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Abstract

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PHYSICS

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THE INFLUENCE OF ION LOSS FROM A DISCHARGE ON THE IONIZATION STATE OF IMPURITIES

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In calculations of energy losses from a hot hydrogen plasma, and also in estimates of the electron temperature from the intensity of individual spectral lines, it is necessary to know the total number of atoms or ions participating in the formation of a given line. For a rarefied plasma this number has been determined from the equilibrium of the processes of ionization by electron impact and photorecombination (Elwert equilibrium) (¹⁻⁴). However, in real installations the lifetime of ions is determined not only by the elementary processes indicated above, but also by the drift and diffusion motions of ions, which remove them from the region of the discharge under consideration. On the other hand, as a result of recombination of ions on the chamber walls, neutral atoms are continuously returned to the discharge volume. These processes manifest themselves differently in each particular experimental installation.

In the present work an attempt is made to take these circumstances into account in a "phenomenological" way, starting from the simplest model of loss in which the number of impurity atoms and ions in the discharge remains constant, while the rate of ion loss does not depend on their charge.

Helium, which is weakly adsorbed by the chamber walls, was considered as a minor impurity. For a homogeneous plasma with prescribed electron temperature and density, the system of equations describing helium ionization with allowance for ion loss from the volume has the form

$$\begin{aligned} dN_1/dt &= k_0 N_0 - (k_1 + l_1 + \nu) N_1 + l_2 N_2, \\ dN_2/dt &= k_1 N_1 - (l_2 + \nu) N_2, \end{aligned} \quad (1)$$

$$N_0 + N_1 + N_2 = N_{\text{imp}}.$$

Here N_0 , N_1 , and N_2 are, respectively, the density of neutral atoms and of singly and doubly charged ions; N_{imp} is the total number of impurity particles per unit volume; $k_i = N_e \langle \sigma_i v \rangle$ and $l_i = N_e \langle \sigma_p v \rangle$ are the ionization and recombination coefficients of the corresponding atom or ion; N_e is the density of plasma

electrons. The angle brackets denote averaging over electron velocities, whose distribution is assumed to be Maxwellian. Values of these coefficients for various temperatures, taken from work ⁽³⁾, are given in Table 1. Finally, $\nu = 1/t_{\text{ion}}$, where t_{ion} is the lifetime of an ion in the discharge associated with its loss.

The initial conditions were taken to be the following: at time $t = 0$, $N_1 = N_2 = 0$ and $N_0 = N_{\text{imp}}$.

The solution of the system of equations (1) has the form

$$N_0 = N_{\text{pr}} - N_1 - N_2,$$

$$N_1 = \frac{D(l_2 + \nu)}{k_1} \left\{ 1 - \frac{1}{(r_2 - r_1)(l_2 + \nu)} [r_2(r_1 + l_2 + \nu)e^{r_1 t} - r_1(r_2 + l_2 + \nu)e^{r_2 t}] \right\},$$

$$N_2 = D \left[1 - \frac{1}{(r_2 - r_1)} (r_2 e^{r_1 t} - r_1 e^{r_2 t}) \right], \quad (2)$$

where

$$D = k_0 k_1 N_{\text{pr}} / (k_0 k_1 + k_0 l_1 + l_2 l_1 + (k_0 + k_1 + l_1 + l_2)\nu + \nu^2);$$

r_1 and r_2 are the roots of the characteristic equation, equal to

$$r_1, r_2 = \frac{1}{2} \{ -(k_0 + k_1 + l_1 + l_2 + 2\nu) \pm \pm [(k_0 + k_1 + l_1 + l_2)^2 - 4(k_0 k_1 + k_0 l_2 + l_1 l_2)]^{1/2} \},$$

and for $T_e = 10$ eV, neglecting l_1 and l_2 in comparison with k_1 and k_2 , we obtain

$$r_1 = -(k_1 + \nu), \quad r_2 = -(k_2 + \nu).$$

(Figure: Fig. 1)

Fig. 1. Variation of the steady-state values N_0 , N_1 , and N_2 with electron temperature.

$a - \nu = 10^4 \text{ s}^{-1}$, $b - \nu = 0$

First of all, let us examine the steady-state values of N_0 , N_1 , and N_2 , putting $t = \infty$ in expressions (2). Figure 1 shows curves of the variation of these quantities as functions of the electron temperature for $\nu = 10^4 \text{ s}^{-1}$ and $\nu = 0$. From these curves it is seen that the introduction of the parameter ν shifts all

curves toward higher temperatures. For example, if in the first case at $T_e = 10$ eV the number of doubly ionized atoms is only 15-17%, that of singly ionized atoms is $\sim 80\%$, and that of neutral atoms is 3-5%, then in the second case, at the same temperature, the entire helium impurity is already completely doubly ionized.

Figure 2 gives curves showing the variation of the steady-state values N_0 , N_1 , and N_2 as functions of ν at $T_e = 10$ eV.

Table 1

Values of the ionization and recombination coefficients at $N_e = 10^{14} \text{ cm}^{-3}$ *

	$T_e, \text{ eV}$							
	1.8	3.2	5.5	10	18	32	55	100
$k_0(\chi_1 = 24.6)$	15	$7 \cdot 10^2$	$3.5 \cdot 10^4$	$3.5 \cdot 10^5$	10^6	$2 \cdot 10^6$	$3 \cdot 10^6$	$4 \cdot 10^6$
$k_1(\chi_2 = 54.4)$	0	0	0	$2 \cdot 10^3$	$5 \cdot 10^4$	$1.3 \cdot 10^5$	$3.5 \cdot 10^5$	$7 \cdot 10^5$
$l_1(z_1 = 1)$	30	20	10	7	5	2.5	1.5	0
$l_2(z_2 = 2)$	$1.1 \cdot 10^2$	80	50	30	20	10	6	3

* χ_i is the ionization potential, z_i is the ion charge.

Finally, the time dependence of the quantities under consideration is given in Fig. 3. As was already indicated in Ref. (3), the times for the establishment of the stationary values N_0 , N_1 , and N_2 are very large and practically comparable with the duration of the discharges themselves. However, when the finite lifetime of ions due to their loss is taken into account, the stationary values are established more rapidly, but at a lower level. Indeed, the establishment time is determined, in order of magnitude, by the reciprocal of the smallest (in absolute value) root of the characteristic equation. If the density of singly charged ions passes through a maximum, then the time at which they attain the maximum value does not depend on the parameter ν . From expressions (2) it follows that

$$t_{\max, N_1} = [\ln(r_2 + l_2 + \nu) - \ln(r_1 + l_2 + \nu)] / (r_1 - r_2)$$

(after substitution of the values of r_1 and r_2 , the expression proves to be independent of ν). Thus, the time at which singly charged ions attain their maximum values is, as was to be expected, a function only of the electron temperature.

Fig. 2. Change in the established values N_0 , N_1 , and N_2 as a function of ν for $T_e = 10$ eV.

Fig. 3. Time variation of N_0 , N_1 , and N_2 for $T_e = 10$ eV. $a - \nu = 10^4 \text{ s}^{-1}$, $b - \nu = 0$, $c - \nu = 10^6 \text{ s}^{-1}$.

The data obtained are mainly illustrative in character. They show how cautiously one should interpret spectral-measurement data for each particular experimental setup. They also indicate the possibility, at least in principle, of estimating the mean lifetime of ions associated with their loss from the discharge.

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