THE TOWNSEND IONIZATION COEFFICIENT FOR He WITH ALLOWANCE FOR INDIRECT IONIZATION

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Abstract

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THE TOWNSEND IONIZATION COEFFICIENT FOR He WITH ALLOWANCE FOR INDIRECT IONIZATION

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In paper $(^1)$ the following mechanism was proposed for the appearance of secondary electrons in streamer breakdown of gases in He. Resonance photons which, owing to the line shape, are shifted from the fundamental frequency propagate over large distances from the avalanche stem. He atoms excited by these photons, colliding with He atoms in the ground state, yield secondary electrons as a result of the reaction

$$\mathrm{He}(3'P) + \mathrm{He} = \mathrm{He}_2^+ + \bar{e}. \quad (1)$$

Since the cross section of the reaction is $\sigma_T \sim 10^{-15}$ cm^2 $(^2)$, it is natural to suppose that in He and in other gases in which reaction (1) proceeds with such large cross sections, it is precisely these processes, and not ionization by electrons, that play the principal role in the formation of ionization. An estimate shows $(^1)$ that at $E/p = 8$ V/cm $\cdot$ mm Hg the fraction of electrons supplied by process (1) is an order of magnitude greater than the fraction from direct ionization by electron impact.

Recently B. A. Dolgoshein et al. $(^3)$ investigated the ionization in He produced by the passage of a high-energy particle and found that it somewhat exceeds the calculated value $(^4)$. Since the calculation took account of the influence of impurities, the assumptions made above may serve to explain the appearance of the additional ionization. In this connection it is of interest to obtain the Townsend ionization coefficient α with allowance for process (1).

It should be noted that process (1) will contribute to the formation of electrons only in the case when the characteristic time of reaction (1), T, is less than the time T' required for a resonance photon to leave the discharge gap as a result of diffusion. However, in He, owing to the fact that the quenching level is not the first excited level, transitions to lower energy levels are also possible. Since the time of these transitions T'' is considerably less than T', it will be the characteristic quenching time of the $3'P$ level without the appearance of an electron. Consequently, process (1) begins to contribute to ionization under the condition

$$T < T'' \tag{2}$$

or

$$N > (T'' \bar{v} \sigma_T)^{-1}, \tag{2a}$$

where N is the number of atoms per unit volume; $\bar{v}$ is the mean velocity of He atoms. Substituting the parameter values into condition (2a), we have

$$N \gtrsim \frac{1}{10^{-7}\ \text{sec} \cdot 10^5\ \dfrac{\text{cm}}{\text{sec}} \cdot 10^{-15}\ \text{cm}^2} = 10^{17}\ \text{cm}^{-3}, \quad \text{i.e.} \quad p \gtrsim 10^{-2}\ \text{atm}.$$

Therefore results for the measurement of the ionization coefficient obtained at pressures below 10^{-2} atm cannot be extrapolated to higher pressures.

We proceed to consider the kinetic equation. The kinetic equation was written in (1, 5-7). For the region $v > v_p$, where v_p is the velocity corresponding to the onset of inelastic energy losses, it has the form

$$\frac{\partial f}{\partial t} + \gamma \left[\cos\theta \frac{\partial f}{\partial v} + \frac{1}{v} \sin^2\theta \frac{\partial f}{\partial(\cos\theta)} \right] =$$

$$= -\nu f + N v \int [f(v,\theta) - f(v,\theta')] \sigma(\alpha) \sin\alpha \, d\alpha. \tag{3}$$

Here $\gamma = eE/m$; E is the field strength; ν is the frequency of inelastic collisions. The first term on the right-hand side appears as a result of electrons being removed from the region $v > v_p$ after inelastic collisions.

Let us consider the stationary case. We shall seek the solution in the form

$$f(v,\theta) = f_0(v) + f_1(v)\cos\theta + ... \tag{4}$$

We multiply both sides by $P_i(\cos\theta)\sin\theta\, d\theta$, where $P_i(\cos\theta)$ is a Legendre polynomial, and integrate with respect to θ, restricting ourselves to the values $i = 0, 1$. Justifications for the possibility of such a restriction are given in (5-7).

After transformations we obtain the system

$$f_1' + \frac{2}{v} f_1 + \frac{3\nu}{\gamma} f_0 = 0; \tag{5}$$

$$\gamma f_0' = -\nu_{\text{y}} f_1. \tag{5a}$$

In (5a) we have neglected ν in comparison with ν_{y}, where ν_{y} is the frequency of elastic collisions.

For us the behavior of $\nu_{\text{y}}(v)$ and $\nu(v)$ is important only near $v = v_p$, since it is natural to assume that the distribution function decreases rapidly for $v > v_p$. From experiments on the angular scattering of electrons by He atoms (8, 9) it follows that, with a good degree of accuracy in this region, ν_{y} does not depend on velocity. Near v_p, ν can be approximated by the function

$$\nu = k\,(v - v_p), \tag{6}$$

where the value of k should be taken from experimental data (10).

After the assumptions made, one can find the solution of the system (5), (5a). It has the form ($\beta v_p^{3/2} \gg 1$)

$$f_0(v) = \frac{C}{v}\sqrt{v - v_p}\,K_{1/3}\left[\beta(v - v_p)^{3/2}\right]; \tag{7}$$

$$f_1(v) = -\frac{\gamma}{\nu_{\text{y}}} f_0'(v). \tag{7a}$$

Here $\beta = \frac{2}{3}(3\nu_{\text{y}} k / \gamma^2)^{1/2}$; $K_{1/3}(x)$ is a Macdonald function. The constant C must be determined from normalization.

In the region $v < v_p$ the kinetic equation has the form (stationary case)

$$\gamma\left[\cos\theta\frac{\partial\varphi}{\partial v} + \frac{1}{v}\sin^2\theta\frac{\partial\varphi}{\partial(\cos\theta)}\right] =$$

$$= Nv\int[\varphi(v,\theta) - \varphi(v,\theta')]\sigma(\alpha)\sin\alpha\, d\alpha + \nu(v_1) f(v_1). \tag{8}$$

Here

$$v_1^2 = v^2 + v_p^2. \tag{9}$$

The second term on the right-hand side appears as a result of the transition of electrons from the region $v > v_p$ after an inelastic collision.

Since $f(v)$ decreases rapidly for $v > v_p$, we can expand expression (9) in a series near v_p and restrict ourselves to two terms

$$v_1 = v_p + \frac{1}{2} v^2 / v_p. \tag{10}$$

Carrying out with equation (8) the same transformations as with (3), we obtain, taking (10) into account,

$$\varphi_1' + \frac{2}{v}\varphi_1 = Ck_\mathrm{n} \frac{3v^3}{2^{3/2} v_\mathrm{p}^{5/2} \gamma} K_{1/3}\left[\beta \frac{v^3}{(2v_\mathrm{p})^{3/2}}\right]; \tag{11}$$

$$\varphi_0' = -\frac{\nu_\mathrm{y}}{\gamma}\varphi_1. \tag{11a}$$

The solution of equation (11), finite at zero, has the form

$$\varphi_1(v) = \frac{Ck_\mathrm{n} 2^{3/2} v_\mathrm{p}^{1/2}}{\gamma\beta^2} \frac{1}{v^2} \int_0^{\beta v^3/(2v_\mathrm{p})^{3/2}} x K_{1/3}(x). \tag{12}$$

Now one can obtain an expression for the Townsend ionization coefficient. By definition

$$\alpha = \frac{\langle \nu_\mathrm{n}' \rangle}{u} = 3 \int_{v_\mathrm{T}}^{\infty} \nu_\mathrm{n}' f_0(v) v^2 \, dv \Bigg/ \left(\int_0^{v_\mathrm{p}} \varphi_1(v) v^3 \, dv + \int_{v_\mathrm{p}}^{\infty} f_1(v) v^3 \, dv \right). \tag{13}$$

Here u is the electron drift velocity; ν_n' is the excitation frequency to the lower of the levels quenched according to scheme (1), i.e., in the case of He, to $3'P$; v_T is the velocity corresponding to the excitation energy of the $3'P$ level.

By analogy with (6), ν_n' may be represented in the form

$$\nu_\mathrm{n}' = k_\mathrm{n}'(v - v_\mathrm{T}), \tag{14}$$

where the value of k_n' is also taken from experiment (11).

Substituting into (13) the values of ν_n', f_0, φ_1, f_1, respectively from (14), (7), (12), (8), and carrying out the integration, we have

$$\alpha = A \left\{ K_{2/3}\left[\beta (v_\mathrm{T} - v_\mathrm{p})^{3/2}\right] - \int_{\beta(v_\mathrm{T} - v_\mathrm{p})^{3/2}}^{\infty} K_{1/3}(x) \, dx \right\}, \tag{15}$$

where

$$A = \frac{2^{5/2} v_{\mathrm{y}} k'_{\mathrm{n}} v_{\mathrm{T}} (v_{\mathrm{T}} - v_{\mathrm{p}})}{\gamma v_{\mathrm{p}}} \left[\pi v_{\mathrm{p}}^{3/2} \beta + 2^{5/6} \Gamma(1/3) v_{\mathrm{p}} \beta^{2/3} - 6 \cdot 2^{2/3} \Gamma(3/2) \Gamma(7/6) v_{\mathrm{p}}^{1/2} \beta^{1/3} + \frac{2^{5/2}\pi}{\sqrt{3}} \right]^{-1}.$$

The expression for the electron drift velocity has the form

$$u = \frac{4\pi}{3} \int_0^{v_{\mathrm{p}}} \varphi_1(v) v^3 \, dv + \frac{4\pi}{3} \int_{v_{\mathrm{p}}}^{\infty} f_1(v) v^3 \, dv = \frac{\gamma}{\nu_{\mathrm{y}}}. \tag{16}$$

Formula (16) is in good agreement with experiment (12) for values of E/p from 3 V/cm · mm Hg and higher.

The discrepancies with experiment for $E/p < 3$ are explained by the more complicated dependence of the elastic-collision cross section on the electron energy corresponding to these values of E/p.

Table 1

	3	4	5	7	10	15	20	30	50	100
$\frac{E}{p}$	3	4	5	7	10	15	20	30	50	100
$\left(\frac{\alpha}{p}\right)_{\text{theor}}$	0.00049	0.00272	0.00601	0.0168	0.0520	0.121	0.196	0.354	0.641	1.42
$\left(\frac{\alpha}{p}\right)_{\text{exp}}$	0.00080	0.00298	0.00597	0.0161	0.0513	0.213	0.189	0.342	0.630	1.31

Table 1 presents the values of $\frac{\alpha}{p} \frac{\text{cm}^{-1}}{\text{mm Hg}}$, calculated from formula (15) for values of E/p from 3 to 100 V/cm · mm Hg. It also gives the latest experimental data, taken from Ref. [13]. The helium used in that experiment was carefully purified in order to avoid the influence of impurities.

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Note: Figure translations are in progress. See original paper for figures.