Processes involving the capture of an electron by the nuclei of atoms near helium atoms and hydrogen molecules at low energies

V. V. Afrosimov, A. A. Basalaev, E. D. Donets, K. O. Lozhkin, and M. N. Panov

A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR

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The cross sections $\sigma^{z,z-1}$ for capture of an electron by C^{+6}, N^{+7}, O^{+8}, Ne^{+10}, and Ar^{+18} nuclei as a result of collisions with helium atoms and hydrogen molecules at incident-particle energies $E = 0.5$–8 keV/amu have been measured.

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One of the processes that plays an important role in the energy balance of high-temperature plasma in controlled thermonuclear fusion devices is the electron capture of heavy elements by impurity atoms. The radiation of the excited ions of lower charge can remove a large amount of energy from the plasma. To estimate the radiation flux, we must know the cross sections for capture of an electron by nuclei of the impurity elements at the energies of colliding particles $E \cong 0.1$–10 keV/amu. However, the available data pertain to the high-energy region $E \sim 100$ keV/amu, because of the difficulties involved in obtaining low-energy nuclear beams. In our work we have measured for the first time the dependence of the cross sections for capture of an electron by C^{+6}, N^{+7}, O^{+8}, Ne^{+10}, and Ar^{+18} nuclei near the He atoms and H_2 molecules in the region of collision energies $E = 0.5$–8 keV/amu that is of interest to high-temperature plasma physicist.

The capture cross sections were determined by analyzing the charge state of the beam passing through a gaseous target. The density of the target satisfied the condition for single collisions.

The total cross section for formation of an ion of lower charge $\sigma^{z,z-1}$, which was measured in the experiment, is the sum of the cross sections of two elementary processes: a) one-electron capture (cross section $\sigma_{0,1}^{z,z-1}$)

$$A^{+z} + B - A^{+(z-1)} + B^{+}, \tag{1}$$

b) electron capture with ionization (cross section $\sigma_{0,2}^{z,z-1}$)

$$A^{+z} + B - A^{+(z-1)} + B^{+2} + e^{-} \tag{2}$$

The measurement results are shown in Figs. 1a and 1b. The errors in determining the absolute cross sections amount to ~20%.

Sufficiently low collision velocities ($v = 0.14$–0.6 a. u.) make it possible to consider the interaction of particles within the framework of quasimolecular concepts and to use the Landau-Zener model for estimating the probability of electron transi-

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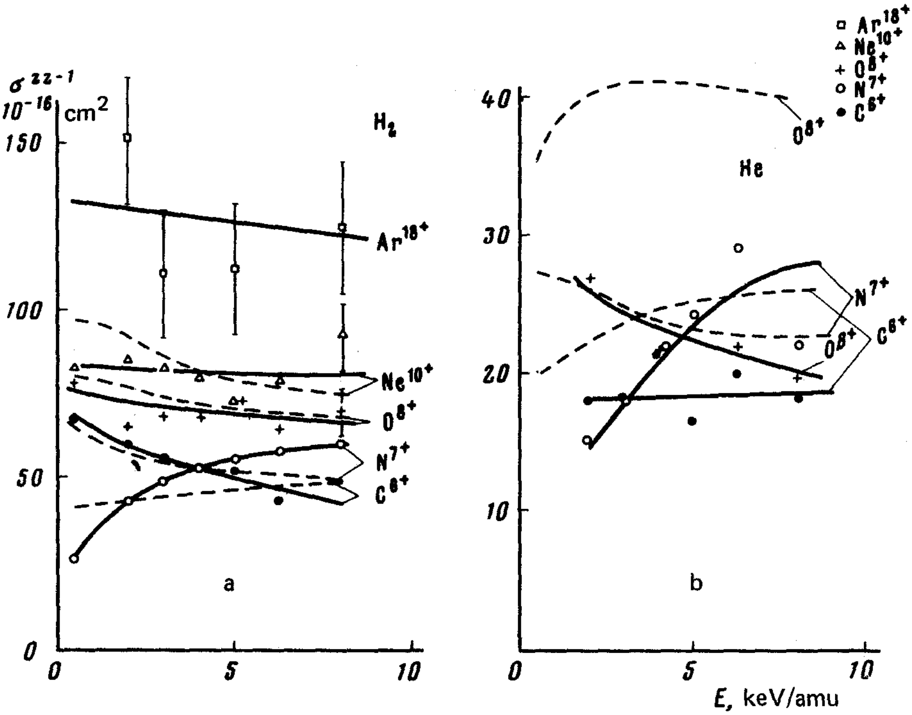

FIG. 1. Total cross sections for capture of an electron by C^{+6}, N^{+7}, O^{+8}, Ne^{+10}, and Ar^{+18} nuclei. The dashed lines are the result of estimates of the cross sections from Eq. (4), The nuclear charges are indicated near the corresponding curves: a—in molecular hydrogen, b—in helium.

tions. [Because of the large capture cross sections and, consequently, the convergence distances R, at which the electron transitions occur, the H_2 molecules can be considered as an atom with the corresponding ionization potential $1(H_2)$.] As the nucleus with a charge z (A^{+z}) approaches the target B, the term of the initial state of the system passes through a series of quasi-intersection points with the terms of the final states corresponding to different excitations of the ion $A^{+(z-1)*}$(Fig. 2). At the approach velocities in question the system passes diabatically through the region of far quasi-intersections (for the O^{+8}-H_2 pair these are $R_1 \cong 300$ and $R_2 \cong 20$ a. u.), and the contribution of these quasi-intersections to the cross section for one-electron capture is negligible. (The splitting of terms, which determines the transition probabilities at the particle-approach velocities, was estimated from the Salop and Olson formula as a function of the internuclear distance.[1]) The contribution to the cross section of the next quasi-intersection at $R_3 \sim 10$ a. u. was estimated from the Landau-Zener formula on the basis of the term splitting,[1] the distance R_3 to the quasi-intersection, and the universal curve for the cross sections, which was obtained in Moiseiwitsch's paper.[2] The R_3 quasi-intersection is well separated from the other quasi-intersections in terms of approach distance, and the problem can be treated as a two-level problem. The value of the cross section $\sigma_{L\text{-}Z}^{z,z-1}$ was corrected for the coefficient K, which takes into account the influence of the finite width of the quasi-intersection

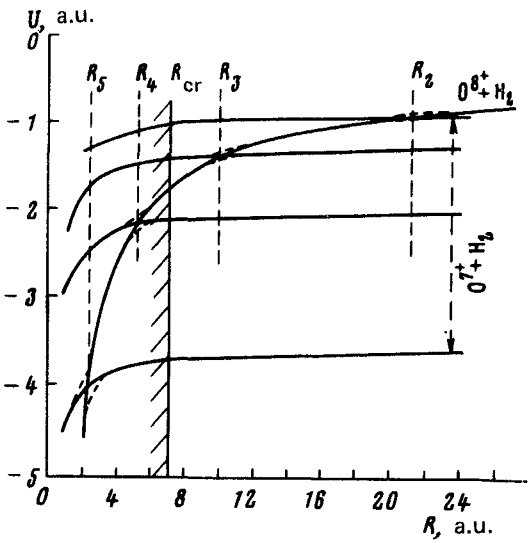

FIG. 2. Schematic diagram of curves for the $O^{+8}+H_2-O^{+7}(n)+H_2^+$ system; $U(O^{+8}+H_2) = -[8\alpha(H_2)/2R^4]-(8/R)-I(H_2)$; $U(O^{+7}+H_2^+) = -(1/R)-I(O^{+7}*(n))$. I_{H_2} is the ionization potential, α is the polarizability of the H_2 molecule, and n is the principal quantum number of the state of the O^{+7} ion. The n values are indicated near the corresponding curves. I—Region of Landau-Zener transitions, II—region of the above-barrier transitions (absorbing-sphere model).

region on the electron-transition probability in accordance with Ovchinnikova's work.[3] The value of K depends on the approach distance of the particles, at which the quasi-intersection is reached, and also on the slope and splitting of the terms in this region. In some cases, allowance for the finite width of the quasi-intersection region can increase the cross section by a factor of 2 compared with the $\sigma_{L\text{-}Z}$ cross section. Transitions in the region $R \sim 10$ a.u. determine the population of the levels of the O^{+7} ion with principal quantum number $n=5$. At smaller $R<5$ a.u. several terms interact at the same time, and the cross section in this region cannot be estimated on the basis of a numerical solution of the two-level Landau-Zener problem that was obtained in Ref. 2. However, the potential barrier between the potential wells of the target atom and the multiply charged ion vanished at a distance R_{cr} ($R_{cr}>R_4$), which is determined on the basis of the study of Komarov *et al.*[4]

$$R_{cr} = \frac{1}{I_{H_2}}[\sqrt{2I_{H_2}} - 1 + \sqrt{2(z-1)+I_{H_2}}], \qquad (3)$$

for a target electron, and the electron transitions from one well to the other are allowed classically. We assumed that the probability of capture of an electron by a multiply charged ion in the region $R<R_{cr}$ is equal to unity ("absorbing -sphere" model), and the total cross section for electron capture is defined by the expression

$$\sigma^{z,\,z-1} = K\sigma_{L\text{-}Z}^{z,\,z-1} + \pi R_{cr}^2 . \qquad (4)$$

In this case it was found that the contribution of the first and second terms is approximately the same (the cross section for the Ar^{+18}-H_2 pair was not estimated because of the presence of two quasi-intersections that contribute to the cross section for one-electron capture). The dashed lines in Figs. 1a and 1b show the results of the estimates of the cross sections $\sigma^{z,z-1}$ using Eq. (4). We should point out the excellent agreement between the estimated and experimental values of the cross sections for C^{+6}, N^{+7}, O^{+8}, Ne^{+10}- H_2 and O^{+6}, N^{+7}- He. The observed deviation of the shape of the curves for the N^{+7}- H_2 and He pairs and the factor-of-two difference in the cross sections for the O^{+8}- He pair are expected for such a method of estimating the cross sections, which gives a satisfactory agreement with experiment, on the whole.

The obtained data for the cross sections $\sigma^{z,z-1}$ indicate that the process of electron capture by multiply charged ions occurs at large internuclear distances $R \sim 10$ a.u., and that the cross sections can exceed 10^{-14} cm^2 (the Ar^{+18}-H_2 pair). The nonmonotonic dependence of the capture cross section on the charge of the bombarding ion, which is observed at low energies, becomes regular with increasing kinetic energy E. In the investigated region of energies E the dependence of the cross sections on the charge z of the bombarding ion is close to linear, as indicated previously in Chibisov's paper[5] and in our paper.[6] A satisfactory agreement between the estimates of the cross sections and the experimental data makes it possible to conclude that at particle-converging velocities of 0.14–0.6 a.u. the one-electron capture process is described sufficiently well by the transitions between the terms of a quasi-molecular system, and the Landau-Zener model can be used to estimate the impact parameters $R > R_{cr}$ and the absorbing-sphere model can be used for $R < R_{cr}$.

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