was applied. This critical value is probably set by the value of the field to enable the electron and positive ion groups to approach the minimum distances for the proper production of ionizing fields for positive ions. Below such a critical potential, no matter how good the more probable fortuitous arrangements of initial ion dis-

[17] L. B. Loeb, Paper before the Am. Electro-Chemical Society, Toronto, May, 1929.

tribution may be, the occurrence of satisfactory arrangements of initial distribution will become so rare as to make the passage of the spark practically impossible. Thus the minimum sparking potential while it may possess no real accurately fixed value assumes a definitely practically realizable value. With a critical field of this practical value the time lags were found by Zuber to vary from very short periods up to numbers of seconds and to be purely chance phenomena, there being no most probable interval of time lag for an electrode space under ordinary conditions. This is to be expected to follow as a necessary consequence of the fortuitous arrangement, or coincidences, of ionized electron paths. Until such an arrangement occurs no spark takes place, and its occurrence is purely a chance phenomenon which is more or less probable. If this fortuitous occurrence happens to lead to an irregular path instead of an ionization straight across between the electrodes the spark takes on the well-known zigzag form. Introduction of electrons near the cathode such as by ultraviolet light or radium, which are for this phenomenon after all relatively few in number, insures the fortuitous arrangement being more probable and consequently makes the long irregular spark lags less likely, as well as possibly lowering the minimum value of the sparking potential slightly. That such illumination at the *cathode* is more satisfactory than elsewhere follows from the direction of motion of the electrons, with the correspondingly longer paths that they have in the direction of the anode.

When intense fields are used such as in the overvoltage experiments of Pedersen,[12], Rogowski,[13] Torok[14] and Beams[15] the critical field strengths for the building up of adequate space charges in proper relation to each other are so far exceeded that far less fortuitous arrangements suffice for sparking and the amazingly short time lags observed can occur.

It is hoped that this suggestion of the mechanism of spark discharge which qualitatively at least seems to explain the rather contradictory observed facts will serve to stimulate some one more gifted in the mathematical handling of such a problem to attempt its solution and thereby help us understand a phenomenon whose mechanism has been sought for since the time of Franklin.

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RESEARCH AT MELLON INSTITUTE DURING 1928–29

DIRECTOR WEIDLEIN in the sixteenth annual report of Mellon Institute of Industrial Research has summarized the progress during the fiscal year 1928–29, the eighteenth since the establishment of the institute at Pittsburgh. The expansion in all activities may be taken as an indication of the extent to which the American manufacturer has become research-minded.

The services which the institute has rendered to industries during the year are the cumulative efforts of 173 senior industrial fellows, industrial fellows, and assistants. A more tangible expression of their results is given by 159 publications, including 25 United States patents, which appeared during 1928. The funds paid to the institute during the fiscal year exceeded $800,000, an increase of nearly $100,000 over the payments for 1927–28. At the close of the year sixty-two distinct problems were under investigation.

The growth of the institute during the year was made possible by the acquisition through gift from the founders, Messrs. Andrew W. Mellon and Richard B. Mellon, of properties which have been altered extensively to provide additional laboratories and offices.

Important results in solving manufacturing problems, in extending uses for industrial products and in creating new products and new processes of manufacture were obtained in the following fields: fertilizers, organic solvents and resins, molded paper articles, insecticides, foods, chrome plating, ceramic products, insulation, kiln studies and vitreous enamel. The institute's previous investigations (1911–14) (1923–24) on the abatement of the smoke nuisance have received wide recognition. This research is of such great importance, not only to the city of Pittsburgh but to every city, that the work has been reestablished.

The yearly renewals of fellowships by the donors are a source of gratification, since the carrying out of extended investigations of industrial problems requiring long periods of time for their solution has been one of the chief aims of the institute from the time of its foundation. One fellowship has been operating continuously since 1911, and one since 1914. Ten fellowships have been maintained for more than ten years, and seventeen additional fellowships for five years or more. In spite of the increase in size of the physical plant, the institute, because of lack of space, has been unable to meet the demands made upon it, and during the past year has been forced to decline investigations of importance.

The Department of Pure Research has a valued function. This department aids the industrial fellows by acting in an advisory capacity, but its major importance lies in the disinterested investigation of problems not suggested by industry. Without pioneer work in pure science, to serve as source material for applied science, the progress of technology would languish.