STUDY OF ELECTRON COLLISIONS IN NOBLE GASES BY MEANS OF A STREAMER CHAMBER

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Submitted February 3, 1969

Zh. Eksp. Teor. Fiz. 57, 84–91 (July, 1969)

A discussion is presented of the thermalization of electrons in the track of an ionizing particle in noble gases, and also of the effect of a molecular impurity on the processes of thermalization and thermal diffusion of electrons. The cross section for attachment of electrons to H_2O molecules in the thermal region has been determined: $\sigma_{att} = (7.5 \pm 0.6) \times 10^{-21}$ cm^2.

THE possibility of studying the behavior of individual electrons arising in the track of a charged particle makes the streamer chamber a convenient device for investigation of electron collision processes in gases.[1] We will discuss some of the possible applications of the streamer chamber in this region of experimental physics.

1. STUDY OF THE SLOWING DOWN (THERMALIZATION) OF ELECTRONS IN A GAS

The thermalization of electrons produced by a charged particle in the chamber gas can be studied by measuring the time dependence of the mean-square deviation of streamers in the track. The mean-square deviation σ can be represented in the form

$$\sigma = [\sigma_\tau^2 + \sigma_D^2]^{1/2}, \tag{1}$$

where σ_τ is the mean-square deviation of an electron in the thermalization process, and σ_D is the deviation of the electron after thermalization as the result of thermal diffusion. By measuring the dependence of σ on time t for $t \leq t_\tau$, where t_τ is the thermalization time, we can study the electron thermalization process as a function of time.

The energy spectrum of the electrons in a particle track in the chamber is unknown, and therefore in comparison of experiment and theory there is some arbitrariness associated with the choice, necessary for the calculation, of the average energy from which the slowing down of the electrons to thermal energy begins. However, it is evident that this energy must be below the first excitation potential of the atoms, since electrons having an energy above the excitation potential rapidly lose it in inelastic collisions with atoms and are unable to contribute appreciably to σ_τ. Therefore, in calculation of the thermalization we will take the average electron energy to be less than the first excitation level of the atoms and will thereby consider only elastic collisions of electrons with atoms.

The number of collisions with atoms in which an electron with energy E loses a part of its energy equal to dE is

$$dn = dE / \varepsilon, \tag{2}$$

where ϵ is the average energy lost by the electron in one collision with an atom. This energy loss (dE) occurs in a time

$$dt = \frac{\lambda}{\bar{v}} dn, \tag{3}$$

where λ is the electron mean free path and v is its average velocity. During this time the mean-square displacement of the electron in the track will amount to

$$d\sigma = (^2/_3 \lambda^2 dn)^{1/2}. \tag{4}$$

From Eqs. (2) and (3) we can write the time of slowing down of the electron from E_0 to E in the form

$$t_\tau = \int_{E_0}^{E} \frac{\lambda}{\bar{v}\varepsilon} dE, \tag{5}$$

and the mean-square displacement of the electron during this time

$$\sigma_\tau = \left[\int_{E_0}^{E} \frac{2}{3} \lambda^2 \frac{dE}{\varepsilon} \right]^{1/2}. \tag{6}$$

The average energy ϵ lost by the electron in a single elastic collision, which enters into Eqs. (2), (5), and (6), is determined by the well known relation (see ref. 2)

$$\varepsilon = \frac{2m}{M}(E - E_T)\frac{\lambda}{\lambda_d}, \tag{7}$$

where m is the electron mass, M is the mass of the atom, E_T is the energy of thermal motion, and λ_d is the momentum transfer length.

We have used formulas (5) and (6) to calculate the functions σ_τ^2 and t_τ in He, Ne, and Xe. It can be shown that, on thermalization of the electrons (slowing down to thermal energy), the main contributions to the mean-square deviation and the thermalization time are obtained in slowing down from an energy of 10 eV for He and Ne, and 3 eV for Xe. Therefore, in calculation of the thermalization time and σ_τ^2 the average electron energy was assumed to be 10 eV in the case of He and Ne, and 3 eV in the case of Xe.

Table I lists the calculated values of thermalization time and mean-square deviation of electrons in the particle track during the thermalization time. In the same table we have also listed the theoretical results obtained by Braglia et al.[3]

On the basis of the data presented in Figs. 1, 2, and 3, and also taking into account the fact that σ_D in

Table I. Values of mean square deviation σ_τ and thermalization time t in different gases (E_0 is the electron energy from which the slowing down begins)

Gas	E_0, eV	P, mm Hg	T, °K	σ_τ, mm	t_τ	References
Ne	10	608	293	2.16	5 μsec	Present work
					1.8 μsec	[3]
Xe	3	38	293	19.6	38 μsec	Present work
	4				33.7 μsec	[3]
He	10	456	293	0.17	190 nsec	Present work
					62.4 nsec	[3]
H_2O	2	1		0.6	8.4 nsec	Present work
N_2O	2	1		1.4	16 nsec	Present work
N_2	2	1		18	4 μsec	Present work

*In ref. 3 the authors do not take into account the thermal motion of the noble-gas atom. Inclusion of this effect greatly increases the thermalization time. This explains the difference in our results from those of Braglia et al.

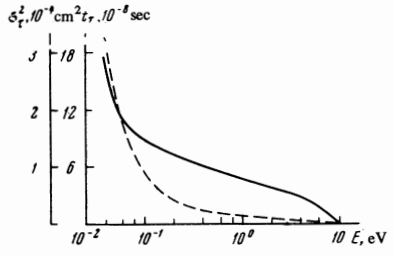


FIG. 1. Time of slowing down t_τ (dashed line) and mean square deviation σ_τ^2 (solid line), as a function of energy of an electron slowing down in He; p = 0.6 atm.

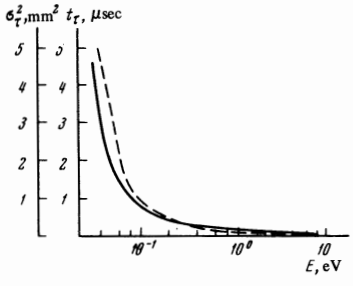


FIG. 2. Slowing down time t_τ (dashed line) and mean square deviation σ_τ^2 (solid line), as a function of energy of an electron slowing down in Ne; p = 0.8 atm.

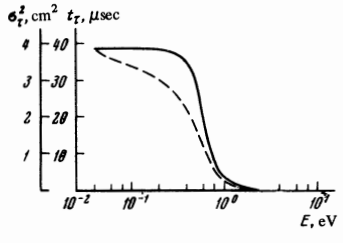


FIG. 3. Slowing down time t_τ (dashed line) and mean square deviation σ_τ^2 (solid line), as a function of energy of an electron slowing down in Xe; p = 38 mm Hg.

formula (1) is $\sigma_D = \sqrt{2Dt'}$ (where D is the diffusion coefficient of a thermal electron and t′ is the time measured from the moment when the electron became thermal), we can obtain σ as a function of time. This

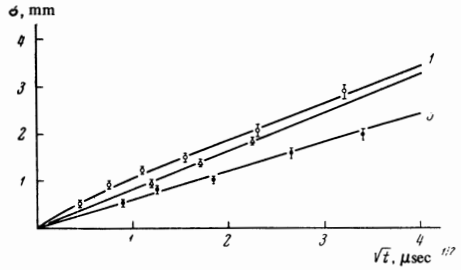
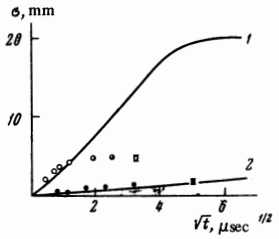


FIG. 4. Mean square deviation of streamers in a particle track, as a function of high-voltage pulse delay time. Curve 1—calculation taking into account electron thermalization. The experimental points were obtained in specially purified Ne; [5] p = 0.8 atm. Curve 2—calculation based on the cross section for momentum transfer [13] for thermal electrons. The experimental points were obtained in Ne with N_2O impurity (see the text). Curve 3 was obtained in our earlier work [1] with technically pure Ne.

FIG. 5. Mean square deviation of streamers in a particle track, as a function of high-voltage pulse delay time. Curve 1—calculation taking into account electron thermalization. The experimental points were obtained in specially purified Xe; [5] p = 38 mm Hg. Curve 2—calculation based on the cross section for momentum transfer [5] for thermal electrons. The experimental points were obtained in Xe with N_2O impurity (see the text).



function is shown in Figs. 4 and 5 for Ne and Xe.

Figures 4 and 5 also show the values of $\sigma = f(\sqrt{t_d})$ (t_d is the high-voltage pulse delay time) measured in a streamer chamber filled with specially purified[5] Ne and Xe to the pressures listed in Table I. The experimental apparatus in which these measurements were made has been described in detail by us previously.[1]

From comparison of the experimental data with the theory it is evident that the experimental results are in good agreement with the calculations in the case of Ne and disagree strongly for the case of a xenon-filled chamber. Since the theoretical values of σ for the case of Xe are greater than the measured values, this indicates the existence of factors leading to a faster electron thermalization than predicted by theory. Such a

factor could be a low concentration of noble-gas molecules.[4,6,7] In fact, the energy loss by electrons in the thermalization process per unit time is

$$\frac{dE}{dt} = \varepsilon\nu + \varepsilon_M\nu_M, \tag{8}$$

where ϵ and ϵ_M are the average energies lost by an electron in a collision with an atom and with a molecule; $\nu = n\sigma_1 v$ and $\nu_M = n_M\sigma_M v$ are the frequencies of collisions of an electron with an atom and with a molecule; n and n_M are the concentrations of atoms and molecules, v is the average electron velocity, σ_1 and σ_M are the cross sections for elastic collision of an electron with an atom and with a molecule.

Since $\epsilon \ll \epsilon_M$, it is clear that a negligibly small concentration of Xe_2 molecules ($\sim 3\times 10^{-3}\%$ for the case of Xe[6,7]) is sufficient to strongly affect the electron thermalization process.

In the case of Ne the role of molecules and the thermalization process should be considerably smaller ($\epsilon/n\sigma_1 \gg \epsilon_M/n_M\sigma_M$) for the following reasons: 1) because of the smaller concentration of Ne_2 molecules in the main gas[4,6]; 2) because $\epsilon_M(Xe_2) > \epsilon_M(Ne_2)$, since the binding energy of the Xe_2 molecule is greater than that of the Ne_2 molecule[6]; 3) because $\epsilon(Ne) > \epsilon(Xe)$, since $M(Ne) < M(Xe)$ (see formula (7)).

2. INVESTIGATION OF EFFECT OF MOLECULAR IMPURITIES ON ELECTRON DIFFUSION IN NOBLE GASES

The effect of a molecular impurity on the diffusion of electrons in a noble gas can appear as follows: a) The presence of low lying excitation levels of the impurity molecules leads to a rapid thermalization of the electrons, as a result of which the diffusion of the electrons during thermalization decreases; b) because the electron collision cross section for some molecular impurities in the thermal region is large, addition of such an impurity to a noble gas can substantially reduce the electron diffusion at thermal energies.[8]

Let us consider these phenomena in more detail.

1. Effect of a Molecular Impurity on Electron Thermalization

The average relative energy loss ϵ of an electron in a collision can be evaluated from the formula[9]

$$\varepsilon = 2v_d^2/\bar{v}^2, \tag{9}$$

where v_d is the electron drift velocity in a uniform electric field of intensity E. The functions $v_d = f(E/p)$ and $v = f(E/p)$ have been determined experimentally by several workers.[10,11] Thus, using formulas (4)–(6), we can easily find the slowing down time and σ_T^2 as a function of the energy of the electron being slowed down in the gas. Figure 6 shows this dependence in H_2O, N_2O, and N_2. The results of the calculation are given in Table I.

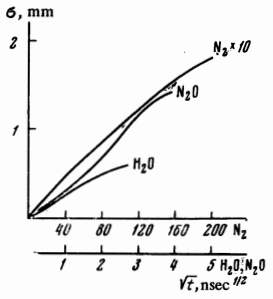


FIG. 6. Mean square deviation of electrons with time in molecular gases; p = 1 mm Hg.

Thus, addition of an insignificant concentration of N_2O or H_2O impurity to a noble gas can reduce considerably the electron thermalization time; this concentration can be chosen such that its effect on the thermal diffusion of electrons can be neglected. We will illustrate this in the case of measurement of electron thermal diffusion coefficients in streamer chambers filled with neon and xenon.

The thermal electron diffusion coefficient of a mixture of two gases is given by the formula

$$D = \frac{1}{3}\frac{v}{n_1\sigma_1 + n_2\sigma_2}, \tag{10}$$

where n_1 and n_2 are the concentrations of the gases, σ_1 and σ_2 are the cross sections for momentum transfer of electrons in collisions with atoms and molecules, respectively.[12-15] In our case, addition of N_2O impurity in the amount of 0.5 mm Hg in Ne and 4 mm Hg in Xe is sufficient to reduce the thermalization time in Ne to 80 nsec and Xe to 10 nsec. In both cases $n_2\sigma_2 \ll n_1\sigma_1$ and, consequently, the effect of the impurity on thermal diffusion of electrons can be neglected. Under these conditions we measured the thermal diffusion coefficients of electrons in Ne and Xe. The results of the measurements are presented in Figs. 4 and 5 and in Table II. In this table we have shown also the diffusion coefficients measured by other workers[16-22] and the results of calculations made on the basis of the measured cross sections for momentum transfer in scattering of electrons of thermal energies.[12-14] From comparison of the data in Table II, it is evident that the thermal electron dif-

Table II

Method	Gas	D, cm²/sec: Experiment	D, cm²/sec: Calculation from cross section for momentum transfer	References
Microwave	Ne	1500	3000 [13]	[16]
Discharge tube	»	1800±100	3000 [13]	[17]
Luminescence chamber	»	1670±50	3000 [13]	[18]
Luminescence chamber	»	2360±100	3000 [13]	[19]
Spark chamber	»	(7.9±0.6)·10³	3000 [13]	[8]
Streamer chamber	»	2000	3000 [13]	[20, 21]
Streamer chamber	»	(4.1±1.3)·10³	3000 [13]	[22]
Streamer chamber	Ne	3000±174	3000 [13]	Present work
Streamer chamber	He	312±14	280 [14]	[1]

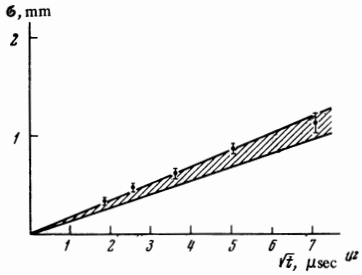


FIG. 7. Mean square deviation of streamers in a particle track in Ne (p = 0.8 atm) with impurity of saturated water vapor at t = 20°C, as a function of high-voltage pulse delay time. The marked region corresponds to a calculation taking into account the error in determination of the momentum-transfer cross section. [23]

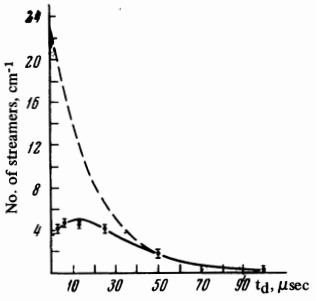


FIG. 8. Number of streamers per unit track length in Ne (p = 0.8 atm) with impurity of saturated water vapor at t = 20°C, as a function of high-voltage pulse delay time. The solid and dashed curves are calculations with and without inclusion of the effect of overlapping of the photographic images of the streamers in the particle track, for $\sigma_{att} = 7.5 \times 10^{-21}$ cm^2.

fusion coefficient obtained in the streamer chamber in Ne differs by a factor of 1.5 from the generally accepted value 2000 cm^2/sec,[1,20,21] which is calculated in the usual way from Ramsauer data for cross sections of elastic collisions of electrons with Ne atoms, extrapolated to the thermal energy region, and agrees with the results of recent work[12-14] on measurement of the cross sections for momentum transfer of electrons in the thermal region.

2. Effect of an Impurity on Electron Thermal Diffusion

The phenomenon of reduction in the diffusion coefficient by an impurity has been noted by Vinogradov et al.[8] This effect can be easily understood if we consider relation (10) (for the case $n_2\sigma_2 \gtrsim n_1\sigma_1$). We have measured in a streamer chamber the effect of water-vapor impurity on electron diffusion in Ne. The results of these measurements are shown in Fig. 7. The same figure shows the results of calculation of the mean square deviation of electrons in the track, obtained on the basis of Eq. (10) with inclusion of data taken from refs. 15 and 23 on the cross section for momentum transfer of electrons in collisions with water molecules. It can be seen from Fig. 7 that the decrease in the electron diffusion coefficient in Ne due to water vapor is explained by the large cross section for collision of electrons with water molecules ($\sigma \sim 7.5 \times 10^{-14}$ cm^2).

3. STUDY OF ELECTRON ATTACHMENT TO IMPURITY MOLECULES

Since the presence of an impurity in the chamber gas leads to a very rapid thermalization of the electrons, as we have shown above, attachment during the thermalization process can be neglected, and the reduction in the number of streamers in the track of the particle with time characterizes the amount of electron attachment in the thermal energy region.

The decrease in the number of electrons with time as the result of attachment to impurity molecules is determined by the relation

$$n = n_0 e^{-t/\tau}, \qquad (11)$$

where n_0 is the number of electrons at the moment of their formation, τ is the attachment time constant, given by $\tau = N\sigma_{att}v$, N is the impurity concentration, and σ_{att} is the attachment cross section. Thus, by measuring the number of streamers in the track as a function of time, we can find τ and, consequently, the attachment cross section.

We have determined the cross section for attachment of electrons to water molecules. This was accomplished by measuring the number of streamers in the track as a function of time, in a chamber filled with neon with an impurity of saturated water vapor at 20°C. The results of these measurements are shown in Fig. 8. The solid curve in this figure corresponds to a calculation taking into account the overlapping of the photographic images of the streamers in the particle track. The data of Fig. 8 permit us to obtain the attachment cross section in water vapor for electrons in the thermal region, $\sigma_{att} = (7.5 \pm 0.6) \times 10^{-21}$ cm^2. This result is in good agreement with the value obtained by Takeda and Dougal.[23]

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

[1] V. A. Davidenko, B. A. Dolgoshein, V. K. Semenov, and S. V. Somov, Zh. Eksp. Teor. Fiz. 55, 426 (1968) [Sov. Phys. JETP 28, 223 (1969)].

[2] D. R. Bates, Atomic and Molecular Processes, New York, Academic Press, 1962 (Russ. Transl., Mir, 1964).

[3] G. L. Braglia, G. M. de'Munari, and G. Mambriani, Thermalization Times of Low Energy Electrons in Rare Gases, Commit. Naz. Energ. Nucl., RT/Fi (65)61, Rome, 1965.

[4] V. G. Fastovskiĭ, A. E. Rovinskiĭ, and Yu. V. Petrovskiĭ, Inertnye gazy (The Inert Gases), Atomizdat, 1964.

[5] V. A. Davidenko, B. A. Dolgoshein, and S. V. Somov, Zh. Eksp. Teor. Fiz. 56, 3 (1969) Sov. Phys. JETP 29, 1 (1969)].

[6] N. Bernardes and H. Primakoff, J. Chem. Phys. 30, 691 (1959).

[7] Shardanand, Phys. Rev. 160, 67 (1967).

[8] A. D. Vinogradov, I. G. Blasov, L. P. Kotenko, and G. I. Merzon, Iskrovaya kamera, napolnennaya neonom s dobavkoĭ parov spirta i vody (A Spark Chamber Filled with Neon with Addition of Alcohol and Water Vapor), Preprint FIAN, 1966. L. P. Kotenko, G. I. Merzon, A. D. Vinogradov, and N. G. Vlasov, Nucl. Instr. and Methods 54, 119 (1967).

[9] H. S. W. Massey and E. H. S. Burhop, Electronic and Ionic Impact Phenomena, Oxford University Press, 1952 (Russian Transl., IIL, 1958).

[10]R. H. Healy and J. W. Reed, The Behavior of Slow Electrons in Gases, Sydney, 1941.
[11]J. J. Lowke and J. A. Rees, Australian J. Phys. **16**, 447 (1963).
[12]E. W. McDaniel, Collision Phenomena in Ionized Gases, John Wiley and Sons, Inc., New York, 1964 (Russ. Transl., Mir, 1967).
[13]C. L. Chen, Phys. Rev. **135**, A627 (1964).
[14]G. L. Braglia, G. M. de'Munari, and G. Mambriani, Elastic Cross Sections of Low Energy Electrons in Rare Gases, Comit. Naz. Energ. Nucl. RT/Fi (65) 60, Rome, 1965.
[15]J. L. Pack, R. E. Voshall, and A. V. Phelps, Phys. Rev. **127**, 2084 (1962).
[16]S. L. Frost and A. V. Phelps, Phys. Rev. **127**, 1621 (1962).
[17]J. L. Lloyd, Proc. Phys. Soc. (London) **75**, 387 (1960).
[18]G. Cavalleri, E. Gatti, and P. Principi, Nuovo Cimento **31**, 318 (1964).
[19]G. Cavalleri, E. Gatti, and A. M. Interlenghi, Nuovo Cimento **B40**, 450 (1965).
[20]F. Bulos, A. Odian, F. Villa, and O. Yount, Streamer Chamber Development, Technical Report SLAC-74, UC-28, 1967.
[21]H. Raether, Electron Avalanches and Breakdown in Gases, Butterworths, London, 1964.
[22]G. E. Chikovani, V. N. Roĭnishvili, and V. A. Mikhaĭlov, Zh. Eksp. Teor. Fiz. **46**, 1228 (1964) [Sov. Phys. JETP **19**, 833 (1964)].
[23]S. Takeda and A. A. Dougal, J. Appl. Phys. **31**, 412 (1960).

Translated by C. S. Robinson
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