[4] M. Reier and M. H. Shamos, Phys. Rev. **100**, 1302 (1955).
[5] C. T. Hibdon and C. D. Muehlhause, Phys. Rev. **88**, 945 (1952).
[6] Estulin, Kalinkin, and Melioranskii, J. Exptl. Theoret. Phys. (U.S.S.R.) **31**, 886 (11956), Soviet Physics JETP **4**, 752 (1957).
[7] Alikhanov, Vladimirskii, Nikitin, Galanin, Gavrilov, and Burgov, *Papers by the Russian Delegation to the International Conference of Peaceful Uses of Atomic Energy*, p. 105 (1955).
[8] C. M. Davisson and R. D. Evans, Rev. Mod. Phys. **24**, 79 (1952).
[9] G. A. Bartholomew and B. B. Kinsey, Phys. Rev. **89**, 368 (1953).
[10] G. M. Foglesong and D. G. Foxwell, Phys. Rev. **96**, 1001 (1954).
[11] M. Deutch and G. Scharff – Goldhaber, Phys. Rev. **83**, 1059 (1951).
[12] L. K. Peker and L. A. Sliv, Izv. Akad. Nauk SSSR, Ser. Fiz. **27**, 411 (1953).
[13] G. A. Bartholomew and B. B. Kinsey, Can. Journ. Phys. **31**, 1025 (1953).
[14] Jordan, Cork, and Burson, Phys. Rev. **90**, 362 (1953).
[15] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, New York, 1952).
[16] Adiasevich, Groshev, and Demilov, U.S.S.R. Acad. Sci., *Conference on Peaceful Uses of Atomic Energy*, p. 270 (1955).
[17] Melaike, Parker, Petruske, and Tomlinson, Can. Journ. Chem. **33**, 830 (1955).
[18] V. Kistiakov – Fischer, Phys. Rev. **96**, 1549 (1956).
[19] B. B. Kinsey and G. A. Bartholomew, Can. Journ. Phys. **31**, 1051 (1953).
[20] H. H. London and V. L. Sailar, Phys. Rev **93**, 1030 (1954).
[21] A. Harvey, Phys. Rev. **81**, 353 (1951).
[22] Brogles, Thomas, and Haynes, Phys. Rev. **89**, 715 (1953).
[23] L. A. Sliv and H. N. Brand, *Tables of Internal Conversion Coefficients*, 1956.
[24] Elliot, Preston, and Wolfson, Can. Journ. Phys. **32**, 153 (1954).
[25] J. Titman and C. Sheer, Phys. Rev. **83**, 747 (1953).
[26] Berostrom, Hill, and de Pasquali, Phys. Rev. **92**, 918 (1953).

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Ignition of the High Voltage Discharge in Hydrogen at Low Pressures

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It has been found that the striking voltages for discharges in hydrogen, corresponding to the left-hand branch of the Paschen curve, do not obey the similarity rules.

After an ignition on the left-hand branch of the Paschen curve, the resultant high-voltage discharge is characterized by electrode voltage drops which are independent of the current. In hydrogen discharges, this constancy of voltage drop is maintained over a very wide range of currents. For discharges produced by 4-μsec voltage pulses, the transition from the high-voltage form to the arc takes place only at currents exceeding 1000 amp.

IN UNIFORM ELECTRIC FIELDS, the striking voltage for a discharge satisfies the similarity rule; *i.e.*, it is a function of the product pd, where p is the pressure and d the distance between electrodes. A number of investigations[1,2] have shown noticeable deviations from the similarity rule when the electric field at the cathode begins to exceed 10^6 v/cm, and spontaneous emission of electrons begins. This situation may arise either at very high gas pressures, on the order of tens of atmospheres, where the electrode voltage reaches hundreds of kilovolts, or at very small gap widths where even at a few hundred volts the field strength at the cathode reaches the above-mentioned figure. In the work re-

ported herein, we first investigated the hydrogen-discharge striking voltage to study those deviations from similarity in the left-hand of the Paschen curve which were not of the nature of spontaneous electron emission. In the second place, we studied those particular forms of discharge which had a high voltage drop at the electrodes.

1. MEASUREMENT PROCEDURE

The tube intended for the study of discharges under the conditions of the left-hand branch of the Paschen curve was constructed to prevent any discharge by way of the "long" path. To test the applicability of Paschen's law, a construction was used in which the electrodes could be kept fixed, or one electrode could be moved so as to vary the separation d between 4 and 32 mm. The electrode diameter was 80 mm to make the interelectric field sufficiently uniform. Before use, the polished nickel electrodes were baked out with a high-frequency current in vacuum, and conditioned by a glow discharge in hydrogen. Control of the hydrogen pressure was obtained by heating titanium hydride placed in a side-arm of the discharge tube. The voltage applied to the electrodes was supplied by a high-voltage rectifier circuit, provided with a filter to smooth out the voltage pulsations. This voltage could be regulated continuously from zero to 40 kv, and its value was measured with an electrostatic voltmeter. The ignition point was indicated by the needle kick of a microammeter connected in series with the low-voltage electrode. The striking of a discharge could also be detected visually through the fine mesh screen surrounding the discharge space. In a darkened room it is possible to establish the occurrence of ignition at currents as low as about 10^{-7} ampere.

2. TEST OF THE APPLICABILITY OF PASCHEN'S LAW TO THE IGNITION OF HYDROGEN DISCHARGES

Repeated measurements of striking potentials U_s have shown the existence of very serious deviations from the similarity rule. Curves of $U_s = f(pd)$ for for different values of d are given in Fig. 1; these curves are quite widely separated. Such effects can be repeated reproducibly in tubes of different constructions, and also in tubes where both the distance d and the hydrogen pressure p can be varied. In these tubes the cathode is kept the same during all changes; this avoids any errors which might

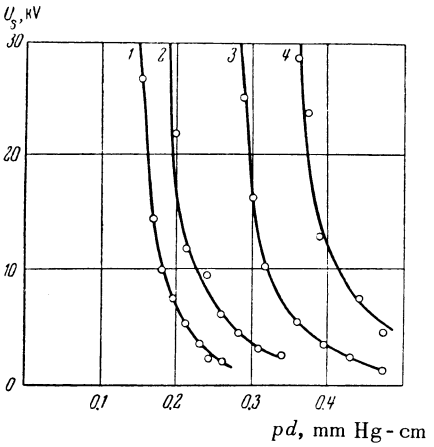

FIG. 1. Deviations from the Paschen law in hydrogen. Curves of $U_s = f(pd)$ at $T = 20°$ C. 1—d = 4 mm; 2—d = 8 mm; 3—d = 16 mm; 4—d = 28 mm.

creep in during the exchange of one cathode for another, due to changes in the coefficient γ, which is very sensitive to the condition of the surface. Repeated experiments have also shown the absence of local effects at the electrodes, and that the results are the same when the electrode polarities are interchanged. All this proves that the deviations from the similarity law are not experimental errors or peculiarities of the apparatus, but are inherent in the nature of the hydrogen discharge. In fact, if hydrogen is replaced by air in the same tubes, the curves of $U_s = f(pd)$ taken at different distances d and pressures p coincide very well (*cf.* Fig. 2) whereas the same curves in hydrogen (Fig. 1) are widely separated. If, following Slepian and Mason[3] we plot $\log p$ *vs.* $\log d$ for constant U_s, we obtain for hydrogen a family of straight lines intersecting the coordinate axes at a very nearly constant angle, differing from 45°. This implies that the striking potential is a function of the derived quantity pd^k. This function is assumed to be of the form

$$U_s = A/(pd^k)^B. \tag{1}$$

If U_s is in kilovolts, the experimental data for hydrogen are well represented by the expression

$$U_s = 46 \cdot 10^{-3}/(pd^{0.58})^6\,(\text{kV}). \tag{2}$$

Formula (2), whose validity has been verified up to a potential of 30 kv, shows that U_s is more sensitive to variations in pressure than to variations in the distance between electrodes.

The data obtained at different values of d agree

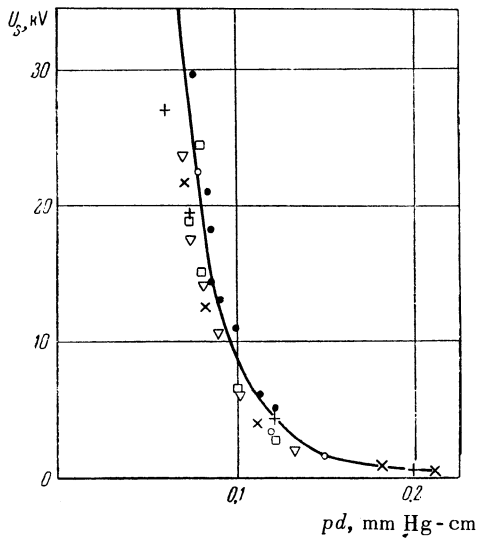

FIG. 2. Curves of $U_s = f(pd)$ for air at $T = 20°$ C. +—$d = 20$ mm; □—$d = 8$ mm; pressure varied. ×—$p = 0.04$ mm Hg; ▽—$p = 0.06$; ○—$p = 0.1$; ●—$p = 0.14$; interelectrode distance varied.

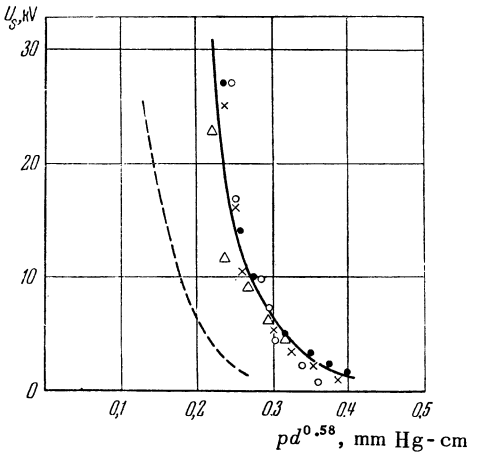

FIG. 3. Striking voltage of hydrogen discharge as function of $pd^{0.58}$. ●—$d = 2.8$ mm; ×—$d = 16$ mm; ▽—$d = 8$ mm; ○—$d = 4$ mm. Dashed curve is from data by Quinn.

well with the relation $U_s = f(pd^{0.58})$ as shown in Fig. 3. Quinn's results for hydrogen[4], shown dotted in Fig 3, give a value of U_s which is lower by almost a full order of magnitude. Apparently the electrodes in Quinn's experiments were not sufficiently outgassed, so that the coefficient γ of his cathode was much larger than in the present work. This is also confirmed by the much lower values of U_s which Quinn obtained in comparison with the results of Dikidzhi and Kliarfel'd[5]. In the high sensitivity of its striking voltage to contamination of the cathode surface, hydrogen is similar to the inert gases or mercury vapor[5,6] and differs from the other molecular gases.

The reasons why hydrogen discharges deviate from the similarity rule can be stated only in relatively general terms as yet. Field emulsion cannot be playing any part here, since the deviations are observed even when the field strength at the cathode is below 10^4 v/cm. Some reasons for the deviations might be: a) ionization processes in the gas space, which may arise in various ways in molecular gases; b) cathode surface effects, explainable by the fact that the coefficient γ depends not only on the energy of the ions, but also on the field strength at the cathode.

Experiments which have been carried out by the probe method in the positive column of hydrogen discharges[7] have shown that the mean mass of the hydrogen ions definitely exceeds the mass of a proton. A number of studies of hydrogen ions[8-10] have indicated the presence of at least three different types of ions in the hydrogen discharge: H^+, H_2^+, and H_3^+. When hydrogen is ionized by an electric spark discharge the yield of H_2^+ ions, at the maximum in the curve of ionization efficiency, is 250 times larger than the yield of protons[11]. The H_3^+ ion is formed from the H_2^+ ion by the reaction[12,13] $H_2^+ + H_2 \rightarrow H_3^+ + H$. The probability of this process falls off as the energy of the H_2^+ ion increases. The H_3^+ ion thus formed can break up again during various types of collisions with hydrogen molecules; hence the disintegration probability of H_3^+ increases with its velocity. Conditions are most favorable for the production and stability of H_3^+ ions when the surrounding medium is made up of other hydrogen ions. The value of γ for different types of hydrogen ions increases with the number of atoms in the given type of ion[14]. Thus a change in the composition of the hydrogen ion mixture striking the cathode will case corresponding changes in U_s. It is entirely possible that some of the processes by which hydrogen ions of different types are formed or destroyed[15] on their way to the cathode may not satisfy the similarity rule. In this case the striking voltage of the discharge will also deviate from the rule.

A second reason for the failure of the similarity rule could be a dependence of the coefficient γ for H^+, H_2^+ and H_3^+ ions on the potential gradient at the cathode. Unfortunately only one study of this dependence has been reported—for H^+ and H_2^+ ions with an energy of 250 kv[16]. It was found that the coefficient γ increased somewhat faster for H_2^+ ions than for protons as the field at the cathode increased. It is very probable that for the slower H_3^+ ion, the coef-

ficient γ increases still more rapidly, and that the increase is effective at still lower cathode field strengths. In this case, the curves $U_s = f(pd)$ for small values of d would be displaced to the left of those for large d, because of the increase of γ. This is what is observed experimentally (Fig. 1).

3. HIGH-VOLTAGE FORM OF THE DISCHARGE AT VERY LOW PRESSURES

On the left-hand branch of the Paschen curve the discharge occurring after ignition is characterized by a running voltage almost exactly equal to the striking voltage[6], whereas on the right-hand branch the transition to a glow discharge is always accompanied by a considerable reduction in the potential drop across the discharge. Hence formula (2) gives the running voltage as well as the striking voltage, provided that the current density in the discharge does not exceed about 0.1 a/cm², as will be shown below. On the left-hand branch of the Paschen curve the normal glow discharge cannot in general occur, since the thickness of the normal region of cathode potential drop is greater than the distance between electrodes. The high-voltage form of discharge occurring in the left-hand branch of the curve therefore has the characteristics of a silent discharge, in that there is only a weak space charge between the electrodes; it also has the characteristics of a hindered discharge, since increasing the distance between the electrodes results in a decreased potential drop across the discharge. The low space charge of this type is a result of the high speed of the charged particles due to the high field and particularly to the fact that when pd is reduced the discharge changes from a slow diffusion of ions and electrons in a gas, characterized by a mobility coefficient in the electric field, to a free fall to the cathode. Particular attention should be paid to the current-voltage characteristics of the high-voltage discharge in hydrogen, where the ionic space charge is least effective. Such characteristic curves, taken at different pressures, are shown in Fig. 4. In these curves the potential drop across the discharge is inpendent of the current over a very wide range of current densities. From the outside, the discharge appears as a diffuse glow, whose intensity falls off continuously from the cathode to the anode, corresponding to the drop in the excitation efficiency of electrons in the energy range 10^3 to 10^5 ev.

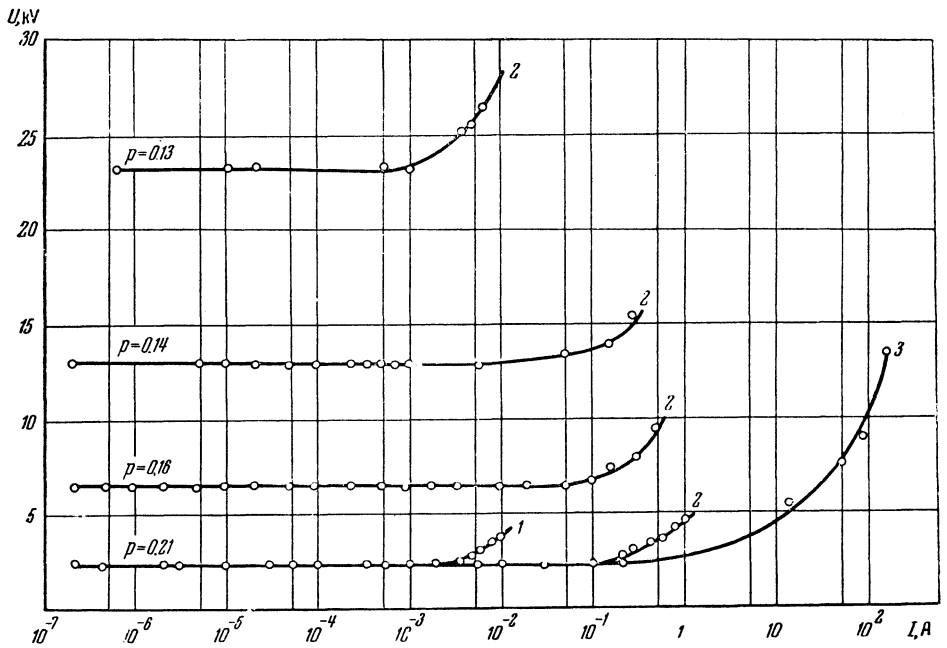

FIG. 4. Current-voltage characteristics for high-voltage form of hydrogen discharge at constant field strength. d = 16 mm; cathode surface = 50 cm²; pressure p in mm Hg. 1—thin nickel foil electrodes, 2—massive copper electrodes, 3—massive copper electrodes with pulsed operation.

The heating of the electrodes, which increases with the current, causes a lowering of the hydrogen density in the interelectrode space. Because of the very steep rise which occurs in the striking voltage (and in the concomitant running voltage) of the high-voltage hydrogen discharge when the value of

$pd^{0.58}$ is reduced, even a slight reduction in gas density is sufficient to raise the voltage necessary to maintain the discharge. Curve 1 of Fig. 4, taken at a pressure of 0.21 mm Hg in a tube with thin nickel-foil electrodes, shows a rise even at current densities of the order of 0.1 ma/cm². Curve 2 was measured in a tube with massive electrodes of electrolytic copper; the discharge was switched on for short periods only. Because of the lower electrode heating, the upward rise in the curve begins only at a current density of a few ma/cm². In order to eliminate the effect of electrode heating, curve 3 was taken by applying voltage pulses of 4 microseconds duration at a repetition rate of 200 per second. By this means the average heat dissipation at the electrodes was reduced by three orders of magnitude. The heating during each pulse could not have caused any rarefaction of the gas, since in 4 microseconds the hydrogen molecules would travel only about one centimeter, and would not be able to leave the discharge space. The rise in curve 3 begins at a current density on the order of 100 ma/cm². The remaining current-voltage characteristics were all measured at lower hydrogen pressures in the tube with massive copper electrodes already referred to, using discharges of short duration. The lower the hydrogen pressure, the smaller is the current density at which the voltage rise begins, since the left-hand branch of the Paschen curve becomes steeper for lower pressures and even a very small amount of heating is sufficient to produce a noticeable voltage rise. If the heating effect is reduced (as in Curve 3) it is possible to obtain a constant voltage drop over a range of at least seven orders of magnitude of current, from 10^{-7} to 1 ampere. It appears likely that this constancy would be maintained for several more orders of magnitude below 10^{-7} ampere.

The rise in voltage across the discharge when the current density increases above 100 ma/cm² cannot be due entirely to heating of the gas. The appearance of a positive-ion space charge at high current densities (the electron space can be neglected, since electrons are removed from the interelectrode space with almost two orders of magnitude faster than the ions) leads to a redistribution of the electric field between the electrodes. This causes an increase in the potential drop at the cathode and a decreased drop at the anode. The results of this will be: 1) a reduction in the number of ionizations caused by electrons on their way from cathode to anode, because it diminishes the region in which the electrons attain energies of 20 to 1000 ev, where they have the greatest effective cross-section for ionization ($Q_i > 1$ cm²/cm³); and 2) an increase in the average value of γ for ions which reach the cathode owing to the increased anode region in which U has a higher value, and a corresponding increase in the proportion of higher-energy ions that strike the cathode. Whether this redistribution of the field will lead to an increase or a decrease of the discharge voltage depends upon the nature of the dependence of γ and Q_i on the energies of the corresponding ions and electrons. An increased potential difference across the discharge will result when the drop in the number of ionizations by electron impact is not compensated by the increase in γ. In the opposite case, there will be a decrease in the running voltage of the discharge due to the more rapid growth of γ with increased ion energy U. In hydrogen, γ rises slowly in the energy interval 0 to 30 kv[14,17]. Therefore for a high-voltage discharge, one would predict that the positive space charge would cause the current-voltage characteristic to rise rather than drop.

It is possible to estimate the order of magnitude of the current density j at which the positive space charge is known to cause a change in the current-voltage characteristic of a high-voltage discharge (regardless of the sign of this change). All the approximations necessary for this estimate are made in such a way that the value obtained for j is an upper limit.

For simplicity let us assume that there is a constant positive space-charge density between the electrodes. If $\rho = 0$, the potential increases linearly from cathode to anode, while the field E is con-

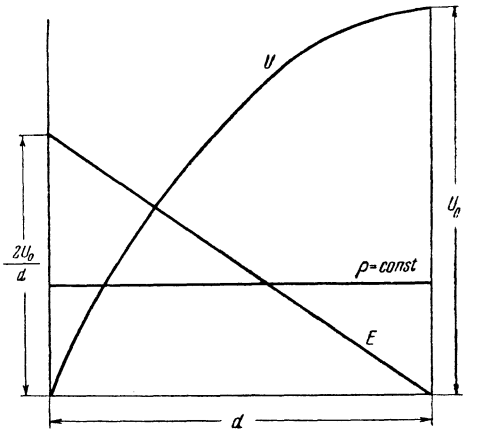

FIG. 5. Assumed conditions of U, E and ρ corresponding to the onset of a change in the running voltage of a high-voltage discharge, as the discharge current is increased.

stant and equal to $E = U_0/d$, where U_0 is the potential difference between the electrodes. Let us find the value of ρ for the case where the mean value of E is still equal to U_0/d, but where E varies from the value $2U/d$ at the cathode to zero at the anode. Since ρ is constant, E must decrease linearly from cathode to anode. The potential U varies in this case as shown in Fig. 5. When the potential deviates from linearity as much as this, it is quite reasonable to expect variations in the running voltage of the discharge.

If x is the distance from the cathode, we obtain

$$E = \frac{2U_0}{d}\left(1 - \frac{x}{d}\right), \quad (3)$$

$$dE/dx = -4\pi\rho = -2U_0/d^2, \quad \rho = U_0/2\pi d^2. \quad (4)$$

On the other hand, the positive-ion space charge produced by a current of j/e electrons passing through one square centimeter each second is equal to

$$\rho = (j/e)\, sp\tau e, \quad (5)$$

where sp is the product of the effective cross-section for ionization by electron impact and the gas pressure, and τ is the mean lifetime of the ions in the discharge. Here we are assuming that spd is considerably smaller than unity, *i.e.*, that most of the discharge current is carried by electrons.

We now determine an approximate lifetime τ as the time for the free fall of an ion from a distance of $d/2$ to the cathode in a field E_1, which is the mean value of E between $x = 0$ and $x = d/2$. (In this derivation we ignore collisions of the ion with gas molecules, which will in fact lead to an increase of τ.) Then

$$E_1 = 3U_0/2d, \quad \tau = \sqrt{2d^2M/3U_0e}, \quad (6)$$

where M is the mass of the ion and e is its charge.

The value of current density j in the discharge, for which the interelectrode field becomes distorted in the manner shown in Fig. 5, is found from Eqs. (4) to (6):

$$j = \sqrt{3/8}\, eU_0^{3/2}/\pi d^3 spM^{1/2}. \quad (7)$$

For the case corresponding to curve 3 of Fig. 4 we have $U_0 = 2500$ v, $sp = 0.2$ cm^{-1} at electron energies of the order of 1000 ev, $d = 1.6$ cm, and $M = 2.33 \times 10^{-24}$ g (we assume that the ions are H_2^+). This gives a value for j of about 2 a/cm^2. At this current density, Curve 3 of Fig. 4 already shows a noticeable rise in the running voltage. Thus, the rise in running voltage with increasing current density in a hydrogen discharge can be due either to a rarefaction of the gas caused by heating of the electrodes, or to distortion of the field under the influence of the ionic space charge.

A dc high-voltage discharge does not turn into an arc until the discharge current reaches 1 ampere. In pulsed discharges, transition to the arc occurs for currents of 1000 ampere only at pressures above 0.2 mm Hg. At lower hydrogen pressures, transition to the arc does not occur until the total discharge current is above 1000 amperes ($j \geq 20$ a/cm^2). This result indicates that the high voltage form of discharge can be supported for short periods of time without going over into an arc, at extremely high current densities, probably considerably in excess of 100 a/cm^2.

For a comparison of the nature of discharge effects on the left- and right-hand branches of the

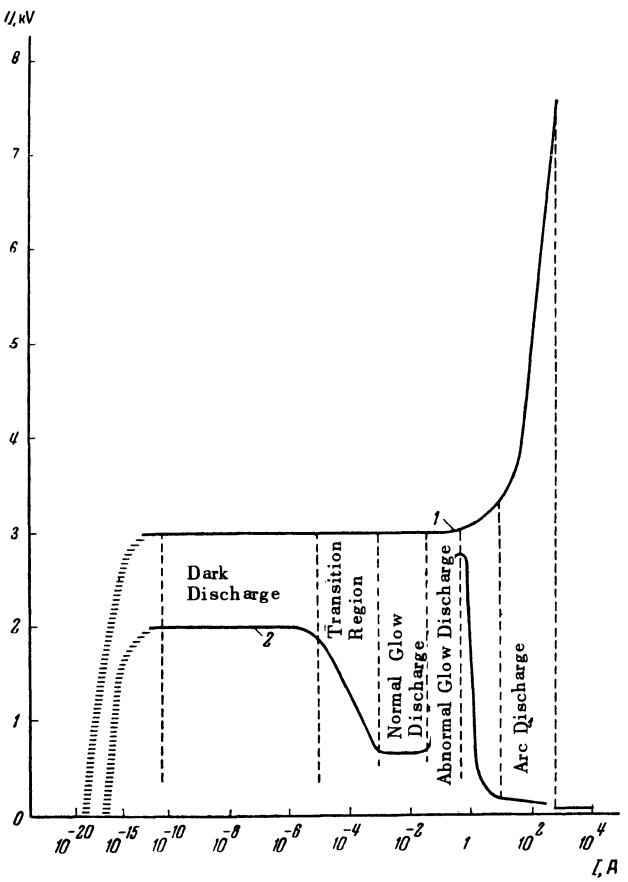

FIG. 6. Schematic form of the current-voltage characteristics of a discharge: 1—for $pd < pd_{min}$; 2— for $pd > pd_{min}$ (after Druyvesteyn and Penning[18]).

Paschen curve, Fig. 6 shows schematically the current-voltage characteristics of a high-voltage discharge (Curve 1) and a discharge on the right-hand branch (Curve 2); the latter curve is borrowed from a well-known survey article[18]. For convenience of comparison, the ordinates of Curve 2 have been increased by ten times. The curves of Fig. 6 demonstrate the relative simplicity of the effects on the left-hand branch of the Paschen curve. The constant potential difference across the discharge agrees very well with Townsend's assumption that the ignition of the discharge is a process in which the current goes to infinity when the voltage on the electrodes exceeds a certain value—the striking voltage.

The high-voltage form of discharge, characterized by voltages in kilovolts or even tens of kilovolts, and a current density up to tens of amperes per cm^2, undoubtedly deserves detailed study, not only in the steady but also in the dynamic state. This form of discharge, at low current densities, was used a great deal in former years, when such discharges were the only source of electron and positive-ion beams with energies of several tens of kilovolts. Methods have recently been sought for obtaining high temperatures with the aid of super-powerful discharges[19,20]. The high-voltage form of discharge appears to be the first stage in the development of a super-powerful discharge of this type, in which the cross-section area of the discharge is still uniformly filled with current.

In conclusion, the authors wish to express their thanks to N. G. Kashnikov and T. B. Fogel'son for valuable critical comment.

[1] W. Boyle and P. Kisliuk, Phys. Rev. 97, 255 (1955).

[2] E. Finkelmann, Arch. Elektrotech. 31, 282 (1937).

[3] J. Slepian and R. Mason, J. Appl. Phys. 8, 618 (1937).

[4] R. Quinn, Phys. Rev. 55, 482 (1939).

[5] A. Dikidzhi and B. Kliarfel'd, J. Tech. Phys. (U.S.S.R.) 25, 1038 (1955).

[6] L. Guseva and B. Kliarfel'd, J. Tech. Phys. (U.S.S.R.) 24, 1170 (1954).

[7] A. Pokrovskaia, J. Tech. Phys. (U.S.S.R.) 21, 617 (1951).

[8] Simons, Fontana, Muschlitz, and Jackson, J. Chem. Phys. 11, 307 (1943).

[10] R. Holzer, Phys. Rev. 36, 1204 (1940).

[11] H. Newhall, Phys. Rev. 62, 11 (1942).

[12] R. Murray, J. Appl. Phys. 23, 6 (1952).

[13] H. Massey and E. Burhop, *Electronic and Ionic Impact Phenomena*, Oxford, (1952).

[14] V. Tel'kovskii, Dokl. Akad. Nauk SSSR, 108, 444 (1956).

[15] N. Fedorenko, J. Tech. Phys. (U.S.S.R.) 24, 769 (1954).

[16] Webster, Van de Graaff, Trump, J. Appl. Phys. 23, 264 (1952).

[17] H. Bourne, Doctoral thesis, Electrical Engineering, Mass. Inst. of Technology, (1952).

[18] M. Druyvesteyn and F. Penning, Rev. Mod. Phys. 12, 89 (1940).

[19] Artsimovich, Andrianov, Bazilevskaia, Prokhorov, and Filippov, Atomnaia Energiia (U.S.S.R.) No. 3, 76 (1956).

[29] M. Leontovich and S. Osovets, Atomnaia Energiia (U.S.S.R.) No 3, 81 (1956).

Translated by D. C. West
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