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The Effect of the Charge-Exchange on the Total Radiative Power Emitted by Light Impurity Elements in Hot Plasmas

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Abstract – When a pellet (a macroscopic-size piece of solid material) interacts with a very high temperature plasma, a special plasma medium – consisting of a mixture of neutral atoms and ions in several different ionizations stages – is formed around the pellet. The magnitude of the total radiated power by the (ablated) pellet material has a crucial importance for the energy balance of both the pellet and the surrounding background plasma.

To calculate the total radiated power of a plasma, the excited state populations of the different ions have to be known with an accuracy as high as possible. Many different atomic physical processes (e.g. electron impact excitation, spontaneous emission, radiative and three-body recombination, charge-exchange) influence the excited state populations.

In the case of radiative power calculations, the charge-exchange is rarely taken into account because of the complexity of the cx process and the waste number of the excited states to be taken into account. With the help of a slight generalization of the Landau-Zener theory for charge-exchange, the handling of the computational difficulties connected with the large number of excited states involved is possible and a reasonable compromise between the accuracy and the time of the calculations can be achieved.

The influence of the charge-exchange on the total radiative power emitted by carbon plasmas is discussed and presented.

Introduction and Theory – The theory here outlined is based on the generalization of the well known Landau-Zener theory discussed in the past in a few papers [1–3]

The Landau-Zener theory is originally devoted to the calculation of the charge-exchange cross-section between a hydrogen-like ion and a bare nucleus. Since for the radiative loss calculations the high accuracy of the cx cross-section is not of crucial importance, we decided to generalize the theory for the cx between ions of charge Z_1 and Z_2.

Let Z_1 be the charge of the projectile, and Z_2 be the charge of the target (both before the electron transfer). Figure 1. depicts the main symbols used in the text. Let E_1 be the bounding potential of the electron *transferred to the projectile* and E_2 the same potential for the electron of the target *before the transfer* (see Fig.1.). It is clear that the relationship of $E_{1,2}$ to the excitation energies $e^{ex}_{1,2}$ of the electron before and after the transfer is $E_{1,2} = I^{pot}_{1,2} - e^{ex}_{1,2}$, where $I^{pot}_{1,2}$ are the respective ionization potentials. The approximate diabatic potential of the electron to be transferred from the target to the projectile at an internuclear separation R is

$$-E_2 - \frac{Z_1}{R}, \tag{1}$$

whereas the approximate diabatic potential of the electron after the transfer is

$$-E_1 - \frac{Z_2+1}{R}. \tag{2}$$

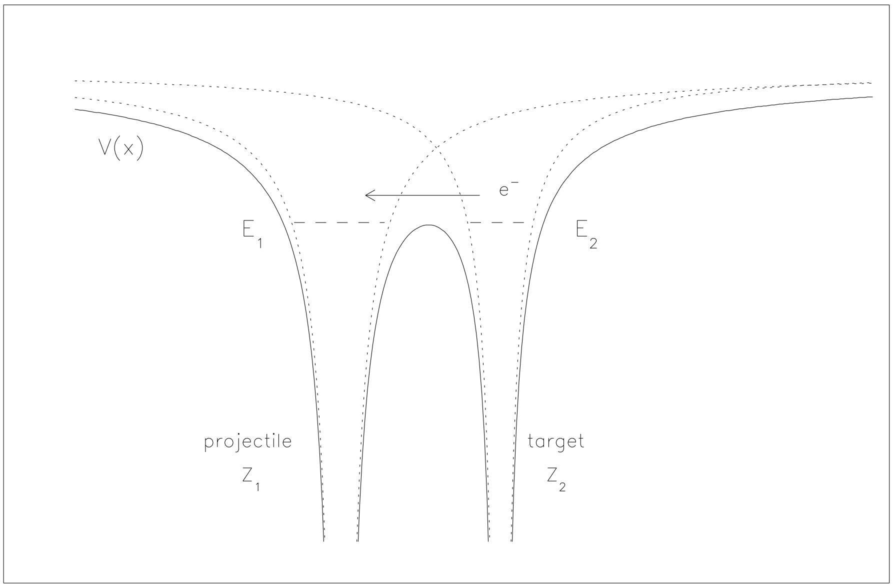

FIG. 1. The explanation of the main symbols used in the text.

The electron is transferred if the two following relations hold:

$$-E_2 - \frac{Z_1}{R} = -E_1 - \frac{Z_2+1}{R}, \tag{3}$$

$$-E_2 - \frac{Z_1}{R} > V_{max}. \tag{4}$$

Here V_{max} is the maximum of the potential barrier to be overcome by the electron during the transfer. If the potential seen by the electron (being transferred) is

$$V(x) = -\frac{Z_1}{x} - \frac{Z_2+1}{R-x}, \tag{5}$$

the hight of the potential maximum for $0 < x < R$ is

$$V_{max} = -(\sqrt{Z_1} + \sqrt{Z_2+1})^2/R. \tag{6}$$

Equation (3) gives the internuclear separation at the crossing point of the diabatic potentials: $R = (Z_1 - Z_2 - 1)/(E_1 - E_2)$. The classical charge-transfer cross-section

σ_{cl} can be written in terms of R by assuming the probability of electron transfer to be $\frac{1}{2}$.

$$\sigma_{cl} = \frac{1}{2}\pi R^2. \tag{7}$$

Now, the approximate rate of the charge transfer is $\alpha^{CX}(Z_1, Z_2, E_1, E_2) = \sigma_{cl} \cdot v_T$, where $v_T = \sqrt{3k_B T_i/m_i}$ is the average thermal velocity of the ions. The system of rate equations (5) in [4] can now be extended with the charge transfer terms as (for notations see [4])

$$\begin{aligned}\frac{dn(z,p)}{dt} = -n(z,p)\{n_e S(T_e,z,p) + n_e \sum_{q\neq p} X(T_e,z,p,q) + \sum_{q<p} A(z,p,q)\} +\\ n_e \sum_{q\neq p} n(z,q) X(T_e,z,p,q) + \sum_{q>p} n(z,q) A(z,q,p) +\\ n_e n(z+1,g)\{n_e \beta(T_e,z,p) + \alpha(T_e,z,p) + \alpha^{DR}(T_e,z,p)\} +\\ \delta(p-g) n_e \sum_{q} n(z-1,q) S(T_e,z-1,q) +\\ \sum_{z^*\neq z} n(z+1,g) n(z^*,q) \alpha^{CX}(z,z^*,p,q) -\\ \sum_{z^*\neq z} n(z^*,g) n(z,p) \alpha^{CX}(z^*,z,q,p).\end{aligned} \tag{8}$$

The solution of equation (8) and the calculation of the total radiative power is done in the same way as in [4].

Discussion – In the collisional-radiative model we assumed quasi-stationary states (equilibrium) between the excited states of a given ion. No equilibrium was assumed between the different ionic species. To present some results obtained with this model we shall assume a uniform carbon plasma in being in the state of equilibrium. The ion and elecron densities and the electron temperature are given. In Fig.2, the total radiative power emitted by a carbon plasma (with the charge-exchange effect included in equation (8)) is plotted as a function of the electron temperature. Here the total number density of the carbon ions is $10^{24} m^{-3}$, the electron density is $10^{21} m^{-3}$ and Saha equilibrium is assumed between the densities of the different ions.

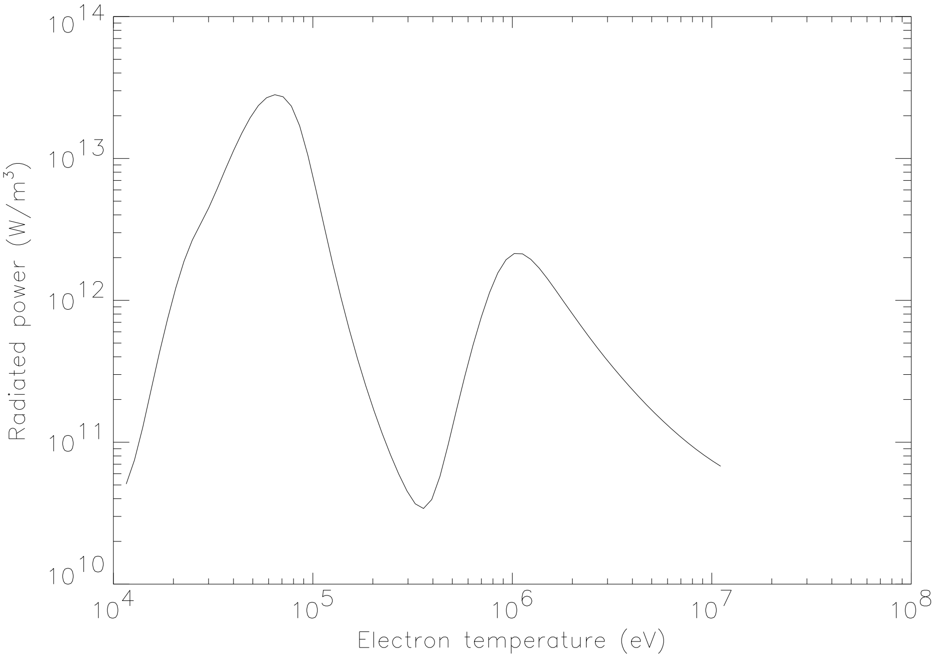

FIG. 2. The total radiative power of a carbon plasma as a function of the electron temperature. $N_{carbon} = 10^{24}m^{-3}$, $N_e = 10^{21}m^{-3}$.

The detailed solution and analysis of equation (8) shows several features of the influence of the charge-exchange on the total radiative power emitted by carbon plasmas.

The main contribution to the charge-exchange rates is given by the two following reactions:

$$C^{3+}_{excited} + C^{4+} \rightarrow C^{4+} + C^{3+}_{excited} \tag{9}$$

and

$$C^{1+}_{excited} + C^{6+} \rightarrow C^{6+} + C^{1+}_{excited}. \tag{10}$$

The influence of the charge exchange on the total emitted radiative power is well below one percent at an electron density of $10^{21}m^{-3}$ and carbon total density of $10^{24}m^{-3}$. At lower densities the effect is even smaller. This is due to the fact that the main contributors to the charge-exchange (the C^{3+}, C^{4+} and the C^{1+}, C^{6+} ions do not coexist in an equlibrium plasma.

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