Change of intensity of spectral lines of multiply charged ions as a result of charge exchange with atomic hydrogen

V. A. Abramov, F. F. Baryshnikov, and V. S. Lisitsa

A general formula is obtained for the distribution W_l of the charge-exchange cross sections with respect to the orbital angular momentum. The results of the calculations are used to analyze an experiment on the injection of a beam in the ORMAK installation. The theory developed explains the main qualitative regularities of the line intensities of the impurity ion O^{+7} and provides an estimate of the ratio of the concentrations of the O^{+8} and O^{+7} ions.

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1. Charge exchange of neutral hydrogen with multiply charged ions is presently under intensive study.[1-4] In many problems, an important role is played not only by the total cross sections σ, but also by the partial charge-exchange cross sections σ_{nl},

where n and l are the principal and orbital quantum numbers of the state of the final ion. We obtain below the distributions W_l of the cross sections with respect to the orbital angular momenta and use them to calculate the intensities of a number of lines of the hydrogenlike ion O^{+8}, which was recently observed in experiment.[5]

The cross sections and the distribution W_l can be obtained by using the Landau-Zener method[8] but the results obtained by this method contradict the experimental data.[5]

The correct distribution W_l can be obtained by taking into account the rotation of the axis joining the nuclei. In fact, according to[3], charge exchange takes place near the points of the crossing of terms in the state $|0\rangle$ with parabolic quantum numbers $n_1 = m = 0$, $n_2 = n - 1$. If the state $|0\rangle$ is correct, then W_l is determined by the square of the Clebsch-Gordan coefficients $|C_{JJJ-J}^{l0}|^2$, $J = n - 1/2$, which determines the expansion of $|0\rangle$ in spherical functions. However, at the high collision velocities of interest to us ($E \sim 10$ keV) the state $|0\rangle$ is not the correct one, owing to transitions to other $n^{-2} - 1$ degenerate states, due to rapid rotation of the axis joining to nuclei, with angular velocity $\Omega \sim v/R_0$ (v is the velocity and R_0 is the charge-exchange radius). In this case the correct states of the ion are parabolic states with OZ axis perpendicular to the axis joining the nuclei. A situation of the "jarring" type is realized: at the charge-exchange point the transition is to the state $|0\rangle$, whereas the correct states between these points are the indicated parabolic states. Expanding the wave function of the initial state $|0\rangle$ in terms of the parabolic states of OZ axis perpendicular to the axis between the nuclei and changing over to spherical harmonics, we easily obtain

$$W_l = \frac{\sum\limits_{L_1 L_2 \neq |0\rangle} |C_{JL_1 J'L_2}^{e\,m}|^2 \binom{2J}{L_1}\binom{2J}{L_2}}{2^{4J} - 1}, \tag{1}$$

where

$$L_{1,2} = \frac{m \pm (n_2 - n_1)}{2}, \quad |0\rangle = |'L_1 = -'L_2 = J\rangle, \quad \binom{n}{m} = \frac{n!}{m!(n-m)!}.$$

Comparison with the more general method of[6] shows that formula (1) gives the correct result in the region $Z^{-3/4} < v/v_0 < 1$ ($v_0 = 2.18 \times 10^8$ cm/sec). Figure 1 shows the
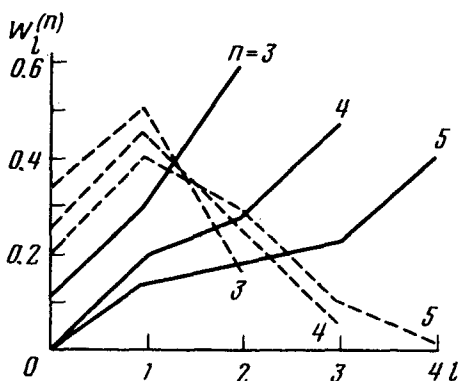

FIG. 1. Distribution of the cross sections of the $H + O^{+8}$ charge exchange with respect to the orbital angular momenta l; solid curves–fast collisions, dashed–slow collisions.

result of the calculation of the distribution W_l for the levels $n = 3$, 4, and 5 of the O^{+8} ions in the two cases of slow and fast collisions.

2. Taking the distributions W_l into account, we calculated the intensities of the lines of the O^{+7} ions for conditions close to those of[5].[1] In the calculations we used the corona model, which takes into account the population of the states by charge exchange (with the atoms of both the beam and of residual gas of density $N_{H_0} = 3 \times 10^8$ cm^{-3}), the excitation (the cross sections were taken from[8]), and their depletion by radiative transitions. Experiments has revealed that the line emission increases not only as a function of the beam intensity but also as a function of a geometric factor equal to the ratio of the volumes occupied by the beam V_1 and by the plasma V_2 along the observation line. The relative change r_k of the intensity of a given line k is

$$r_k = 1 \div \frac{\int\limits_{V_1} (I_k - I_k^{(0)})\, dv}{\int\limits_{V_1 + V_2} I_k^{(0)}\, dv} \approx 1 + \frac{V_1}{V_1 + V_2}\left(\frac{I_k}{I_k^{(0)}} - 1\right), \tag{2}$$

where I_k and $I_k^{(0)}$ are the intensities of the emission from a unit volume with the beam turned on and off, respectively. If we assume, in accord with[5], that $r_k = 4$ for the H_α line, then we have for the other lines

Line	L_α	L_β	L_γ	L_δ	H_α	H_β	H_γ	P_α	P_β	B_α
r_k	1.25	1.23	1.44	2.4	4	3.9	8	18	12	26

The results of the calculations are in good qualitative agreement with[5], with exception of the H_β line, whose intensity changes insignificantly according to[5]. This discrepancy can apparently be attributed to the insufficient experimental accuracy of the intensities of the O^{+7} Balmer lines that lie near the intense iron lines.

Our analysis leads to certain conclusions concerning the ratio $\gamma = N_{O^{+8}} / N_{O^{+7}}$ of the concentrations of the ions of different multiplicity. According to the corona model, with account taken of the finite diffusion lifetime $\tau \sim 35$ msec of the ion, under the conditions of[5] γ changes from 15 to 3 when N_{H_0} changes from 3×10^8 to 3×10^9 cm^{-3}. The experimental value determined from the change of the intensity of the H_α line is much smaller, and ranges from 3.6 to 0.6 when the geometric factor changes from 0.1 to 0.5. Both values of γ can be reconciled only with the rather small geometric factor (0.1) and a large density of the residual gas ($N_{H_0} \sim 3 \times 10^9$ cm^{-3}). However, since a typical value for ORMAK is $N_{H_0} \sim 3 \times 10^8$ cm^{-3}, the aforementioned discrepancy points to a considerably higher diffusion rate of the O^{+8} nuclei than given by the neoclassical theory.

[1] The general scheme of such experiments is discussed in[7].

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