Changes in effective charge-exchange cross sections in a plasma

V. A. Abramov, V. S. Lisitsa, and A. Yu. Pigarov
I. V. Kurchatov Institute of Atomic Energy, Moscow

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The effective cross sections for the charge exchange of protons and multiply charged ions with hydrogen atoms in a plasma are calculated. The presence of excited atoms is taken into account. For typical plasma properties, these effective cross sections may exceed by an order of magnitude or more the values ordinarily used for the charge exchange of ground-state atoms.

The charge exchange of ions with atoms is usually analyzed on the basis of calculations or measurements of the charge-exchange cross sections for ground-state atoms. The effective values of these cross sections may be quite different in a plasma, however, because of the charge exchange of ions with excited atoms. For this reason, the penetrability for ions of a plasma slab containing excited neutral atoms may be sharply different from the penetrability estimated from the results of beam experiments, where excited atoms play no role.

Let us estimate the excited-state component of the effective cross sections for the charge exchange of atomic hydrogen with protons and multiply charged ions. This component is conveniently characterized by the effective cross section for the charge exchange of the ion with the atom, σ_{eff}:

$$\sigma_{eff}(E, N_e, T_e) = \sigma_1(E)[1 + \sum_{n \geqslant 2}^{n_{max}} N_n(N_e, T_e)\sigma_n(E)/N_1\sigma_1(E)]. \tag{1}$$

Here $\sigma_1(E)$ and $\sigma_n(E)$ are the charge-exchange cross sections in the ground state ($n = 1$) and excited states ($n \geqslant 2$) of the atom; N_1 and N_n are the corresponding populations of atomic levels; and n_{max} is the maximum quantum number in the plasma. The effective cross section for charge exchange in the plasma, σ_{eff}, depends on not only the energy (E) of the particles but also the plasma properties: the temperature T_e and the density N_e (and also other properties, e.g., the magnetic field B; more on this below).

Under ordinary conditions the populations N_n are extremely small, on the order of $10^{-5}N_1$ (see Ref. 1, for example). This small value is offset, however, by the sharp increase in the cross section with increasing n: $\sigma_n \sim n^4$ (Refs. 2 and 3). This functional dependence can easily be found from calculations for charge exchange by the classical mechanism[2,4]:

$$\sigma^{\text{res}}(n) = 18\pi n^4, \quad \sigma^Z(n) = 8\pi Z n^4, \tag{2}$$

were $\sigma^{\text{res}}(n)$ is the cross section for the resonant charge exchange of a proton with an atom in state n, and $\sigma^Z(n)$ is the cross section for charge exchange with an ion of charge $Z \gg 1$. It is important to note that relations (2), which follow from the classical mechanism, are "universal" in the sense that at $n \gg 1$ they do not depend on the detailed behavior of the terms of the particles involved in the charge exchange (in contrast with the situation in the case of charge exchange in the ground state).

As can be seen from (1) and (2), σ_{eff} depends strongly on the number $n_{\max}$, which is itself determined by three effects. First, at $n \gg 1$ the cross sections σ_n become very strong functions of the energy. This functional dependence can be found by comparing the collision scale time $\tau_n \sim R_n / v(R_n \sim \sqrt{\sigma_n} \sim n^2)$ with the period of the orbital revolution of an electron, $\tau_n \sim n^3$. It is then a simple matter to determine the scaling law, which relates the energy dependence of the cross section in the ground state to that in the excited state (cf. Ref. 3):

$$\sigma_n^{\text{res}}(E) = n^4 \sigma_1^{\text{res}}(En^2), \quad \sigma_n^Z(E) = \sigma_1^Z\left(\frac{En^2}{Z}\right) n^4, \tag{3}$$

where $\sigma_1^{\text{res}}(E)$ and $\sigma_1^Z(E)$ are the charge-exchange cross sections in the ground state. In the calculations below, we use the data of Ref. 5 for resonant charge exchange and the decay model of Ref. 6 for charge exchange with an ion with $Z \gg 1$.

Second, the values of $n_{\max}$ may be determined by the ionization of states with $n \gg 1$ in the ion "microfield" of the plasma. The critical field value F_c, corresponding to ionization of level n, is given in order of magnitude by $F_c \sim 1/8n^4$ (Ref. 7, for example). The ionization of the states is taken into account (after Ref. 7) by multiplying the populations N_n by the probabilities (f_n) for the realization of field F below F_c. When we use a field distribution function $W(F)$ in the form of a nearest-neighbor distribution, the factor f_n is

$$f_n = \exp[-95(N_e/N_A)n^6], \tag{4}$$

where $N_A = 8 \times 10^{24}$ cm^{-3} is the atomic density.

Finally, a third group of effects limiting $n \leqslant n_{\max}$ stems from the ionization of atomic states in the Lorentz electric field $F_L \sim (v/c)B$ which arises as atoms move in systems with a strong magnetic field B.

For a plasma with $T_e \gtrsim 10$–10^2 eV and $N_e \lesssim 10^{15}$ cm^{-3}, some 20 levels are involved ($n_{\max} \sim 20$).

We have calculated effective cross sections from expressions (1), (3), and (4), using populations N_n determined numerically on the basis of a standard collision-radiation model.[1] We consider, in addition to the excitation and ionization by electrons, the contribution of protons. For the resonant charge exchange we also take into account the resonance shift of the type in Ref. 8 in the plasma "microfield."

Figure 1 shows the cross section for resonant charge exchange, $\sigma_{\text{eff}}(E)$, as a function of the energy E for various plasma parameters N_e and T_e. The curve corresponding to $T_e = 1$ eV coincides with the cross section for the ground state.[5] We see that the cross section is increased substantially by the charge exchange with excited atoms. Figure 2 shows how excited states ($n \geqslant 2$) contribute to the charge exchange of

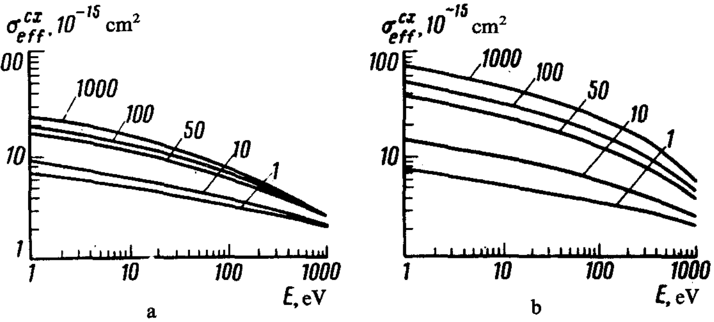

FIG. 1. Effective cross section for resonant charge exchange of atomic hydrogen, $\sigma_{\rm eff}$, versus the energy E for various values of N_e and T_e. a—$N_e = 10^{13}$ cm^{-3}; b—$N_e = 10^{15}$ cm^{-3}. The curves are labeled with the temperature T_e in electronvolts.

carbon nuclei (C^{+6}) with atomic hydrogen. The charge-exchange cross section in the ground state, according to the data of Ref. 9, is shown by the dot-dashed line. We see that excited states can change the cross section by more than an order of magnitude at small energies E. The reason for the change is the universal mechanism for charge exchange from excited states mentioned above [see (2)], which does not lead to a sharp decay at small energies E, in contrast with charge exchange in the ground state. For large values of E, the contribution of excited states falls off in accordance with scaling law (3). Calculations have been carried out for various values of the parameters N_e and T_e (see the curves in Fig. 2) in a plasma with a magnetic field $B = 5$ T (this value is close to the magnetic field in several magnetic-confinement fusion devices).

It can also be seen from Fig. 2 that the contribution of excited states to the cross section can be comparable (curve 1) to the cross section for classical charge exchange from the ground state, $\sigma_1^Z \sim 8\pi Z$. However, the classical mechanism for charge exchange does not operate at low energies for the ground state, but it can operate for excited states, since large distances $R \sim n^2\sqrt{Z}$, over which the exchange interaction is weak, are a factor in this case.[2]

These calculations thus confirm that the effective cross sections for charge ex-

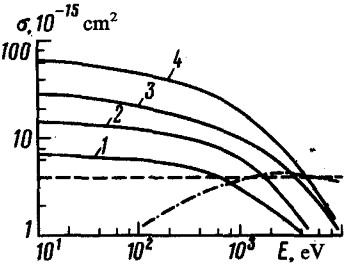

FIG. 2. Component of the cross section (σ) for the charge exchange $H^0(n) + C^{+6}$ from excited states ($n \geqslant 2$) versus the energy E for various parameter values. 1—$N_e = 10^{13}$ cm^{-3}, $T_e = T_i = T = 500$ eV; 2—$N_e = 10^{13}$ cm^{-3}, $T = 100$ eV; 3—$N_e = 10^{14}$, $T = 500$ eV; 4—$N_e = 10^{14}$ cm^{-3}, $T = 100$ eV. Dot-dashed line—Calculations of Ref. 9 for charge exchange in the ground state; dashed line—classical cross section for the ground state ($8\pi Z$).

change in a plasma may differ sharply from the estimates and measurements of these cross sections for the ground state.

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