SOVIET PHYSICS JETP VOLUME 28, NUMBER 2 FEBRUARY 1969

EXPERIMENTAL INVESTIGATION OF STREAMER DISCHARGE DEVELOPMENT IN NEON

V. A. DAVIDENKO, B. A. DOLGOSHEIN, and S. V. SOMOV

Moscow Engineering-Physics Institute

Submitted February 26, 1968

Zh. Eksp. Teor. Fiz. 55, 435–442 (August, 1968)

An image converter has been used to study the development of an electrical discharge in pure neon and in neon with a molecular impurity. We have measured the rate of development of direct and reverse streamers as a function of the electric field strength and streamer length. Possible mechanisms of photoionization of the gas are discussed.

As is well known, the breakdown of large interelectrode gaps at gas pressures near atmospheric is satisfactorily described by the streamer theory of spark breakdown development by Meek,[1] Raether,[2] and Loeb[3] on the basis of a generalization of extensive experimental data. A number of experimental and theoretical studies which have appeared in recent years have introduced important changes in our understanding of the processes occurring in electrical breakdown in a gas. References 4–6 discuss possible causes of the experimentally observed[4,5] departure from the one-shower streamer mechanism for discharge development times $\leq 10^{-8}$ sec. In an electron-optical study of the velocity of a streamer moving toward the cathode,[7] two stages have been observed in its development; Wagner considers that photoionization at the cathode is necessary to explain the existence of the two stages. In addition to the detailed discussion by Stankevich[6] of the photorecombination process in the shower as the main source of photons ionizing the gas in streamer breakdown of a molecular gas, Lozanskiĭ[8] has suggested a new mechanism of photoionization in a pure noble gas.

Interest in a detailed study of the development of the streamer discharge in neon is dictated by the following considerations.

The development of the technology of spark chambers[9] which can be used for charged-particle detection and which are filled in most cases with neon makes it necessary to know the characteristics of the streamer discharge occurring in the interelectrode gap of the chamber.

It is known that a streamer being propagated toward the cathode can arise only as the result of ionization of the gas by photons emitted by a shower. In molecular gases the main source of ionizing photons is clearly photorecombination to the ground level. Since the cross section for photorecombination depends strongly electron energy,[10] the number of photons necessary for ionization of the gas in the direction of the streamer motion is obtained only on equalization of the electron and ion temperatures in the shower.[6] The time of equalization of the electron and ion temperatures (the thermalization time) may be the cause of the delay, noted by Stankevich,[6] in development of a streamer moving toward the cathode. In a pure noble gas, photorecombination does not provide a sufficient quantity of photons ionizing the gas, since the thermalization time of electrons in a noble gas is considerably greater than the discharge development time (for example, in neon the thermalization time is 1.27 μsec[11]). Thus, a streamer discharge in neon may have some features related to the specific photoionization mechanism in pure noble gases.

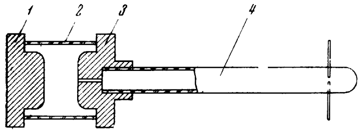

FIG. 1. Design of discharge chamber: 1, 3–electrodes, 2–glass tube, 4–illumination source.

The present work is a study of the initial stages of streamer breakdown in neon by means of high-speed photography and image converters.

DETERMINATION OF THE VELOCITY AND DIRECTION OF DEVELOPMENT OF A DISCHARGE ARISING FROM INDIVIDUAL ELECTRONS IN THE CENTER OF THE DISCHARGE GAP

To observe the initial stages of development of an electrical discharge arising from individual electrons in the center of the discharge gap, we used the technique described in detail by us in Ref. 12. The experimental apparatus consisted of a discharge chamber, a type PIM-3 electronic shutter in combination with an image amplifier with a gain of $\sim 10^7$, and an electronic circuit for control of the chamber and the image amplifier.

The design of the chamber, which is shown schematically in Fig. 1, does not differ in principle from the discharge chambers usually used for study of discharge development.[2–4] The chamber consists of a section of cylindrical glass tubing 2 and two flat brass electrodes 1 and 3. Through an opening in the center of one of the electrodes 3 the opposite electrode 1 is illuminated by a pulse of ultraviolet light from an electrical discharge between auxiliary electrodes 4. The electrons ejected from the brass electrode of the chamber by the pulse of ultraviolet light drift in a small constant electric field (~20 V/cm) applied to the chamber electrodes. The delay time in supplying the high-voltage pulse to the electrodes, relative to the flash of ultraviolet light, is chosen so that the transition of the shower to a streamer

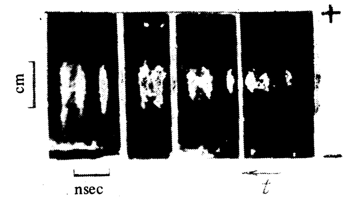

FIG. 2. Development of electrical discharge in neon as a function of time t.

occurs at the time when the head of the shower reaches the center of the discharge gap. The high-voltage pulse supplied to the chamber electrodes had a rise time of ~ 7 nsec and a flat top.

In order to observe on the image amplifier screen several successive stages of the discharge developing in the chamber, several images of the same discharge are projected on the photocathode of the PIM-3 electronic shutter and the shutter control is arranged so that the images are exposed successively with a shift of 0.5–1 nsec with an exposure of ~ 1.5 nsec.[12] The characteristic pattern of the images obtained in this way on the image amplifier screen is shown in Fig. 2. Here are pictured several successive stages in time of the development of an electrical discharge in neon. The apparatus described was used to measure the dependence of the velocity of propagation of direct (moving in the direction of the electron shower toward the positive electrode) and reverse (moving toward the negative electrode) streamers as a function of streamer length and of electric-field intensity.

The experimental results are presented in Figs. 3 and 4. The data obtained allow us to draw the following conclusions on the nature of the development of the initial stages of the electrical discharge in neon.

1. The development of the discharge in neon occurs in such a way that the place of origin of the discharge cannot be distinguished—the streamer plasma is uniform along the length.

2. As follows also from streamer theory, starting from a definite moment of time, the discharge develops in two directions—to the positive and negative electrodes of the chamber.

3. The velocities of propagation of the direct (v^+) and reverse (v^-) streamers increase monotonically with increasing streamer length l.

4. The dependence of the velocities of the direct and reverse streamers, and also the combined streamer velocity, on the electric-field strength E has a shape similar to that shown in Fig. 4, over the entire range of streamer lengths investigated by us. It is evident from Fig. 4 that, depending on the electric-field strength, the velocity of the reverse streamer can be either greater or less than the velocity of the direct streamer.

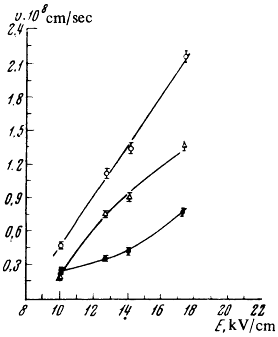

FIG. 4. Velocities of direct and reverse streamers of length 4.5 mm as a function of electric-field intensity: ●—direct streamer velocity, Δ—reverse streamer velocity, O—combined velocity.

5. In the region E = 9.5–10 kV/cm the velocities of the direct and reverse streamers are equal. It is interesting to note that this field-strength value, at which the direct and reverse streamer velocities are the same, does not change as the total streamer length varies from 3.5 to 7 mm.

MEASUREMENT OF THE RATE OF DEVELOPMENT OF A DISCHARGE ORIGINATING IN A PARTICLE TRACK

The nature of the streamer-discharge development may be different for different configurations of the electron groups in which the discharge originates. In this sense an event in which the electrons are knocked out of a chamber electrode and subsequently transported to a given place may differ from an event in which the electron groups are produced by a charged particle passing through the chamber. In order to investigate the applicability of the preceding measurements to the case of development of a discharge in a particle track, we made measurements of the combined propagation velocities of the direct and reverse streamers in a discharge chamber in which the discharge developed in the track of a relativistic electron (with energy 1.3 MeV $\leq E_e < 2.26$ MeV) from an $Sr^{90}(Y)$ source.

A diagram of the experimental apparatus is shown in Fig. 5. The discharge chamber of dimensions 15 × 10 × 3 cm had glass side walls and metal upper and lower electrodes. The construction of the electrodes allowed electrons to pass through the electrodes at an angle of

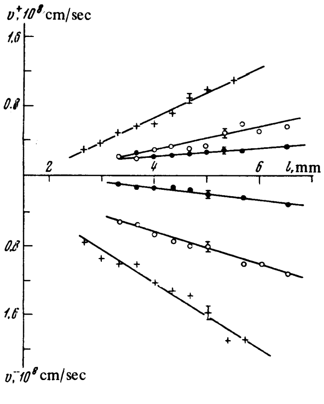

FIG. 3. Velocities of the direct streamer (v^+) and reverse streamer (v^-) as a function of streamer length l for different electric-field intensities E: ●—E = 9.6, O—E = 12.1, +—E = 16.7 kV/cm.

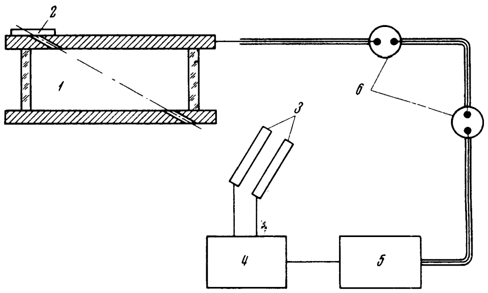

FIG. 5. Diagram of experimental setup: 1—discharge chamber, 2—source, 3—scintillation counters, 4—coincidence circuit, 5—high-voltage pulse generator, 6—peaking spark gaps.

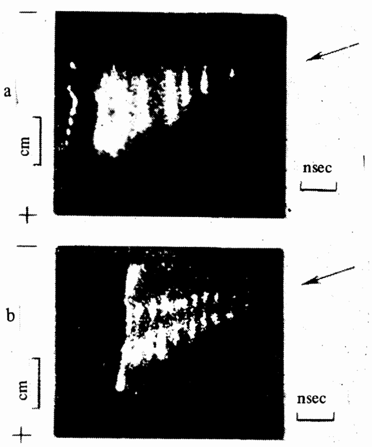

FIG. 6. Development of a discharge as a function of time in a particle track, a—in pure neon, b—in neon with alcohol-vapor impurity. The arrow indicates the direction of flight of the particle through the chamber.

76° to the electric field direction. A scintillation counter telescope controlled the high-voltage pulse generator (PG), which consisted of sections of coaxial lines connected in an Arkad'ev–Marx circuit. The PG produced in a 75-ohm load a voltage pulse of rectangular form up to 60 kV high. To reduce the rise time of the pulse from 20 to 1.5 nsec, two "peaking" spark gaps in 10 atm of nitrogen were connected to the coaxial cable in the path of the pulse along the cable. In this case the rise time of the pulse at the chamber electrodes was 3 nsec.

The image of a discharge originating in a particle track was projected on the photocathode of an image converter tube equipped with a PIM-3 electronic shutter. The electronic shutter provided continuous, successive exposure of portions of the track by means similar to that described by us previously.[12] Figure 6 shows a characteristic pattern of discharge development in a particle track, photographed by this means.

This method was used to investigate the dependence of the combined velocity of the direct and reverse streamers on electric-field intensity E. Comparison of the results obtained with the previously measured dependence of combined velocity on E for a discharge initiated by an ultraviolet light shows that in the field-strength range from 8 to 13 kV/cm the combined velocity is the same for the two means of initiation of the discharge (see Fig. 7). Thus, the experimental measurements presented in Fig. 3 of the velocities of the direct and reverse streamers are applicable to the operation of a streamer chamber filled with neon.

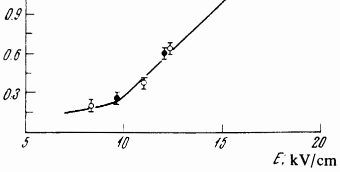

FIG. 7. Combined velocity of direct and reverse streamers for a length of 3 mm as a function of electric-field intensity: ●—in a chamber with ultraviolet illumination, ○—in a chamber with a radioactive source.

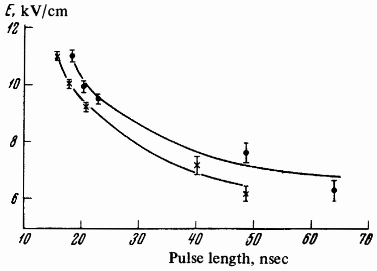

FIG. 8. Breakdown time of a 35-mm gap as a function of electric-field intensity; ●—pure neon, X—neon with alcohol-vapor impurity.

BREAKDOWN IN NEON IN THE PRESENCE OF IMPURITIES

The presence of a molecular impurity in the neon can lead to the following effects:

a) The electron mobility increases substantially as the result of decrease of the average energy of the electrons by inelastic collisions with impurity molecules.[13]

b) The Townsend ionization coefficient decreases as the result of inelastic collisions with impurity molecules; this should reduce the rate of growth of the shower.

c) In some cases (for example, in the case of addition of water, alcohol, or epoxy-resin vapors) the electron diffusion coefficient decreases markedly (by factors of ten).[14, 15]

d) In the case when the ionization potential of the mixture is less than the energy of the photons emitted by the excited atoms and molecules of the noble gas, the probability of photoionization is increased in comparison with the pure noble gas. Therefore the shower-streamer transition should begin at a lower concentration of charge in the shower head in the presence of the impurity, and the development of the streamers may be more rapid.[7]

e) The spectrum and intensity of the radiation of the discharge plasma may change appreciably as the result of radiationless quenching of the excited atoms and ions of the noble gas in collisions with impurity molecules and as the result of change in the electron temperature in the plasma of the shower and streamer.

We have studied the discharge in neon with impurities of saturated vapors of epoxy resin and alcohol at room temperature. The discharge arose in the track of a charged particle traveling at an angle of 76° to the electric-field direction. The results of the measurements are shown in Fig. 8 and in the table, and reduce to the following.

1. The presence of the impurity leads to a characteristic distinguishing of the place of origin of the discharge. In the case of epoxy-resin and alcohol impurities this place looks like a dark gap separating the direct and reverse streamers (a strong variation in the intensity of radiation in the shower, see Fig. 6b). A similar occurrence is observed in many of the investigations of streamer chambers,[9, 16–18] the particle track appearing symmetric with respect to the dark gap—the

Chamber filling	E, kV/cm	l, mm	v, 10^8 cm/sec	Length of dark gap, L, mm
Pure neon	10.7	9.1	1.75±0.03	0
Neon with alcohol vapor	10.7	9.1	1.87±0.05	2.5±0,3
	17.8	9.1	—	0.94±0.14

lengths of the direct and reverse streamers are identical. The existence of this gap apparently indicates contamination of the chamber gas, and the symmetric nature of the track can be explained by the fact that the effective field intensity does not exceed 10–11 kV/cm (see Fig. 3). The length of the dark gap decreases with increasing electric-field intensity (see the table). The streamer brightness also decreases considerably, particularly in the case of alcohol-vapor admixture.

2. If we assume that the length of the dark gap corresponds to the critical size of the shower d_{cr} at the moment of transition to a streamer, and if we assume that the Townsend ionization coefficient α is substantially less in the case of the impurity than in the case of pure neon ($\alpha < \alpha_{Ne}$), then we obtain from the data of the table

$$\alpha d_{cr} < 20,$$

i.e., the shower-streamer transition occurs at a smaller charge concentration in the shower head than in the case of pure neon.

3. It follows from Fig. 8 that, in spite of the decrease in the Townsend coefficient, breakdown of a gap 35 mm long occurs more rapidly in the case of neon with an impurity than in pure neon. This phenomenon can be understood if we consider the acceleration of the shower-streamer transition (see Point 2) and some degree of increase in streamer velocity (see the table) in the presence of an impurity.

DISCUSSION OF RESULTS

The experimental data obtained indicate that the streamer mechanism of breakdown exists in pure neon. Consequently, there exists a photoionization mechanism not connected either with the ionization of the impurity by radiation from the excited atoms of the main gas or with photorecombination, since, as we have noted above, photorecombination is retarded in a discharge in pure neon. For development of the reverse streamer it is necessary to have photoionization of the gas at a distance of the order of the shower length in the direction of motion of the streamer. Lozanskiĭ[8] has shown that such ionization can be provided as the result of formation of a molecular ion in collision of an excited atom with a neutral atom:

$$X^* + X \rightarrow X_2^+ + e.$$

Since the cross section for this reaction is large ($\sigma \sim 10^{-15}$ cm^2 [19]) at pressures near atmospheric, ionization occurs practically instantaneously (in a time of 10^{-10} sec). The occurrence of excited noble gas atoms producing the above reaction rather far from the shower cannot be due to diffusion of resonance radiation, since the time of diffusion of resonance radiation in neon to a distance of the order of a millimeter is hundreds of nanoseconds.[20] As has been shown by Lozanskiĭ[8] excitation of atoms at a large distance from the shower can occur because photons with a rather high penetrating power appear in the shower as the result of broadening of the excitation levels by atomic collisions.

The linear dependence obtained by us for the velocity of the reverse streamer as a function of its length is in good agreement with the discharge mechanism proposed by Lozanskiĭ.[8] On the other hand, the existence of two stages in the development of the reverse streamer observed by Wagner[7] apparently indicates different photoionization mechanisms in neon and nitrogen.

The authors are grateful to V. Boĭtsov and R. Krasnokutskiĭ for major assistance in this work.

---

[1] J. M. Meek, Phys. Rev. **57**, 722 (1940).

[2] H. Raether, Arch. Elektrotech. **34**, 49 (1940).

[3] L. Loeb, Fundamental Processes of Electrical Discharges in Gases, Wiley, New York, 1939; Russ. transl. Gostekhizdat, 1950.

[4] Yu. E. Nesterikhin, V. S. Komel'kov, and E. Z. Meĭlikhov, Zh. Tekh. Fiz. **34**, 40 (1964) [Sov. Phys.-Tech. Phys. **9**, 29 (1964)].

[5] V. V. Vorob'ev and A. M. Iskol'dskiĭ, Zh. Tekh. Fiz. **36**, 2095 (1966) [Sov. Phys.-Tech. Phys. **11**, 1560 (1967)].

[6] Yu. L. Stankevich, Doklad na Vsesoyuznoĭ mezhvuzovskoĭ konferentsii po voprosam sozdaniya i metodam ispytaniĭ vysokovol'tnoĭ fizicheskoĭ apparatury (Report at the All-Union Interuniversity Conference on the Design and Testing of High Voltage Apparatus for Physics), Tomsk, 1967.

[7] K. H. Wagner, Z. Physik **189**, 466 (1966).

[8] É. D. Lozanskiĭ, Zh. Tekh. Fiz. **38**, No. 12 (December, 1968) [Sov. Phys.-Tech. Phys. **13**, No. 12 (June, 1969)].

[9] M. I. Daĭon, B. A. Dolgoshein, V. I. Efremenko, G. A. Leksin, and V. A. Lyubimov, Iskrovaya kamera (The Spark Chamber), Atomizdat, 1967.

[10] Ya. B. Zel'dovich and Yu. P. Raĭzer, Fizika udarnykh voln i vysokotemperaturnykh gidrodinamicheskikh yavleniĭ (Physics of Shock Waves and High Temperature Hydrodynamic Phenomena), Nauka, 1966.

[11] V. A. Davidenko, B. A. Dolgoshein, and S. V. Somov, Prib. Teckh. Éksp. No. 4, (1968).

[12] V. A. Davidenko, B. A. Dolgoshein, and S. V. Somov, Prib. Tekh. Éksp., No. 1, 167 (1967).

[13] B. Rossi and H. Staub, Ionization Chambers and Counters, New York, McGraw-Hill, 1949; Russ transl., IIL, 1951.

[14] A. D. Vinogradov, N. G. Vlasov, L. P. Kotenko, and G. I. Merzon, Iskrovaya kamera, napolnennaya neonom s dobavkami parov spirta i vody (A Spark Chamber Filled with Neon with Addition of Alcohol and Water Vapor), Preprint, Physics Institute, Academy of Sciences, USSR, 1966.

[15] V. A. Davidenko, B. A. Dolgoshein, V. K. Semenov, and S. V. Somov, Zh. Éksp. Teor. Fiz. **55**, 426 (1968) [this issue, p. 223] (preceding article).

[16] G. E. Chikovani, V. N. Roĭnishvili, and V. A. Mikhaĭlov, Zh. Éksp. Teor. Fiz. **46**, 1228 (1964) [Sov. Phys.-JETP **19**, 833 (1964)].

[17] B. A. Dolgoshein, B. I. Luchkov, and B. U. Rodionov, Zh. Éksp. Teor. Fiz. **46**, 1953 (1964) [Sov. Phys.-JETP **19**, 1315 (1964)].

[18] T. L. Asatiani, K. A. Gazaryan, V. P. Zhmirov, E. M. Matevosyan, A. A. Nazaryan, and R. O. Sharkhatunyan, JINR Preprint, E-2324, Dubna, 1965.

[19] W. Kaul, P. Seyfried, and R. Taubert, Z. Naturforsch. **18a**, 432 (1963).

[20] A. V. Phelps, Phys. Rev. **114**, 1011 (1959).

Translated by C. S. Robinson
51