

nl-Kinetics in H-like Impurity Ions Populated by Diagnostic Neutral Beam Charge-Exchange

S.N. Tugarinov, M.B. Kadomtsev*, M.G. Levashova*, V.S. Lisitsa*, N.N. Nagel*

TRINITI, Troitsk, Moscow region, Russia

** NFI RRC "Kurchatov Institute", Moscow, Russia*

Spectroscopy of line radiation from plasma impurity ions populated by charge-exchange recombination reactions with energetic neutral-beam atoms is recognized as a powerful diagnostic for magnetically confined tokamak plasmas [1], in particular for ITER plasma [2]. The effectiveness of this diagnostic depends strongly on cross-sections for charge exchange recombination of neutral beam into excited states of impurity ions.

The charge transfer preferentially populates the atomic states of impurity ions with principal quantum numbers [3,4]:

$$n_Z \approx nZ^{0,768} \quad (1),$$

where Z – is the charge of the acceptor ion, n , n_Z – are the principal quantum numbers of electron in the donor atom and the acceptor ion, respectively.

In the reaction of charge transfer collisions of fully ionized carbon ions ($Z=6$) and hydrogen atoms in the first excited states ($n=2$) the predominantly populated level is $n_Z = 8$ while the charge transfer from the ground states of hydrogen atoms mainly populates the principal quantum numbers of carbon ions near $n_Z=4$ which emit VUV photons.

Thus the maxima of charge transfer cross sections for ground-state neutral atoms and for those in excited states may be substantially shifted over principal quantum numbers of the acceptor ion which may result in increasing of selective population of particular excited states of impurity ions and, therefore, in increasing of intensities of respective spectral lines.

It has been suggested to increase the fraction of hydrogen atoms in the excited states ($n=2$) by using laser excitation of the neutral beam. The estimations of *nl*-selective cross sections for charge exchange of hydrogen beam with 100 keV energy and fully ionized carbon ions show that atomic states of acceptor ion at $n_Z > 8$ are predominantly populated. Therefore, the levels near $n_Z = 8$ are effectively populated first of all by indirectly, by radiative cascades from excited states with $n_Z > 8$. The cascade process is an additional mechanism leading to an increase of photon emissivities used to evaluate the CXS observations. This is a basis for more optimistic forecasting for possibilities of employing a laser excitation in the charge-exchange recombination spectroscopy diagnostic.

In the present work we investigate a two-dimensional *nl*-kinetics in H-like impurity ion atomic states populated by diagnostic neutral beam charge-exchange.

To calculate the populations of atomic states for sufficiently high energy of charge transfer collisions (100 keV), where the relative velocities of reactants are comparable to that of the bound electron or even higher, we use the cross sections of charge transfer from ground and excited states of hydrogen atom,



taken from classical trajectory Monte Carlo simulations [3,5]. Figure 1 shows the *nl*-selective cross sections for charge transfer for C^{6+} on $\text{H}(n=1)$ (the data plotted were taken from [1]). Due to the strong *nl*-selectivity of these cross sections (see fig.1) the *nl*-kinetics should be involved for calculating the bound electron's population distribution function $N(n_Z, l_Z)$. We applied the previously developed code *nl-KINRYD* [6] which is based on the quasi-classical model of the radiative-collisional cascade of a highly-excited bound electron in a hydrogen-like ion in plasmas.

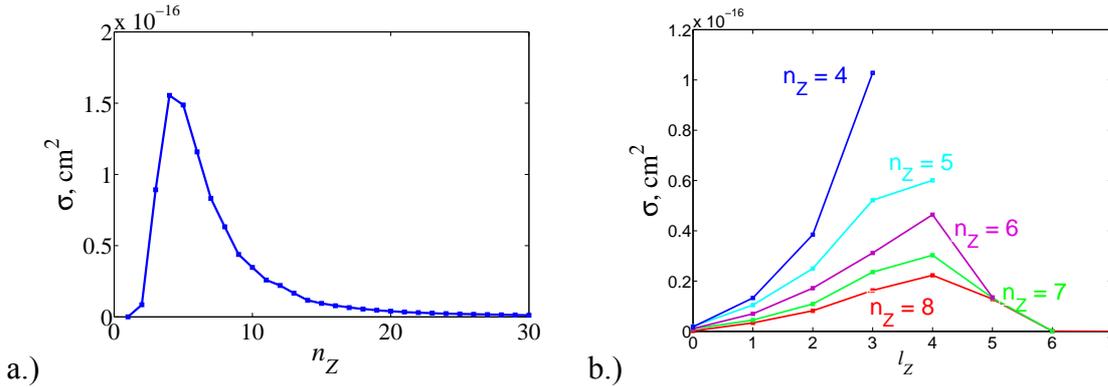


Fig. 1. Partial cross sections of charge exchange reaction: $\text{C}^{6+} + \text{H}^0(n=1) = \text{C}^{5+} + \text{H}^+$ as a function of a.) principal (n_Z) and b.) orbital (l_Z) quantum numbers of final state of excited electron C^{5+} (the plotted data were taken from [1]).

The calculated population distribution function $N(n_Z, l_Z)$ of the bound electron in C^{5+} (corresponding to the charge exchange cross section shown in Fig.1) is shown in Fig 2(a,b). Results are given for deuterium plasma with electron and deuteron densities $N_e = N_i = 10^{14} \text{ cm}^{-3}$ and temperatures $T_e = T_i = 15 \text{ keV}$. The impact of cascade processes and direct population into the total population distribution function is shown in Fig. 2b. One can see that the cascades make a contribution of order 10-15 % for large l_Z values and relatively low n_Z -levels (see Fig.2b, the curves for $n_Z=5$ and $n_Z=8$) while for higher n_Z -levels the impact of cascade population is much more smaller (see Fig.2b, the curve for $n_Z=12$). This occurs because the cascade processes result in increase of circularity of bound electron's classical

orbit. For larger n_Z -levels, the collisions with plasma ions lead to redistributing of populations over l_Z [6] which reduces the role of cascade processes.

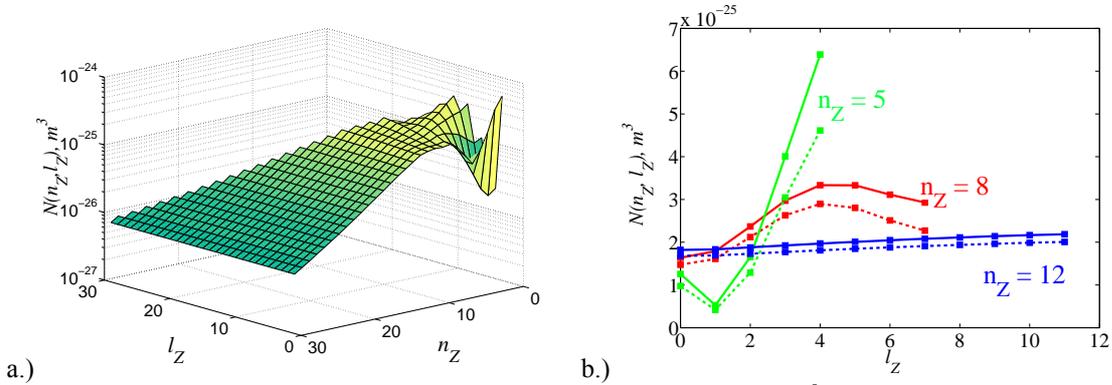


Fig. 2. a.) Population distribution function of bound atomic electron in C^{5+} as a function of a.) principal (n_Z) and orbital (l_Z) quantum numbers for charge exchange collisions of C^{6+} on diagnostic beam of Hydrogen atoms in the ground states ($n=1$) per one atom of C^{5+} and one atom of Hydrogen. b.) Population distribution function of bound atomic electron in C^{5+} as a function of l_Z for $n_Z=5, n_Z=8, n_Z=12$. Solid lines is the total population (calculation with account of cascades), dashed lines is the direct population only. The charge exchange partial cross sections are the same as in Fig.1. The populations are given for 3D radiative-collisional kinetics (i.e. 2D-population is divided by statistical factor $2l_Z+1$). Results are given for a deuterium plasma with electron and deuteron densities $N_e = N_i = 10^{14} \text{ cm}^{-3}$ and temperatures $T_e = T_i = 15 \text{ keV}$.

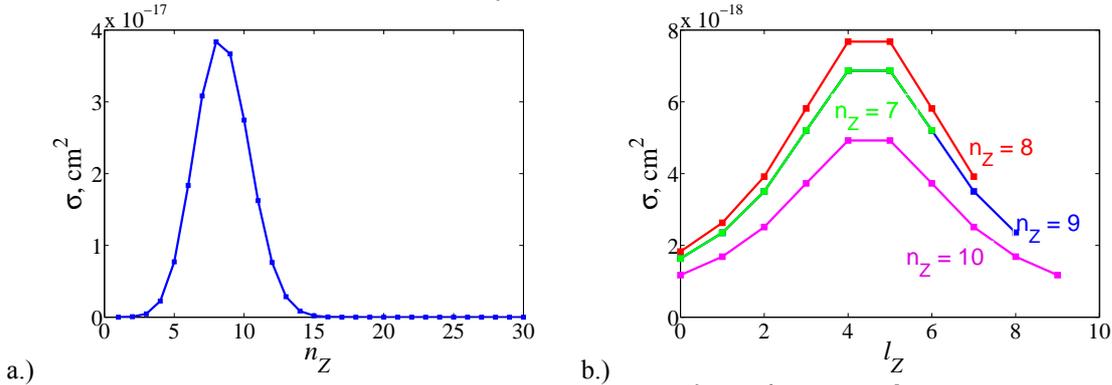


Fig. 3. Partial cross sections of charge exchange reaction: $C^{6+} + H^0(n=2) = C^{5+} + H^+$ as a function of a.) principal (n_Z) and b.) orbital (l_Z) quantum numbers of final state of excited electron C^{5+} (the plotted data is the fit of data from [3]).

The partial (nl -selective) cross sections for charge transfer for C^{6+} on $H(n = 2)$ is shown in Fig.3. (the plotted data is the fit of data from [3]). The corresponding calculated population distribution function in C^{5+} is given in Fig.4. Based on the populations found, we calculated the effective emission coefficients for the CVI($n_Z = 8 \rightarrow 7$) CXS line with $H(n = 2)$ and $H(n = 1)$ beam donors. The results are given in Table 1.

One can see from the Table 1 that the account of cascade processes leads to the increase of effective emission coefficients by 10-15 %. At beam energies of 100 keV an excited $H(n = 2)$ state the total (summarized over n and l) cross section of charge transfer is five times smaller than ground-state H [3-5]. Because of that reason the effective

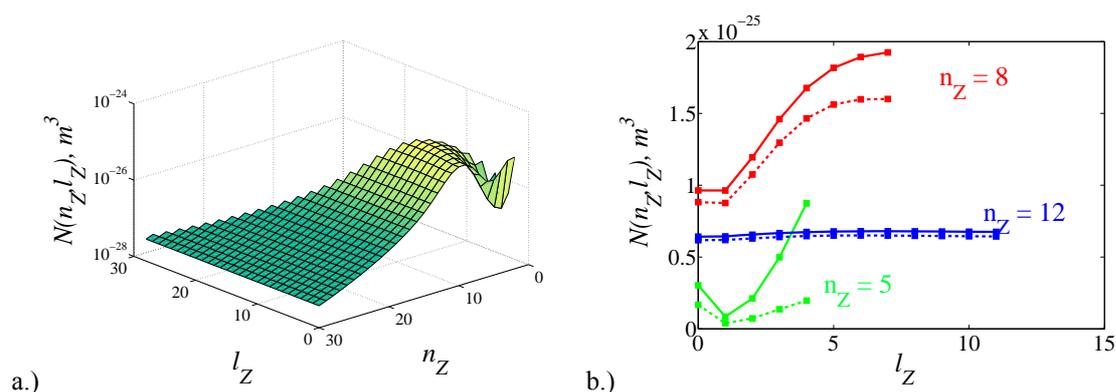


Рис. 4. а.) Population distribution function of bound atomic electron in C^{5+} as a function of principal (n_Z) and orbital (l_Z) quantum numbers for charge exchange collisions of C^{6+} on diagnostic beam of Hydrogen atoms in the first excited state ($n=2$) per one atom of C^{5+} and one atom of Hydrogen. б.) Population distribution function of bound atomic electron in C^{5+} as a function of l_Z for $n_Z=5$, $n_Z=8$, $n_Z=12$. Solid lines is the total population (calculation with account of cascades), dashed lines is the direct population only. The charge exchange partial cross sections are the same as in Fig.3. The populations are given for 3D radiative-collisional kinetics (i.e. 2D-population is divided by statistical factor $2l_Z+1$). Results are given for a deuterium plasma with electron and deuteron densities $N_e = N_i = 10^{14} \text{ cm}^{-3}$ and temperatures $T_e = T_i = 15 \text{ keV}$.

Table 1. Effective emission coefficients in $10^{-14} \text{ m}^3/\text{s}$ for the CVI($n_Z = 8 \rightarrow 7$) CXS line for a 100-keV Hydrogen beam for a deuterium plasma with electron and deuteron densities $N_e = N_i = 10^{14} \text{ cm}^{-3}$ and temperatures $T_e = T_i = 15 \text{ keV}$.

	Calculation with account of both direct population of atomic states of C^{6+} and cascade processes	Calculation with account of direct population of atomic states of C^{6+} only
H($n=1$)	0.57	0.47
H($n=2$)	0.34	0.29

emission coefficients for the CVI($n_Z = 8 \rightarrow 7$) CXS line for H($n = 2$) donor is smaller than that of the ground-state H. This makes the observation of the effect of laser excitation for CVI($n_Z = 8 \rightarrow 7$) CXS line rather difficult. The transitions from the excited states of C^{5+} for $n_Z > 8$ may be of interest.

ACKNOWLEDGMENTS

This work is supported by the Russian Foundation for Basic Research (project no. 08-02-00294a), a grant for Support of Leading Research Schools.

REFERENCES

- [1] R.C. Isler, Plasma Phys. Control. Fusion **36** (1994) 171-208.
- [2] S. N. Tugarinov et al., Plasma Physics Reports 30 (2004) 128.
- [3] K.R. Cornelius, K. Wojtkowski, R.E. Olson. J. Phys. B, 33 (2000) 2017-2035.
- [4] R.K. Janev, L.P. Presnyakov, V.P. Shevelko. Physics of Highly Charged Ions. Springer. 1985
- [5] R.E. Olson, D.R. Schultz. Physica Scripta. Vol. T28, 71-76, 1989
- [6] M.B. Kadomtsev, M.G. Levashova, V.S. Lisitsa, JETP **106** (2008) 635-649 (more references at http://vo.nfi.kiae.ru/atomic_physics)