Scaling for the filling of highly excited states of ions in charge-exchange reaction with hydrogen atoms and the emission cross sections of optical lines for diagnostic study of impurities in a plasma

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A scaling is proposed for determining the probabilities for the filling of highly excited *nl* states as a result of capture of an electron by a multiply charged ion in hydrogen atoms in the ground state and the excited states. The cross sections for the emission of optical lines of He^+ and C^{5+} ions are calculated. These cross sections are used to diagnose the impurities in a plasma by means of hydrogen atom beams.

A collision of multiply charged ions with hydrogen atoms as a result of charge-exchange reaction leads to a filling of highly excited states of ions with a subsequent emission of a characteristic radiation. This process is used extensively in corpuscular-spectroscopic diagnostic studies of the concentration of impurities, ion temperature, rotation velocity, and other plasma parameters.[1] The most important characteristic of a charge-exchange reaction, which determines the emission intensities of the lines, is the scheme for the filling of the excited states of ions. Reliable numerical calculations of the cross sections for the filling of *nl* states are available only for a limited number of ions (particularly for the charge exchange from the excited states of atoms), while the data are given for only some values of the relative velocity of particles. In the present letter we propose a scaling which would make it possible to determine the scheme for the filling of the excited states of various ions in the charge-exchange reaction over a broad range of collision velocities.

In the collisions of $A^{z+} - H(n_0)$ the most probable level to be filled is, as we know, the level of the ion with $n = n_m = n_0 Z^{0.75}$. The filling of levels with different values of n will be described with the help of the function $F(t,s)$, which is a ratio of the level population of an ion with a given n to the level population with $n = n_m$ $[F(t=1,s) = 1]$. Here $t = n/n_m$, and $s = Vn_0/Z^{0.25}$ is the ratio of the collision velocity V to the orbital velocity of an electron at the level of an ion with $n = n_m$. If the values of the function F are fixed, the dependence of the parameter t on the variable s is a universal dependence. These dependences are constructed in Fig. 1a on the basis of the well-known theoretical calculations of the n-filling of levels in order to capture an electron from the ground state and excited states of hydrogen atoms. The data in Fig. 1a pertain to the velocity region near the maximum of the cross section, when many states are involved in the interaction, a situation which apparently accounts for the observed universal behavior. At lower velocities the particular features of the quasimolecular picture of the terms and the relationship between them become a factor, but at higher velocities the Z dependence of the parameters of the function F should be changed. As an example of the way in which the scaling can be used, we show in Fig. 1b the function $F(t, s = 0.84)$ of the He^+ ion for the collision $He^{2+} - H$ $(n_0 = 1)$, $E = 25$ keV/nucleon, in good agreement with the results of the calculations based on the strong-coupling method.[8] To determine the cross sections for the filling of n states, we must multiply the function F by the total charge-exchange cross section σ_{cx}. The value of σ_{cx} can be determined from the universal dependence of the reduced cross section $\tilde{\sigma}$ on the reduced collision rate $\widetilde{V}$ from Ref. 9 if it is assumed that $\tilde{\sigma} = \sigma_{cx}/(Z^{1.07} n_0^4)$ and $\widetilde{V} = s$.

At $V \gtrsim 1$, a region of interest in plasma diagnostics, a dependence which approximates the results of classical numerical calculations can be used for the filling of l states[10]: $P(n,l) = (3/\tilde{n})(l^2 + 1.7l + 1.1/\tilde{n}^2 + 1.05\tilde{n} + 1.25)$, where $\tilde{n} = n$ if $\tilde{n} \leqslant n_m$, $\tilde{n} = n_m + 1$ if $n > n_m$, and $l \leqslant n_m$, $P(n,l) = 0$ if $n > n_m$, $l > n_m$ and $\Sigma_l P(n,l) = 1$. It should be noted that collisions of excited ions with deuterons at an adequate plasma density may lead to a statistical filling of l states in the level with a given n and the initial (charge-exchange) filling of l states has virtually no effect on the intensity of the line emission. Estimates show that this situation occurs at a plasma density $n_D^* = 4 \times 10^{14} [Z^6 \sqrt{T}/n^7 (n^2 - 4)] \ln(n^3 - n/2)$, where T is the plasma temperature in eV. For the optical lines of He^+ and C^{5+} ions we have $n_D^* \approx 10^{13}$ cm^{-3} and $\approx 10^{14}$ cm^{-3}, respectively.

We used the scaling, which we found, to determine the initial (charge-exchange) filling of the nl states of He^+ and C^{5+} ions in the charge-exchange reaction of α particles and carbon nuclei with fast hydrogen atoms in a plasma in the calculations of the cross sections for the emission of the optical lines of ions, σ_λ, which hold promise for diagnostic studies of α particles and carbon impurity. Since in plasma the radiation lifetimes of the excited states of ions, which correspond to the optical transitions, and of atoms are usually comparable to the collision lifetimes, we solved a system of equations for a collision-radiation model for the populations of the (nlj) states of plasma ions and of atoms of a diagnostic beam[11,12] $(n, n_0 \lesssim 12)$. We analyzed the plasma consisting of deuterons and electrons in a magnetic field.

The calculated cross sections σ_λ, shown in Fig. 2 and 3, demonstrate that the

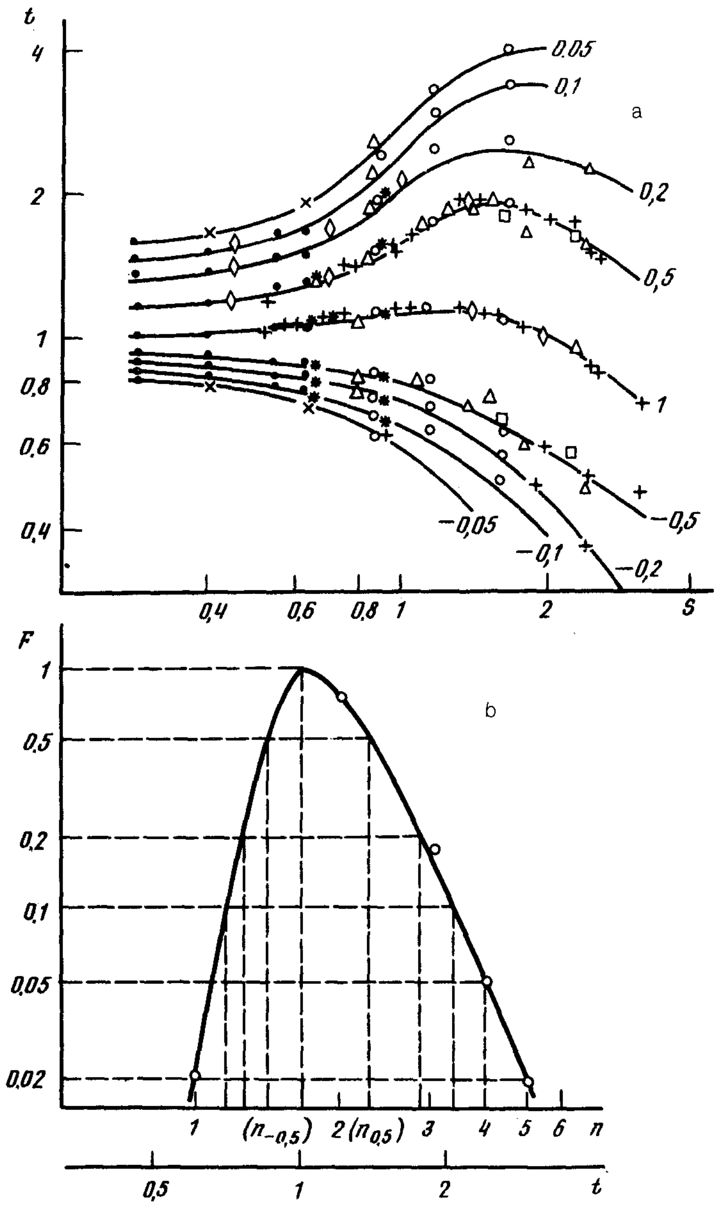

FIG. 1. (a) Universal dependence of the parameter $t = n_k/n_m$ on the reduced velocity s, where n_k is the principal quantum number of the ion state for which $F(t,s) = |k|$. This dependence was constructed from the results of numerical calculations of the cross sections for the charge exchange of nuclei of the elements in which there are ground-state hydrogen atoms: ●—$Z = 6$(2); × — $Z = 2.4$–8(3); + — $Z = 2$–6, 8, 9(4); ◊—$Z = 3$–5(5), * — $Z = 2$,6,8(6); and excited-state atoms (7): 0–$Z = 6$, $n_0 = 2$, ▲—$Z = 6$, $n_0 = 3$, Δ–$Z = 8$, $n_0 = 2$, ■ – $Z = 8$, $n_0 = 3$ (the labels on the curves give the values of the function $F = |k|$, where $k < 0$ for $n < n_m$ and $k > 0$ for $n \geqslant n_m$). (b) The normalized filling of the n states of the He^+ ion in the reaction $He^{2+} - H(n_0 = 1)$, constructed from the data in Fig. 1a; points—results of calculations of Ref. 8, $E = 25$ keV/nucleon.

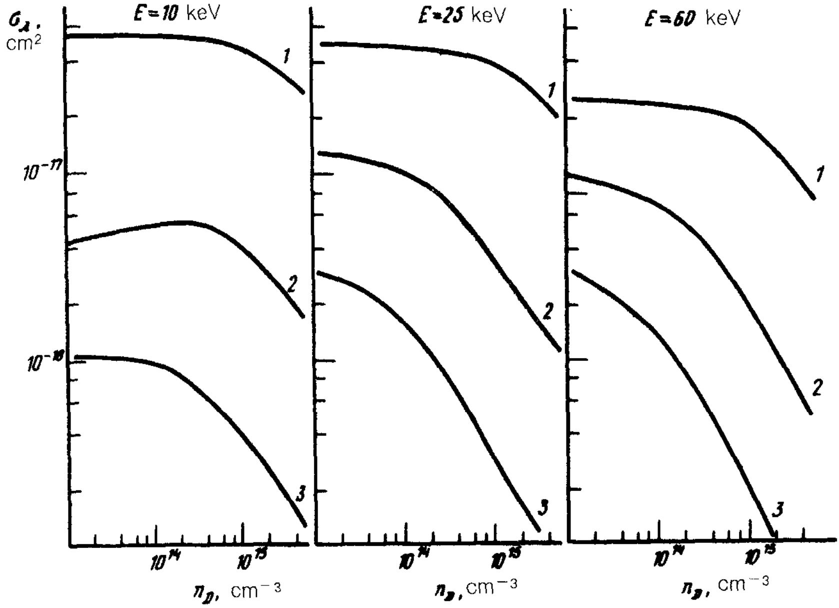

FIG. 2. Effective cross sections for the emission of He^+ – ion lines in a charge-exchange reaction of α particles with hydrogen atoms vs the plasma density. 1—$\lambda = 1640$ Å ($n = 3 \to 2$); 2—$\lambda = 4685$ Å($n = 4 \to 3$); 3-$\lambda = 3203$ Å ($n = 5 \to 3$). $T = 1$ keV, $H = 22$ kOe.

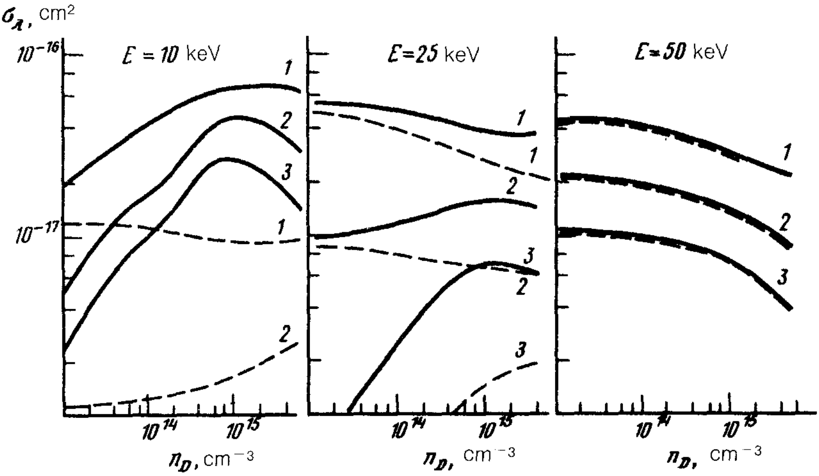

FIG. 3. Effective cross sections for the emissions of C^{5+}-ion lines in a charge-exchange reaction of carbon nuclei with hydrogen atoms vs the plasma density. 1—$\lambda = 3434$ Å ($n = 7 \to 6$); 2—$\lambda = 5291$ Å ($n = 8 \to 7$); 3—$\lambda = 7717$ Å ($n = 9 \to 8$). Dashed curve— The excited atoms in the diagnostic beam are ignored. $T = 1$ keV, $H = 22$ kOe.

intensity of optical lines of ions increases appreciably (up to an order of magnitude) because of the excitation of atoms of the diagnostic beam at $E \leqslant 25$ keV/nucleon (Fig. 3). At $E = 10$ keV/nucleon the contribution of the states with $n_0 \geqslant 3$ is appreciable. Since the role of this effect increases with increasing charge of the ion nucleus, the plots of σ_λ vs n_D for He^+ and C^{5+} ions at $E \leqslant 25$ keV/nucleon are different. In the second case an increase in the population of the excited states of hydrogen atoms with an increase in n_D increases σ_λ, while in the first case the role of quenching collisions is more prominent.

Because the intensity of the optical lines of ions increases significantly at moderate energies of atoms, relatively simple diagnostic injectors can be used in the experiments. The use of these lines for the measurement of ion temperature and plasma rotation velocity holds most promise. To measure the ion concentration, it is advisable to use atoms with energies $E \gtrsim 50$ keV/nucleon, at which σ_λ does not depend on the number of excited atoms in the diagnostic beam.

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