Electron capture cross sections of nuclei and multiply charged ions at hydrogen atoms

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Cross sections for capturing an electron at hydrogen atoms by nuclei and hydrogen- and helium-like carbon, nitrogen, oxygen, and neon ions with approach velocities $(3-10)\times 10^7$ cm/s, corresponding to plasma-particle velocities in modern thermonuclear installations, are measured. The measured cross sections are compared with the results of theoretical calculations.

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Interest in studying the interactions of multiply charged ions with hydrogen atoms is primarily due to the multiply charged ionic impurities in high-temperature plasma devices for controlled thermonuclear fusion. In the range of velocities of the colliding particles $v = 10^7$–10^8 cm/s, such as experiment encounters considerable difficulties related to problems of obtaining beams of nuclei or multiply charged ions with such velocities and with creating targets consisting of atomic hydrogen. Until now, in this range of velocities the cross sections for capture of an electron in hydrogen atoms by nuclei were measured only for the pair C^{+6}-H for two values $v = 1.7$ and 2×10^7 cm/s.[1] For this reason, in analyzing processes occurring in a plasma and estimating the concentration of impurities in it theoretical values of the cross section for electron capture at H atoms by nuclei calculated in Refs. 2–13 are used. However, the theoretical calculations of the cross sections differ strongly (Fig. 1), and it is necessary to have experimentally measured quantities.

In this work, the cross sections for electron capture at hydrogen atoms by nuclei and hydrogen-like C, N, O, and Ne ions are measured for the first time and the measurements for helium-like ions of these elements are repeated.

The total cross section σ for capture of an electron by an ion with a charge z, when an ion with a charge lower by one unit $z-1$ is formed, was determined by analyzing the charge composition of a beam passing through a gaseous target with known density. The KRION-2 source was used in order to obtain a beam of multiply charged ions.[14] The target consisting of atomic hydrogen was created by thermally dissociating H_2 molecules in a tantalum collision chamber and heated with an electron beam to temperature 2500 K. The temperature was monitored with a pyrometer. The density of the target was determined by a method analogous to that used by Bayfield.[15] The temperature dependence of the target density was determined by measuring the nuber of C^{+5} ions formed in the capture process $C^{+6} + Ar \rightarrow C^{+5} + Ar^{+}$. The fraction of undissociated H_2 molecules was determined from the number of C^{+2} ions formed by two-electron capture $C^{+4} + H_2 \rightarrow C^{+2} + 2H^{+}$. The last process was chosen because it has a large cross section and the process that makes it, involving formation

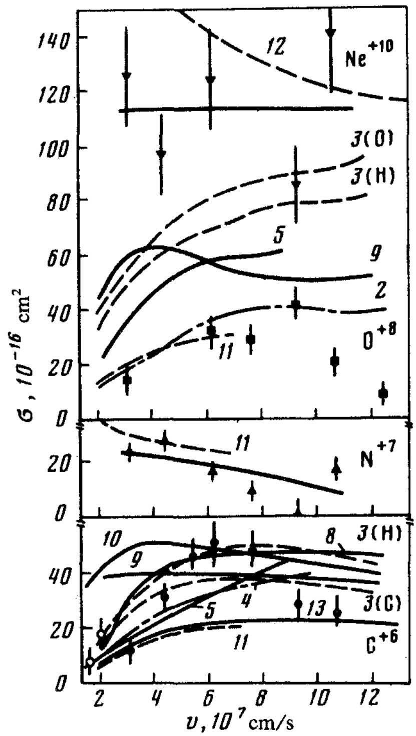

FIG. 1. Cross sections for electron capture at hydrogen atoms by nuclei. Experiment: ● — C^{+6}, ▲ — N^{+7}, ■ — O^{+8}, ▼ — Ne^{+10}—our data; ○—data from Ref. 1 for C^{+6}. Theory: the numbers on the curves correspond to the numbers of the references from which the data were taken. The indices (H), (C), and (O) on curves 3 correspond to the origin of the coordinates for the proton and for C^{+6} and O^{+8} nuclei, respectively.

of C^{+2} ions via single-electron capture at H atoms or H_2 molecules in two subsequent collisions $C^{+4}\to C^{+3}$ and $C^{+3}\to C^{+2}$, has a low probability because of the small cross section of single-electron capture by the C^{+3} ion. The degree of dissociation of the molecules in the collision chamber was 85%. The density of the target in the chamber satisfied the condition for single collisions. In the experiment, the ratio of the cross sections for electron capture at atomic and molecular hydrogen was determined by performing measurements on cold (H_2) and hot (H and H_2) targets. Absolute calibration of the cross sections was achieved by using the previously measured cross sections for electron capture at molecular hydrogen.[16] The errors in the measurements were $\pm 20\%$.

The results of the measurements are presented in Figs. 1–3. Our data for helium-like ions C^{+4}, N^{+5}, O^{+6} agree well with the available experimental data obtained by others.[17,19]

When nuclei and multiply charged ions interact with hydrogen atoms, there is a general tendency for the capture cross section to increase with increasing charge of the incident particle. However, there are exceptions: C^{+6} and N^{+7} in Fig. 1, C^{+4} and N^{+5} in Fig. 3. The nonmonotonic dependence of the electron capture cross section on the

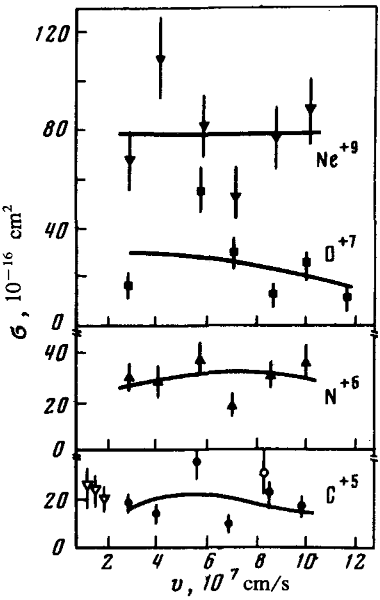

FIG. 2. Cross section for electron capture at hydrogen atoms by hydrogen-like ions. Experiment: ● — C^{+5}, ▲ — N^{+6}, ■ — O^{+7}, ▼ — Ne^{+9}—our data; ∇—from Ref. 11; O—from Ref. 17.

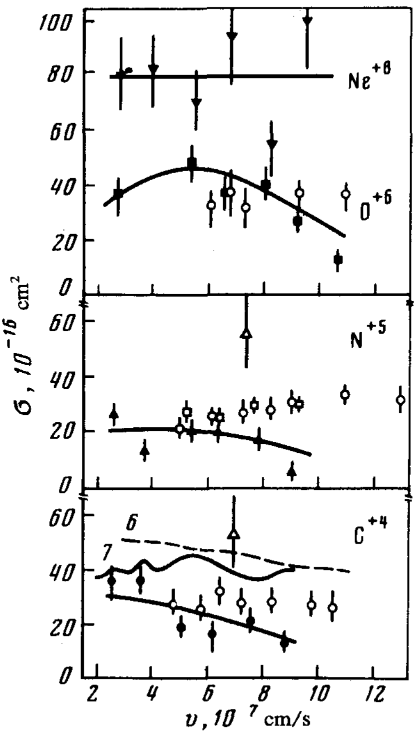

FIG. 3. Cross section for electron capture at hydrogen atoms by helium-like ions. Experiment: ● — C^{+4}, ▲ — N^{+5}, ■ — O^{+6}, ▼ — Ne^{+8}—our data; O—data from Ref. 18; Δ—data from Ref. 17; □—data from Ref. 19. Theory: the numbers on the curves correspond to the reference numbers.

charge of the incident ion (for v = const) was pointed out theoretically in Ref. 20. This effect is attributed to the small number of points of pseudocrossings of terms of the initial and final states of quasimolecules in hydrogen atom–nucleus systems with nuclear charges $z \lesssim 10$. For this reason, the increase in the capture cross section with increasing nuclear charge breaks down in cases when the intersection points fall in the region of internuclear separation distances, where the probabilities for a transition become small (for example, $N^{+7} + H$). As far as the shape of the curves $\sigma(v)$ is concerned, for the pairs $C^{+6} + H$, $O^{+8} + H$ capture occurs nearly into a single state,[5] and the curve has a maximum. For $Ne^{+10} + H$, where capture occurs into several levels, the dependence on the approach velocity is weaker, since $\sigma(v)$ is determined by the sum of partial cross sections for capture into separate states. In the experiment, we also obtained a sharper decrease in the cross sections for electron capture by nuclei with increasing velocity than indicated by theory (Fig. 1, pairs $C^{+6} + H$, $O^{+8} + H$). This could be due to the fact that for velocities $v > 10^8$ cm/s the real interaction picture differs from the quasimolecular picture,[5] used in the calculations, since the collision time for atomic particles is comparable to the electronic transition times.

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