Filling of various electronic states in collisions of multiply charged argon ions with hydrogen atoms and molecules

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The absolute values of the cross sections for the capture of an electron to various specific levels, with excitation energies of 20–70 eV, by multiply charged ions at closing velocities in the range $(1\text{–}6)\times 10^7$ cm/s have been measured for atomic hydrogen for the first time.

Studies of the interaction of multiply charged ions I^{k+} with H atoms have been stimulated by problems associated with impurities of heavy elements in a hot hydrogen plasma.[1] An admixture of argon in hydrogen was used in Ref. 2 to model the behavior of ions in a plasma. Spectroscopic diagnostics of impurities on the basis of the emission which appears during the decay of excited states of multiply charged ions requires data on the filling of these states during the capture of electrons from H atoms by multiply charged ions. The difficulties in the corresponding experiments have so far limited the data to primarily the total capture cross sections. Estimates of the partial cross sections for the capture of electrons to specific states can be calculated. The reliability of model calculations is usually tested by comparing the values of total cross sections, but that method does not guarantee that the values of the partial cross sections will be correct. The most sensitive method for testing models would be to compare experimental and theoretical values of specifically the partial cross sections.

In this letter we report measurements of the filling of definite levels of $I^{(k-1)+}$ ions formed in the capture process $I^{k+} + \mathrm{H} \rightarrow I^{(k-1)+} + \mathrm{H}^+ + \Delta E$, where ΔE is the energy defect of the process. For these measurements we used a method of "collisional spectroscopy" at velocities of the colliding particles in the range $V = (1-6)\times 10^7$ cm/s. A beam of multiply charged Ar^{k+} ions with an initial energy spread of 0.3·keV passes through a gas-filled chamber and is then analyzed by charge and kinetic energy by an electrostatic analyzer with a resolution of 6×10^3 (Ref. 3). Since for each state of the $\mathrm{Ar}^{(k-1)+}$ ion which is populated, there is a corresponding value of ΔE, the states can be identified from the positions of the peaks in the kinetic-energy spectrum of the ions after the capture of the electron. The corresponding partial cross section is found from the area under this peak. An important point is that this method also makes it possible to monitor for the presence of ions in metastable states in the primary beam of impurities, since in this case the spectrum would contain several systems of peaks, displaced along the energy scale. An absolute calibration of the cross sections for the capture of electrons to various electronic states of the $\mathrm{Ar}^{(k-1)+}$ ion was carried out on the basis of measurements of the absolute values of the total capture cross sections by a potential method. Since the scattering of the ion beam after the capture is only slight, this method makes it possible to detect essentially all of the $\mathrm{Ar}^{(k-1)+}$ ions

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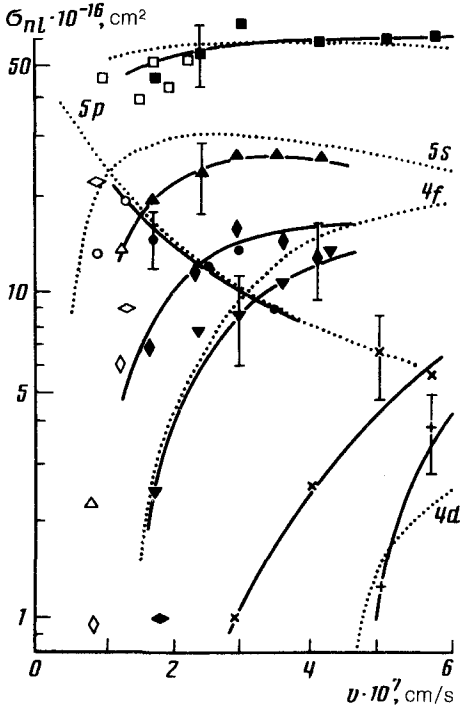

FIG. 1. Cross sections for the capture of an electron from H atoms by Ar^{+6} ions. ■—Total cross sections; ●—capture to the Ar^{+5} ($5p$) state; ▲—$5s$; ♦—$4f$; ▼—$4d$; ×—$4p$; +—$4s$. ○, △, ◇, ▽—5p, $5s$, $4f$, $4d$, from Ref. 5. The dotted lines were calculated from the Landau–Zener model in accordance with Ref. 7.

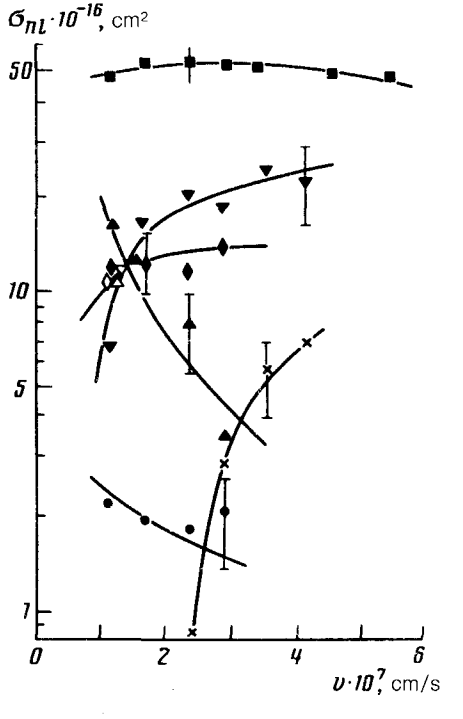

FIG. 2. Capture cross sections for the Ar^{+6}–H_2 pair (the notation is the same as in Fig.1).

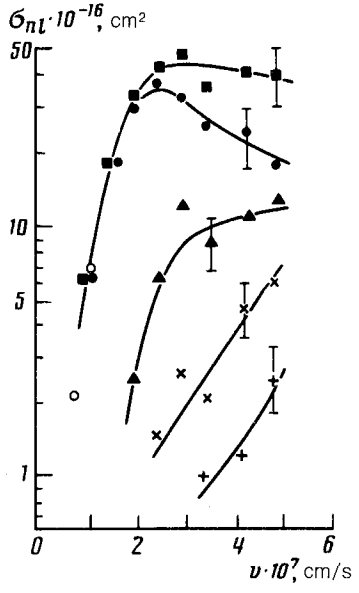

FIG. 3. Capture cross sections for the Ar^{+4}–H pair. ■—Total cross sections; ●—$3s^23p^24p$; ▲—$3s^23p^24s$; ×—$3s^23p^23d$; +—$3s3p^4$; and ○—$3s^23p^24p$ (Ref. 5).

which have captured an electron. The method is thus three orders of magnitude more sensitive than the optical method of detecting the emission accompanying the decay of excited states of the ions. A further advantage of the method of collisional spectroscopy is that its sensitivity does not depend on the excitation energy of the level between a few electron volts and hundreds of electron volts; nor does it depend on the lifetime of the level.

The experimental results are shown in Figs. 1–3. The values which we found for the total cross sections agree well with the data reported by other investigators.[4] Over the velocity range studied, the total cross sections depend weakly on the velocity, and they increase essentially linearly with increasing charge of the impinging ion. Some of the partial cross sections do vary markedly with the collision velocity. Their values agree well with data from Ref. 5, found for several states by the same method at $V \cong 10^7$ cm/s. At the closing velocities studied, the capture results from electronic transitions at quasicrossings of the incoming term $[Ar^{+k} + H(1s)]$ with terms of the final states $[Ar^{(k-1)+}(nl) + H^+]$. It can be seen from Figs. 1–3 that the curves of the captured cross section, which increase with increasing V, correspond to states with the smallest excitation energies, i.e., with the largest resonance defect for the process. Consequently, the points of their quasicrossings with the incoming term lie at smaller distances, while the decaying curves correspond to states with a larger excitation energy. Comparison of the partial cross sections for the filling of the same levels of the Ar^{+5} ion in H and H_2 (Figs. 1 and 2) shows that as the ionization potential of the target increases (H_2), some deeper levels become populated. As the charge of the impinging ion increases, with a given target particle (Figs. 1 and 3), levels with higher quantum numbers are filled more effectively. Because of the increase in the charge of the ion, these levels have a high ionization potential and a large excitation energy.

Our estimates of the partial cross sections on the basis of the multilevel Landau-Zener model,[6] with the matrix elements given by the formulas of Ref. 7, provide a statisfactory agreement for the total cross sections and for the cross sections for the filling of highly excited states [the $5p$ and $5s$ states for the Ar^{+6}–$H(1s)$ pair]. The partial cross sections for capture to the deeper $4d$ and $4f$ levels are significantly lower, apparently because of the fact that the matrix elements in Ref. 7 were determined through the use of asymptotic wave functions, which give a satisfactory description of a quasimolecule in the case in which the electronic levels in the potential wells of the multiply charged ion and the proton are separated by a barrier. At $R = 2(2\sqrt{k} + 1)$, however, the barrier disappears at the axis joining the nuclei, and at $R = \sqrt{8k}$ there is no barrier between the nuclei at all.[8] At distances $R < \sqrt{8k}$ it is thus necessary to calculate the wave functions of the system directly and to determine the matrix elements.

In summary, the method of collisional spectroscopy makes it possible to directly measure the populations of various electronic states, differing greatly in excitation energy, and to extract data important for practical use in the diagnostics of multiply charged impurity ions and also for testing the validity of various models.

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