EFFECTS OF COLLISIONS OF THE SECOND KIND BETWEEN ELECTRONS AND EXCITED ATOMS ON THE ELECTRON ENERGY DISTRIBUTION IN AN INERT-GAS PLASMA

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A numerical solution to the kinetic equation is used to consider the effects of collisions of the second kind between electrons and excited atoms on the electron energy distribution and the rates of inelastic processes in a stationary neon-xenon plasma. The effects become substantial at values of the reduced electric field E/o of the order of tenths of a $V \cdot cm^{-1} \cdot Torr^{-1}$ and degrees of ionization $\rho < 10^{-6}$ if the over-all concentration of the atoms in the lower excited levels exceeds the electron concentration.

It is usual to restrict oneself to considering stepwise excitation and ionization [1-3] in examining the effects of excited atoms on the form of the electron energy distribution EED $f_0(\varepsilon)$ in the plasma of a positive column PC in an inert gas. At the same time, it is clear that there should be an effect from superelastic collisions of excited atoms with electrons that transfer the latter to the high-energy range, and this should be more substantial than that from stepwise processes and should increase with ε because of the sharp fall in $f_0(\varepsilon)$ in this region. However, the numerical method of solving the kinetic equation [1] used in most EED calculations for inert gases does not enable one to include collisions of the second kind. Here we provide a numerical solution to the kinetic equation by the method of [4] to examine the effects of collisions of the second kind on the EED and the rates of processes in PC plasmas in Ne and Xe.

Processes involving excited atoms play their largest part at pressures $p \gtrsim 1$ Torr, which enables one to neglect the effects of the space-charge field and the radial inhomogeneity in the plasma in calculating the EED [5]. Then the kinetic equation takes the form

$$\frac{d}{d\varepsilon}\left\{\frac{2}{3}\varepsilon^{3/2}\left[\frac{e^2E^2}{m\nu_{ec}}+\nu_e A_1(\varepsilon)\right]\frac{df_0}{d\varepsilon}+\varepsilon^{3/2}\left[\frac{2m}{M}\nu_{ec}+\nu_e A_2(\varepsilon)\right]f_0(\varepsilon)\right\}=\left(\frac{\delta f_0}{\delta t}\right)_{co}.$$

Here ν_{ec} is the frequency of the elastic collisions between electrons and atoms ($\nu_{ec} = \sigma_{ec} N v$, where σ_{ec} is the elastic-collision cross section, N is the concentration of atoms, and v is electron velocity), while ν_e is the frequency of electron-electron collisions, and the terms $A_1(\varepsilon)$ and $A_2(\varepsilon)$ incorporate the effects of electron-electron collisions:

$$A_1(\varepsilon) = 2\left\{\int_0^{\varepsilon} \varepsilon^{3/2} f_0(\varepsilon)\, d\varepsilon + \varepsilon^{3/2}\int_{\varepsilon}^{\infty} f_0(\varepsilon)\, d\varepsilon\right\},$$

$$A_2(\varepsilon) = 2\int_0^{\varepsilon} \varepsilon^{1/2} f_0(\varepsilon)\, d\varepsilon,$$

and $(\delta f_0/\delta t)_{co}$ is the inelastic-collision integral. This is the sum of the collision integrals for the elementary processes considered (direct and stepwise exitation and ionization, and collisions of the second kind between electrons and excited atoms):

$$\left(\frac{\delta f_0}{\delta t}\right)_{co} = \left(\frac{\delta f_0}{\delta t}\right)_{de} + \left(\frac{\delta f_0}{\delta t}\right)_{di} + \left(\frac{\delta f_0}{\delta t}\right)_{se} + \left(\frac{\delta f_0}{\delta t}\right)_{si} + \left(\frac{\delta f_0}{\delta t}\right)_{II\ kind}.$$

To describe the excitation and ionization by electron impact, we use Margenau's expression [6] for the collision integral. We assume that on exciting level s, an electron loses energy equal to the excitation potential ε_s:

$$\left(\frac{\delta f_0}{\delta t}\right)_{de} = \sum_s \{\nu_s(\varepsilon)\, \varepsilon^{1/2} f_0(\varepsilon) - \nu_s(\varepsilon + \varepsilon_s)(\varepsilon + \varepsilon_s)^{1/2} f_0(\varepsilon + \varepsilon_s)\},$$

and on ionization loses energy equal to the ionization potential ε_i, with the remaining energy divided equally between the ionizing electron and the newly produced one:

$$\left(\frac{\delta f_0}{\delta t}\right)_{di} = \nu_i(\varepsilon)\, \varepsilon^{1/2} f_0(\varepsilon) - 2\nu_i(2\varepsilon + \varepsilon_i)(2\varepsilon + \varepsilon_i)^{1/2} f_0(2\varepsilon + \varepsilon_i).$$

Here $\nu_s = \sigma_s N_0 v$ is the frequency of direct excitation for level s, $\nu_i = \sigma_i N_0 v$ is the frequency of direct ionization, σ_s and σ_i are the cross sections of the corresponding processes, and N_0 is the concentration of atoms in the ground state. Similarly, on replacing the frequencies of the direct processes by those of the stepwise ones we have $\nu^*_s = \sigma^*_s N^*_s v$, $\nu^*_{is} = \sigma^*_{is} N^*_s v$ where σ^*_s and σ^*_{is} are the corresponding cross sections and N^*_s is the concentration of excited atoms in state s, and then we can write expressions for the collision integrals for stepwise excitation $(\delta f_0/\delta t)_{se}$ and stepwise ionization $(\delta f_0/\delta t)_{si}$. The following form is given to the integral for collisions of the second kind between electrons and excited atoms [7]:

$$\left(\frac{\delta f_0}{\delta t}\right)_{II\ kind} = \sum_s \left\{-\nu_s(\varepsilon)\, \varepsilon^{1/2} \frac{g_0}{g_s} \frac{N^*_s}{N_0} f_0(\varepsilon - \varepsilon_s) + \nu_s(\varepsilon + \varepsilon_s)(\varepsilon + \varepsilon_s)^{1/2} \frac{g_0}{g_s} \frac{N^*_s}{N_0} f_0(\varepsilon)\right\},$$

where g_0 and g_s are the statistical weights of the ground state and state s.

A four-level scheme for the atom was used in the calculations. The four levels of the ns group were replaced by a single effective one with the excitation potential of the $^3P_2$ level having the maximum population. This does not cause a large error for Ne because of the small energy distances between the levels, while for Xe the same applies because of the large distances. The cross sections were taken from [8,9]. The levels of the np group were replaced by a single effective one, whose cross section was chosen by fitting to the dependence of the first Townsend coefficient on E/p_0. The direct-ionization cross sections were taken from [10], while the stepwise ionization ones were calculated from Dravin's formula, and those for stepwise excitation from Thomson's formula. Although Draving's and Thomson's formulas do not give good accuracy, the error in these cross sections does not have a marked effect on the form of the EED becaue of the low relative concentration of excited atoms $N_s{}^*/N_0$. The cross section for collisions of the second kind and the dependence on energy have been measured for Ne in [11] and for Xe in [12]. They agree satisfactorily with the cross sections calculated from the principle of detailed balancing via the cross sections for the first effective excitation level. The cross sections for elastic collisions of electrons with atoms were taken from [13,14].

Analytical estimates show that the effects of collisions of the second kind may be appreciable when the over-all concentration of excited atoms in the lower levels N^* is greater than the electron concentration n_e. This condition is typical of a decaying plasma, but it can also be realized in the stationary state for an Ne plasma [15] at $p \sim 1$ Torr and low discharge currents $i_d \lesssim 10$ mA. Measurements with Ne [15,16] give the following ranges in the initial parameters:

$$E/p_0 \sim 10^{-1}\text{—}10^{0} \ \text{V}\cdot\text{cm}^{-1}\cdot\text{Torr}^{-1}, \quad \eta = N^*/N_0 \sim 10^{-8}\text{—}10^{-5},$$
$$\rho = n_e/N_0 \sim 10^{-8}\text{—}10^{-6}.$$

The form of the EED is shown (for the inelastic range) in Figs. 1 and 2. Even values of N^*, low by comparison with the equilibrium concentration, lead to a marked reduction in the rate of fall in the EED in this range; the number of fast electrons is almost proportional to the excited-atom concentration (Fig. 1a). As E/p_0 decreases, the region where collisions of the second kind have an effect expands towards smaller energies, and it may attain the excitation potential if η is appreciable (Fig. 1b). On the other hand, an increase in the degree of ionization shifts it towards larger energies (Fig. 2). Collisions of the second kind have the largest effect for E/p_0 of about 10^{-1} $\text{V}\cdot\text{cm}^{-1}\cdot\text{Torr}^{-1}$ and $\rho \sim 10^{-8}$–10^{-7}. For $E/p_0 > 1$ $\text{V}\cdot\text{cm}^{-1}\cdot\text{Torr}^{-1}$ and $\rho > \eta$, it can be neglected, as this corresponds to $\rho \gtrsim 10^{-5}$ for typical values of η. The cross section for collisions of the second kind increases with the atomic number of the gas, while the threshold energy acquired by an electron decreases. Therefore, the absolute values of the EED at which effects of the second kind occur in Xe (Fig. 2) are higher than those for Ne. However, as N^* decreases as the atomic number increases, the effects of collisions of the second kind are only slightly dependent on the nature of the gas. On the whole, as N^* is dependent on the discharge current, pressure, and nature of the gas, one expects an effect from collisions of the second kind on the form of the EED at $p \sim 1$-10 Torr and currents $i_d \lesssim 10$ mA. In [17], it was found that the high-energy part of the EED became enriched in a PC plasma in Xe at $p \simeq 1$ Torr and $i_d \simeq 1$ mA.

In practice, it is more convenient to use not the energy range but the range in $f_0(\varepsilon)$ itself to estimate the effects of collisions of the second kind on the form of the EED, because the proportion of fast electrons is almost proportional to η. For example, in Ne with $\rho \sim 10^{-8}$-10^{-7} and E/p in the range from 10^{-1} to 1 $\text{V}\cdot\text{cm}^{-1}\cdot\text{Torr}^{-1}$, there is an appreciable effect from collisions of the second kind

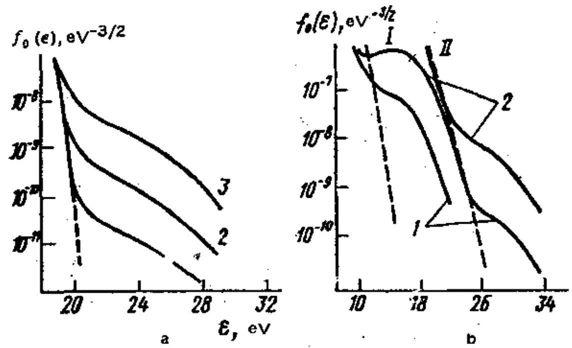

Fig. 1

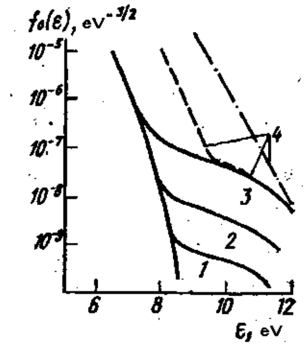

Fig. 2

Fig. 1. Form of the EED in the inelastic energy range in an Ne plasma with allowance for collisions of the second kind (solid lines) and without allowance (dashed line, $\eta = 0$): a) $E/p = 0.5\ V\cdot cm^{-1}\cdot Torr^{-1}$, $\rho = 10^{-7}$, $\eta = 10^{-8}$ (1), 10^{-7} (2) and 10^{-6} (3); b) $E/p = 0.2$ (I) and 1 (II) $V\cdot cm^{-1}\cdot Torr^{-1}$; $\rho = 10^{-8}$, $\eta = 10^{-6}$ (1) and 10^{-5} (2).

Fig. 2. Form of the EED in the inelastic range for an Xe plasma, $E/p = 0.5\ V\cdot cm^{-1}\cdot Torr^{-1}$ and $\rho = 10^{-7}$ (solid lines), 10^{-6} (dashed lines), and 10^{-5} (dot-dash line); $\eta = 0$ (1), 10^{-8} (2), 10^{-7} (3) and 10^{-6} (4).

for values of $f_0(\varepsilon)$ from $10^{-1}\eta$ to $10^{-3}\eta\ eV^{-3/2}$, correspondingly. For example, with $\eta = 10^{-6}$, the values of $f_0(\varepsilon)$ vary from 10^{-7} to $10^{-9}\ eV^{-3/2}$. In this range of EED values with measurements by the second-derivative method, the effects may be masked by the second derivative of the ion current [18]. The ratio $i_e''(V)/i_d''(V)$ increases as the ratio of the Debye screening radius to the probe radius decreases, and therefore to measure the EED at high energies one has to use thick probes or else a method of isolating $i_e''(V)$ as in [19].

Allowance for collisions of the second kind leads to a substantial increase in the rates of the inelastic processes at small E/p_0 and ρ. The effect is most substantial for the direct-ionization frequency. However, if there is a marked effect from collisions of the second kind, the frequency of stepwise ionization exceeds the latter. This applies also to the excitation rates for the high-lying levels: stepwise excitation from the lower levels exceeds the increase in the direct population from the ground state. The effects of collisions of the second kind on the total frequency of inelastic collisions becomes substantial, for example, in Ne at $E/p_0 \lesssim 0.3\ V\cdot cm^{-1}\cdot Torr^{-1}$ and $\rho < 10^{-6}$. Calculations show that in this case and with $\eta \gg 0$, the EED acquires a local maximum near the excitation potential (Fig. 1b). However, in the stationary state such values of E/p_0 are usually realized for $\rho \gtrsim 10^{-6}$. On the other hand, the condition $\eta \gg \rho$ is typical for an afterglow plasma; such a local peak in $f_0(\varepsilon)$ has been observed for He and Ne [20]. In EED calculations for decaying plasma [3] and a stationary plasma for small E/p_0 [1,2], no allowance was made for collisions of the second kind, which affected the correctness of the EED.

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