# Electron capture by multiply charged ions and nuclei of hydrogen molecule atoms

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The cross sections for capture of an electron by $C^{+6}$, $O^{+8}$, $N^{+7}$, and $Ne^{+10}$ nuclei and also by the ions of these elements and by $Ar^{+z}/(z<10)$ ions with a kinetic energy $E = 1z$ keV were measured. A nonmonotonic increase of the capture cross section was observed as the charge of the nuclei increased.

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One of the channels of energy loss in a high-temperature plasma produced in controlled thermonuclear fusion devices is the emission of excited impurity ions produced as a result of electron capture by ions of the atoms in the plasma. A determination of the capture cross sections, therefore, is very important. The light impurities in the plasma of modern thermonuclear devices exist predominantly as nuclei. However, because of the experimental difficulties of obtaining beams of nuclei of adequate intensity with an energy corresponding to the ion energies in the plasma ($E = 1$–$10$ keV), currently there are no experimental cross sections for capture by nuclei with $z > 2$. The calculations of the cross sections using different model representations[1–3] give different dependences of the cross sections on the charge $z$ of the incident ion for a specified relative velocity of the colliding particles.

In our investigation we measured for the first time the cross sections for capture of electrons by nuclei and by multiply charged carbon, nitrogen, oxygen, and neon ions as well as by argon ions from $H_2$ molecules at an energy of $1z$ keV, which corre-

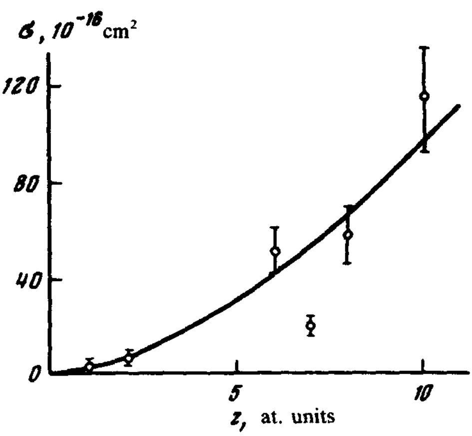


FIG. 1. Dependence of a single-electron capture cross section on the charge of the incident nucleus for $v = 0.31\times 10^8$ cm/sec. Solid curve is $\sigma_z = 3.6\, z^{1.4}\times 10^{-16}$ cm$^2$.

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TABLE 1.

| z | + 1 | + 2 | + 3 | + 4 | + 6 | + 7 | + 8 | + 9 | + 10 |
|---|---|---|---|---|---|---|---|---|---|
| H | 3.4 [5] | – | – | – | – | – | – | – | – |
| He | – | 5.6 [6] | – | – | – | – | – | – | – |
| C | – | – | – | 8.8 | 49.7 | – | – | – | – |
| N | – | 2.7 | – | – | 44.8 | 19.6 | – | – | – |
| O | – | 4.0 | 18 | – | 60.6 | 24.9 | 57.4 | – | – |
| Ne | – | – | 28.2 | – | 59 | – | 57.2 | 50.7 | 115 |
| Ar | – | – | 20.3 | – | 46.5 | 59.3 | 53.6 | 62.5 | 43.3 |

sponds to a velocity of nuclei $v = 0.31 \times 10^8$ cm/sec (0.14 at. unit). The beams of ions and nuclei were obtained from a "Krion-2" source developed at the High Energy Laboratory, Joint Institute of Nuclear Research.[4] An analysis of the charged state of a beam of fast particles transmitted through a hydrogen gas target under conditions of single collisions was used to measure the cross sections. The obtained data for the capture cross sections of a single electron are given in Table I in units of $10^{-16}$ cm$^2$. The errors in the cross section measurements were $\pm 20\%$. Table I also gives the cross sections for protons and helium nuclei at the same collision velocity.[5,6]

We can see in the table that the cross sections of capture by ions with the same charge and similar velocities ($C^{+6}$–$N^{+6}$, $N^{+7}$–$O^{+7}$, $O^{+8}$–$Ne^{+8}$) do not differ greatly. This shows that the capture occurs at large distances between the particles ($R \sim 10$ at. units); this follows directly from the cross sections and proceeds to the excited ion

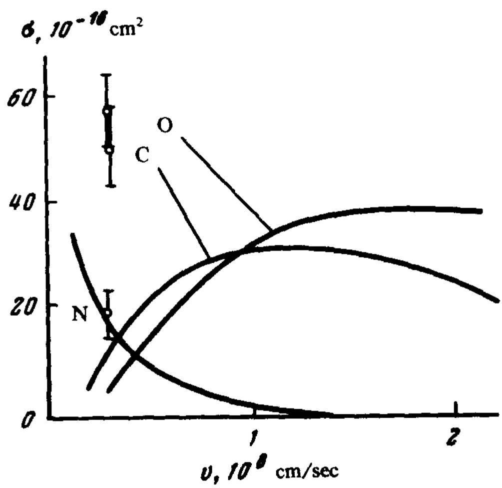


FIG. 2. Dependence of a single-electron capture cross section on the velocity of the incident $C^{+6}$, $N^{+7}$, and $O^{+8}$ nuclei.

levels. As a result, the influence of the internal structure of the ion on the cross section is small. It was suggested[1,2] that the capture cross section should be described by a universal power function $\sigma = Az^B$. The data in this paper agree best with this dependence when $A = 3.6$ and $B = 1.4$ (solid curve in Fig. 1). However, such an approximation of the dependence $\sigma = f(z)$ should be considered as purely phenomenological, since the $H^+$ and $He^{+2}$ capture processes are endothermic,[5,6] whereas the capture by $C^{+6}$, $N^{+7}$, $O^{+8}$, $Ne^{+10}$ ions is exothermic and has different electron-transition mechanisms. In addition, as seen in Fig. 1, a deviation from a monotonic increase of the cross sections with increasing charge is observed in the $N^{+7}$–$H_2$ pair. This is apparently a consequence of the small number of quasi-intersections of the potential energy curves of the initial and final states for pairs with $z < 10$.

We have calculated within the framework of the Landau-Zener model the cross sections for the $C^{+6}$,$N^{+7}$, and $O^{+8}$ ions (curves in Fig. 2). In view of the large internuclear distances at which capture occurs, the $H_2$ molecule was considered as an atom with corresponding ionization potential ($I_{H_2} = 15.43$ eV). The quasi-intersection points were determined from the distances $R$ corresponding to the equality of the defects of the energy for $R = \infty$ of the capture process in the electron state with principal quantum number $n$ and the Coulomb repulsion energy in the final states, and the matrix element of the interaction was determined on the basis of the formulas of Olson and Salop.[8] In the case of $N^{+7}$–$H_2$ a situation is realized in which the capture is determined by the quasi-intersection at $R = 14.65$ at. units ($n = 5$), which the system passes, nearly adiabatically at the investigated velocity, in view of the weak interaction of terms at such a large distance $R$. This intersection gives a small capture cross section for $v = 0.14$ at. unit. A closer quasi-intersection for $n = 4$ at $R = 6.22$ at. units does not contribute to the cross section because of the large splitting of the terms. For the $C^{+6}$ and $O^{+8}$ ions the quasi-intersection points lie at $R = 8.96$ for $n = 5$ of the $C^{+5}$ ion and $R = 9.82$ for $n = 6$ of the $O^{+7}$ ion, where the transition probability is relatively high. Figure 2 shows that there is a region of velocities where the ratios of the capture cross sections for $N^{+7}$, $C^{+6}$, and $O^{+8}$ correspond to the experimentally measured values ($v \sim 6 \times 10^7$ cm/sec). However, the experimental cross sections for $v = 3 \times 10^7$ cm/sec differ from the calculated cross sections -- the calculated $\sigma(v)$ curves are shifted toward higher particle-approach velocities. This indicates that the matrix elements, obtained from the formulas,[8] give too large values in the case of interaction between a multiply charged ion and a hydrogen molecule.

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