Interaction of Fast Ion Beams with Low- and High-Density Targets

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Electron capture processes into excited states

$$X^{q+} + A \rightarrow X^{(q-1)+}(n) + A^{+} \tag{1}$$

are considered in collisions of fast positive ions X^{q+} with low- and high-density targets A. In the case of a low density, the electron-capture cross section $\sigma_{ec}(n)$ has a certain distribution over the principal quantum number n with a maximum at $n = n_{max}$ and asymptotic behavior $\sigma_{ec}(n) \approx n^{-3}$ at $n \gg n_{max}$. For Rydberg states $n \gg 1$, ions with the orbital quantum numbers $\ell = 0$ and 1 are created with the highest probability (see, e.g. [1]).

The distribution of σ_{ec} over n states depends not only on the relative velocity v and the atomic structure of colliding systems but also on the target density. In a dense target, the largest possible principal quantum number n_{cut} which the $X^{(q-1)+}(n)$ ion can be created with, is limited because the population of highly excited n states is destroyed by ionization collisions with the target:

$$X^{(q-1)+}(n) + A \rightarrow X^{q+} + A + e^{-}. \tag{2}$$

The ionization rate from the n state is quite large and proportional to $N \cdot n^4 \cdot Z_T^2$ where Z_T and N are the nuclear charge and density of the target particles, respectively.

The value of n_{cut} can be estimated from equality condition of the radiative decay rate $A(n, n_0)$ into all low-lying states of the $X^{(q-1)+}$ ion and the ionization rate:

$$A(n_{cut}, n_0) = N \cdot \sigma_{ion}(n) \cdot v, \tag{3}$$

where n_0 is the ground state and $\sigma_{ion}(n)$ is the ionization cross section from the n state induced by the target. Employing the Kramers formula for $A(n, n_0)$ and the Thomson formula for $\sigma_{ion}(n)$, one has from (3):

$$n_{cut} = n_0 + \Delta n, \tag{4}$$

$$\Delta n \approx Z_P \left(\frac{10^{18}}{Z_T^2 N[\mathrm{cm}^{-3}]} \right)^{1/7} \left(\frac{E[\mathrm{keV/u}]}{260\, Z_P^2} \right)^{1/14}, \tag{5}$$

where E and Z_P are the projectile energy and ion charge. As is seen from (5), the higher is the target density and the target charge, the lower is the largest possible quantum number n_{cut} and, therefore, the lower is the total capture cross section $\sigma_{tot} = \sum_{n=n_0}^{n_{cut}} \sigma_{ec}(n)$.

In Fig. 1, the electron-capture cross sections for collisions of bare Ni^{28+} ions with low- and high-density SiO_2 molecules are shown. The cross sections were calculated by the CAPTURE code based on the normalized electron-capture probabilities in the impact parameter representation and described in [2]. At energies E = 100 keV/u – 10 MeV/u, the capture of L and M subshells of the low-density SiO_2 molecules (curve 1) is suppressed by the density effect (curve 2) leading mainly to the capture of K electrons. At energies E > 10 MeV/u, both cross sections are approximately equal because only K electrons of SiO_2 molecules are mostly captured with $n_{cut} \approx 4$.

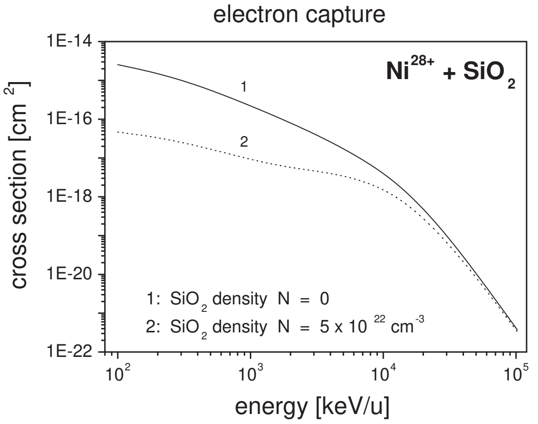

Figure 1: Influence of the target-density effect on the total electron-capture cross sections in Ni^{28+} + SiO_2 collisions:
1 – low-density target, $N = 0$;
2 – high-density target, $N = 5 \times 10^{22}$ cm^{-3}.

Due to the density effect considered, the average (mean) charge of the ion beam after the solid target is larger than that after a low-dense target. This problem was studied in [3] for collisions of fast U^{q+} ions with the hydrogen-carbon plasma in the MeV/u energy regime.

In general, consideration of the charge-changing processes arising in collisions of fast beams with atomic and plasma targets [2]–[4] shows the following peculiarities:

1) the distribution of the projectiles over excited states after interaction with a target depend on the target density: interaction with high-density targets cuts off the maximum possible principal quantum numbers of the projectile after collision and *reduces* the total electron-capture cross sections,

2) the distribution over the quantum numbers nl of the projectile due to charge-changing collisions with a target defines the *spectroscopic* properties (radiative spectra) of the projectile,

3) account for the density effect together with the Coulomb distortion of the projectile wave functions and multi-electron processes allows one to describe the *mean charge* of the fast-ion beams penetrating through atomic and plasma targets.

References

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