Electron capture in different electronic states by multiply charged Ar^{+Z} ions in He atoms

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It was found experimentally that the cross section for the capture by the ions Ar^{+Z} ($Z=3$–7) is (1–2)$\times 10^{-15}$ cm^2. There is no monotonic dependence of the cross section on Z. The ions $Ar^{+(Z-1)}$ are produced only in excited states, while the number of the states populated upon capture is small (2–3).

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A study of the interaction of mutiply charged ions with atoms of a gas, and particularly of the capture of electrons by these ions, is of considerable interest for the analysis of the role of multiply charged impurity ions in the energy balance of a high-temperature plasma, as well as for the development of effective methods of obtaining particles with excitation energies of dozens of electron-volts.

The main task in the study of the capture processes is the determination of the capture cross sections and of the dependence of the cross sections on the charge of the incident ion, and the determination of the electronic states of the produced less-charged ions. Experimental data evidencing the formation of excited ions in electron-capture processes were cited already earlier,[1,2] but no information was available so far on the population of the states or on the absolute values of the cross sections of such processes.

We have developed a procedure for measuring the absolute cross sections of electron capture in definite electronic states. To separate the process $Ar^{+Z}+He \rightarrow Ar^{+(Z-1)}+He^{+}$ we used an analysis of the charge states of the fast and slow ions and registration of both ions ($Ar^{+(Z-1)}$ and He^{+}) produced in the same collision, by a coincidence method. No free electrons are produced in

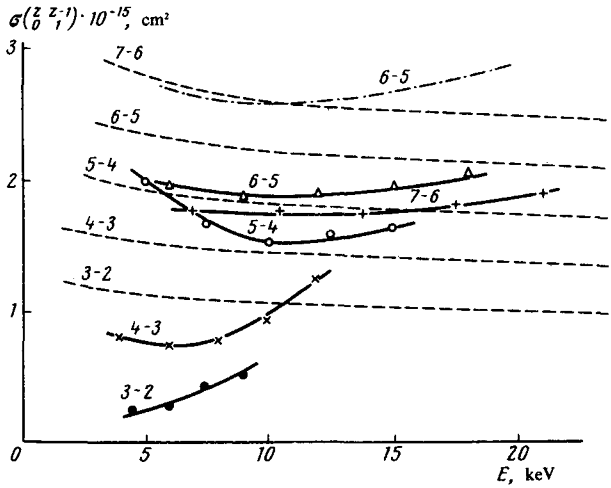

FIG. 1. Total cross sections for the capture of one electron $Ar^{+z}He(1s^2) \rightarrow Ar^{+(z-1)} + He^{+}(1s)$ in all states of the produced argon ions $Ar^{+(z-1)}$, $z=3$–7. The change in the charge of the argon is marked on the corresponding curves. Solid curves—present study, dashed—calculation on the basis of[7], dash-dot—data of[3].

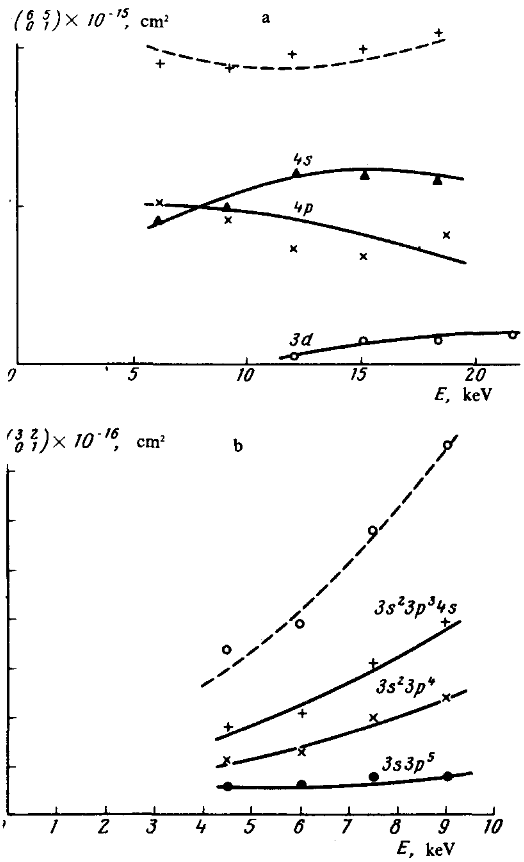

FIG. 2. Cross sections for electron capture in definite states: a) for the process $Ar^{+6}+He(1s^2)\rightarrow Ar^{+5}(n,l)+He^{+}(1s)$. Dashed line—total cross section for the capture into all states, solid—into definite states of Ar^{+5} as marked on the corresponding curves. b) for the process $Ar^{+3}+He(1s^2)\rightarrow Ar^{+2}(n,l)+He^{+}(1s)$. The notation is the same.

he capture process, and each electronic state of the produced ions corresponds to a definite change of their kinetic energy. Therefore, to determine the electronic states of the recorded ion—the collision products—we used a precision analysis of the kinetic energies of these ions. The investigated range of energies E of the incident Ar^{+Z} ions was $(1–4)Z$ keV. The resolving power in the analysis of the energy spectra of the ions, determined by the scatter of the ion energies in the primary ion beam and by the parameters of the energy analyzer of the product ions, made it possible to study separately the population of levels separated by a distance $\Delta E \gtrsim 0.5Z$ eV. The described procedure made it possible not only to separate directly the single-electron capture and to measure its absolute cross section, but also to obtain, for the first time ever, data on the population of the states produced by capture of multiply charged ions.

Data on the total cross sections for electron capture in all states of the ions $Ar^{+(Z-1)}$ (Fig. 1) show that the monotonic dependence of the cross section on the charge Z, predicted by the theory (Z^2,[4,5] $Z^{1.5}$,[6] $Z \ln Z$ [7]) for $Z=3–7$, is not observed. It is seen at the same time that the absolute cross sections calculated on the basis of the formulas of[7] agree satisfactorily, in order of magnitude, with the experimental data and can be used to estimate the scattering cross sections. We note also that the total capture cross sections depend little on the energies of the incident ions E in the investigated interval, while for the processes 4–3, 5–4, and 6–5 the experimental curves even have minima.

The investigation of the cross sections for capture into definite states of the ions $Ar^{+(Z-1)}$

shows that only excited states are populated in practice at $Z>3$. The number of these states i small (2–3), and transitions to these states correspond to exothermal processes. The presence o minima on the curves of Fig. 1 is due to the redistribution of the population of the excited state when the energies E of the colliding particles change, and to the different behaviors of the cros sections $\sigma(E)$ for capture into each of the states. By way of illustration, Fig. 2a shows the result of our measurements of the cross section for electron capture into different states of the Ar^{+5} ion $-4s$ (ion excitation energy $\Delta E=42.4$ eV, $-4p(\Delta E=53.2$ eV) and $3d(\Delta E=27.1$ eV) for th process $Ar^{+6}+He \to Ar^{+5}(n,l)+He^{+}(1s)$.

In the investigated range of the velocities of the ions Ar^{+Z}(0.03–0.15 a.u.), the electroı capture process can be regarded as the result of Landau-Zener transitions following a quasicrossin of the initial term of the system $[Ar^{+Z}+He(1s^2)]$ with the terms of the final states $[Ar^{+(Z-1)}(n,l)$ $+He^{+}(1s)]$. It is known that for each such transition the cross section at the maximum can be use to estimate the internuclear distance R where the quasicrossing is located.[8] The transition to th $4s$ state of the Ar^{+5} ion has a maximum cross section 1.2×10^{-15} cm^2 at $E\sim15$ keV (Fig. 2a), henc $R=5.5a$. An estimate of R from the condition that the energy difference of the states $[Ar^{+6}-He$ and $[Ar^{+5}4s-He^{+}(1s)]$ be equal to the energy of the Coulomb repulsion of the ions Ar^{+5} and He yields $R=5.7a_0$. The agreement of such estimates of R obtained also for other pairs attests to th applicability of the Landau-Zener model to the description of the capture of the electron.

In the case of smaller Z (Ar^{+3}–He, Fig. 2b), the picture of the transitions turns out to be mor complicated and one observes both exothermal transitions to the $3s^23p^4$ level of the Ar^{+2} io $(\Delta E\sim2$ eV), and endothermal transitions to the $3s^23p^34s$ level $(\Delta E\sim26$ eV).The reason is that th state of the system $[Ar^{+2}2s^23p^34s$–$He^{+}(1s)]$ lies higher, but close enough (~2 eV) to the initia Ar^{+3}–He state. Under these conditions, in addition to Landau-Zener transitions to the $3s^23p^4$ leve transitions that are describable by the Rosen–Zener–Demkov model become possible. The excita tion energy of the third state shows that its population is connected with the process of one mor type—two-electron transition—capture of an electron from the shell of the He atom with simulta neous excitation of the core of the Ar^{+3} ion, which leads to formation of the ion Ar^{+2} in the stat $3s3p^5$.

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