Electron-capture collisions at keV energies of multiply charged ions of carbon and argon with molecular deuterium

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Single- and double-electron-capture cross sections have been measured for C^{q+} with initial charges $2 \leq q \leq 6$ and for Ar^{q+} with initial charges $2 \leq q \leq 12$ incident on molecular deuterium gas targets. The cross sections show little dependence on the incident-ion energy for the range studied $2q$–$10q$ keV. The single-electron-capture cross sections do not vary monotonically with the initial charge, but show an oscillation about a mean curve, reflecting the projectile electronic structure.

I. INTRODUCTION

The study of electron capture by multiply charged ions during collisions with atoms and molecules has grown rapidly in the last years,[1] primarily because the cross sections for such processes may be quite large and also because it has been recognized that in such collisions the electron is most likely captured in an excited state which may then decay via photon emission.[2,3]

It is thus evident that electron capture may play an important role in the behavior of fusion plasmas as an energy-loss mechanism[4,5] and may also influence the heating of plasmas by injection of neutral D_0 beams. Experimental determination of cross sections for electron capture by carbon, nitrogen, and oxygen slow ions with charges $(2 \leq q \leq Z-2)$ (with Z atomic number) incident on H_2 has been done recently by Crandall *et al.*[6–8] at the energy $8q$ keV. At energies greater than 100 keV ($v > v_0$, v_0 is the unit of atomic velocities), Shah *et al.*,[9] Goffe *et al.*,[10] Nutt *et al.*,[11,12] and Phaneuf *et al.*[13] have measured electron capture cross sections of C^{q+} $(1 \leq q \leq 6)$ colliding on H_2. Bliman *et al.* reported results for N^{q+} $(2 \leq q \leq 7)$ (Ref. 14) and O^{q+} $(2 \leq q \leq 8)$ (Ref. 15) collisions on molecular deuterium at energies $2q$–$10q$ keV and Huber *et al.*[16] for Kr^{q+} $(4 \leq q \leq 7)$ on molecular hydrogen at velocities $v < v_0$. The primary purpose of this paper is to report experimental values for the single- and double-electron capture cross sections for $^{13}C^{q+}$ $(2 \leq q \leq 6)$ and for Ar^{q+} $(2 \leq q \leq 12)$ at laboratory kinetic energies in the range $2q$–$10q$ keV on D_2. With the single exception of C^{2+}, C^{3+}, C^{4+} single-electron capture, these collision systems had not been studied previously.

II. THEORETICAL BACKGROUND

In atomic collisions with low relative velocities $(v < v_0)$ the colliding partners are viewed as forming a transient quasimolecule. The quasimolecule eigenenergies are parametric functions of the internuclear separation R: They are usually called potential energy curves.

Curve-crossing methods have been used extensively to estimate cross sections. For the purpose of interpretation of the experimental results presented hereafter, two types of treatments are considered.

When a large number of curve crossings exist within a small range of internuclear separation, two types of models are used to estimate the transfer cross sections in slow collisions of multicharged ions with H_2: an "absorbing sphere" model (Olson *et al.*,[17]) where the total transfer cross section is estimated (the single electron capture is largely dominant, thus allowing the approximation σ total $\approx \sigma q$, $q-1$) or an "electron tunneling" model (Grozdanov et al.,[18]) where the electron transfer is described as a transition of the valence electron of the H_2 molecule to the ion. Since the transition probability is assumed to be unity for some crossing distance R_c and zero otherwise, the cross section is simply set to be πR_c^2. These procedures, as observed experimentally,[13,14] are seen to place reasonable limits on the cross sections.

The present results, as given below, show a cross section mean variation in good agreement with the electron tunneling model results.[18]

III. EXPERIMENTAL METHOD

The cross sections in the present work, as in the previous ones, were measured using a standard beam target method. The projectile ions were extracted from an electron cyclotron resonance ion source Micromafios. In order to avoid any confusion due to parasitic impurity species, in the experiments with carbon ions, carbon dioxide was injected in the source: It was made from ^{13}C and ^{16}O. In the case of argon, spectroscopically pure gas was used in the

source. Figure 1 represents a typical argon current distribution as collected on a movable Faraday cup in the collision chamber. The impurity ions are due to source wall degassing. Since the O^+ current is low, it is recognized that higher charges for this element contribute negligibly ($^{16}O^{2+}$ has a charge-to-mass ratio equal to $^{40}Ar^{5+}$ and $^{16}O^{4+}$ equals that of $^{40}Ar^{10+}$). After acceleration by a known potential difference (2–10 kV), a magnet separates a charge-to-mass ratio of the working species. At the exit from the magnet, this beam is collimated and allowed to pass through a gas target—here molecular deuterium—of known length. The pressure is varied from its base value (5×10^{-7} Torr) up to 5×10^{-4} Torr. The ions resulting from the capture of one or two electrons are charge analyzed, utilizing a second magnet identical to the first one.

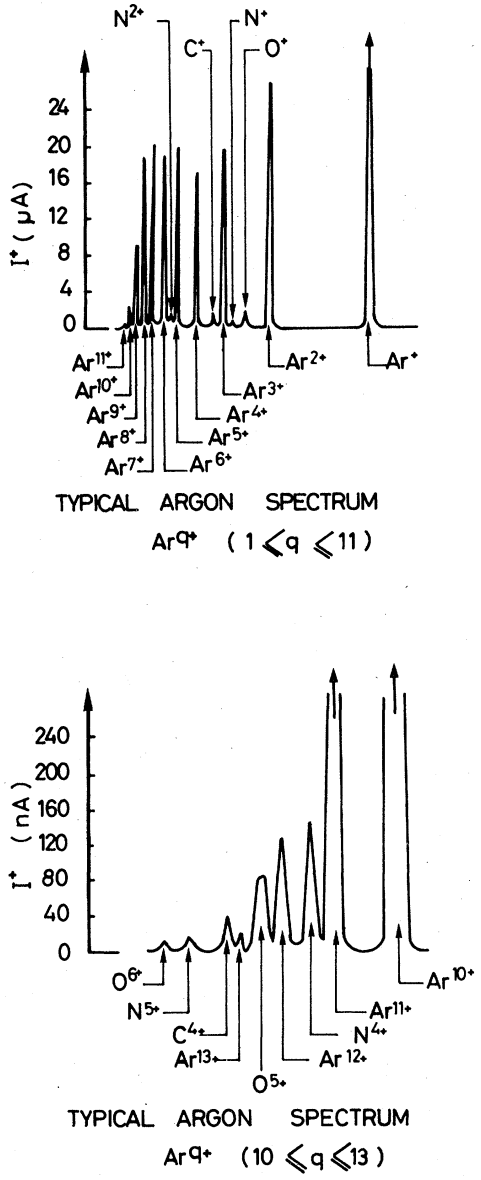

FIG. 1. Typical argon spectrum as collected on the movable Faraday cup in the collision chamber. Impurity ions seen are: oxygen, nitrogen, carbon.

In the single-collision approximation, the slope of the linear part of the curve

$$\frac{dI_f(0)}{d\pi} = I_i(0)\sigma_{if}$$

gives the cross section σ_{if}. In this relation, $I_f(0)$ and $I_i(0)$ are, respectively, the ion currents in final charge state f in the limit of zero target thickness and the ion current in initial charge state i. The slope is obtained in the limit of zero gas target thickness π, where $\pi = n_0 l$ (where n_0 is the target number density and l is the length).

When gas is admitted to the collision chamber, it leaks out to the surrounding space where differential pumping has been installed. With a knowledge of the pressure increase, a measure of the contribution to I_f due to gas surrounding the collision chamber is performed and thus subtracted from the total I_f. This procedure avoids a systematic error which would be made otherwise.

The estimate of the errors in a typical cross section value is of the order of ±20% as in previously obtained results.[14,15,19]

IV. RESULTS AND DISCUSSION

A. Results

The cross sections for single- and double-electron capture for carbon ions incident on deuterium are shown in Fig. 2 as a function of the projectile incident charge. This representation is possible since in the energy range where the measurements are made, the cross sections are nearly independent of the ion velocity. However, the cross sections $\sigma_{4,3}$ are large and always larger than $\sigma_{5,4}$. $\sigma_{6,5}$ is larger than $\sigma_{4,3}$. This remarkable feature is also observed in the case of nitrogen and oxygen ions in the same charge states. It is seen that double-electron capture is generally one order of magnitude smaller than single transfer.

In Fig. 2 the experimental points (solid triangles) of Cranall *et al.*[7] have also been represented. The agreement is fair (the error bars overlap).

The cross sections for single- and double-electron capture for argon ions incident on deuterium are shown in Fig. 3 as a function of the incident-ion charge. For these collisions, the general trend of cross sections nearly independent of

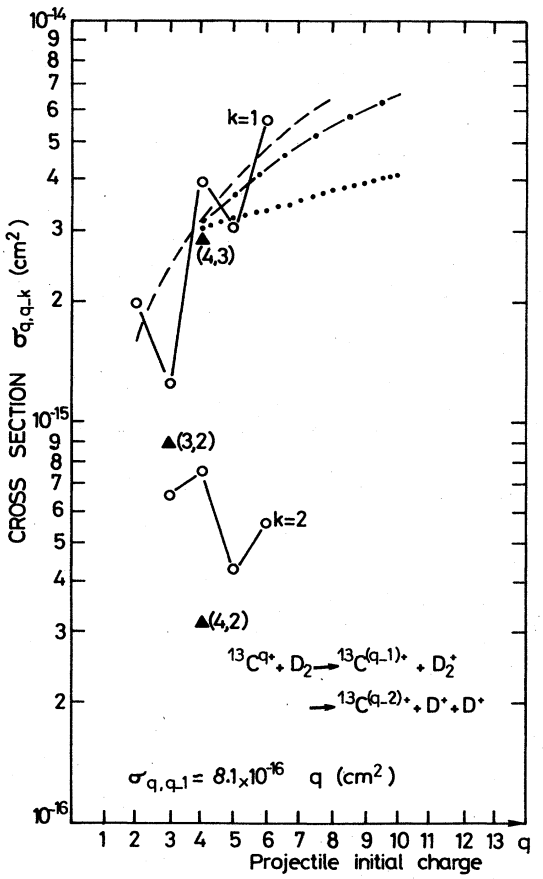

FIG. 2. One- and two-electron transfer cross sections to carbon ions colliding with D_2 as a function of initial charge: ○ (open circles—present results), ▲ (closed triangles—Refs. 6, 7, 8), Broken curve experimental fit ($\sigma_{q,q-1} \approx 8.1\times10^{-16} q$ cm^2), dotted line (Ref. 17), dot. slash line (Ref. 18).

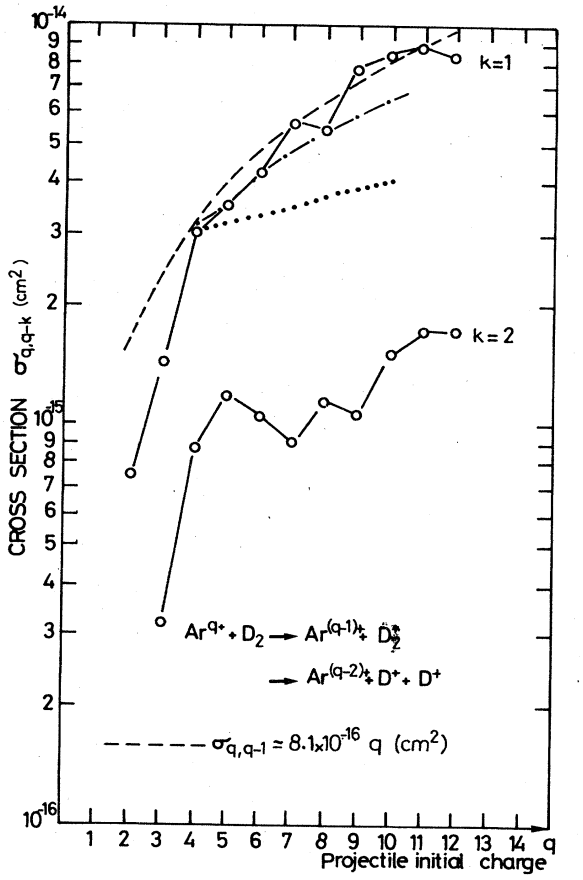

FIG. 3. One- and two-electron transfer cross sections to argon ions colliding with D_2 as a function of initial charge: ○ (open circles—present results), broken curve experimental fit ($\sigma_{q,q-1} \approx 8.1\times10^{-16} q$ cm^2), dotted line (Ref. 17), dot. slash line (Ref. 18).

velocity is observed. For the collision system $Ar^{q+} + D_2$, the single-electron-capture cross section shows, as the system $Ar^{q+} + Ar$, some peculiarities.[19] The $\sigma_{8,7}$ value is slightly smaller than the $\sigma_{7,6}$ value which in turn is smaller than the $\sigma_{9,8}$ value. The relative minimum $\sigma_{8,7}$ is associated with a relative maximum $\sigma_{8,6}$. This trend is observed in any one of the collision systems $Ar^{8+} + X$, where X is any target atom or molecule studied at this laboratory[20] (X = He, Ne, ^{19}Ar, Kr, Xe, D_2). There are no published data to compare with the argon results on D_2. As is usually observed, the double transfer which leaves two D^+ ions is significantly lower than single transfer.

It has been checked many times that the results are not influenced by the presence of ions in metastable states. In this regard, two ion source parameters are important: neutral gas pressure and high-frequency power level fed to the plasma electrons. Charge-exchange collisions are effective in leaving ions in metastable states; in the ion source the charge-exchange collision frequency $n_0 \langle \sigma_{q,q-1} v_i \rangle$ is of order 10^2 s^{-1} (n_0 is the neutral gas number density in the source, v_i the ion velocity in the source plasma, their temperature there being of order 1–5 eV). The probability that the ions are left in metastable states is thus extremely small. The hf power level influences the electron temperature. The excitation rate coefficient $\langle \sigma_{exc} v_e \rangle$ is mostly dependent on the cross section σ_{exc} which is smaller than the ionization cross section. From the Lotz ionization rate coefficients, a maximum limit may be assigned to the collision frequency for excitation and is of order 10^3 s^{-1}. Finally, the ion time of flight from the ion source to the collision chamber is longer or of order of the ion ex-

cited-state lifetimes. These arguments and those of Crandall,[6] of Muller,[21] and of Bliman[22] suggest no significant metastable contamination of present data.

B. Discussion

Each point on Figs. 2 and 3 is the mean value calculated from cross sections obtained in the energy range $2q-10q$ keV. The reproducibility of each value is of order 95%. From inspection of these results, an experimental fit to a general curve can be proposed. For the single electron transfer to multiply charged ions colliding with D_2 the curve expression writes

$$\sigma_{q,q-1} \approx (8.1\times10^{-16})q \text{ cm}^2.$$

This curve is represented in Figs. 2 and 3. For comparison, Fig. 4 represents the results of S. Bliman et al.[14,15] for the case of nitrogen and oxygen collisions on deuterium. The fit of the experimental points to the semiempirical curve proposed above is highly satisfactory.

C. Comparisons to theories

In Figs. 2 and 3, we compare the present experimental cross section values with theoretical results obtained by Olson[17] and by Grozdanov.[18] Olson *et al.* developed, to describe the electron transfer to the incident ion, a reduced coupling matrix element formula. Combining the matrix elements with an absorbing-sphere model based on the Landau-Zener method, the total transfer cross sections are finally obtained. Grozdanov *et al.* used an electron tunneling model: In this approach the electron transfer process is viewed as an under-barrier transition of the target valence electron from the initial state to a quasicontinuum of excited states of the projectile ion. The results of these calculations are represented in Figs. 2 and 3. The agreement is satisfactory with the tunneling model results, which fall within the experimental uncertainties. The absorbing sphere model gives results smaller than the experimental values by about 50%.

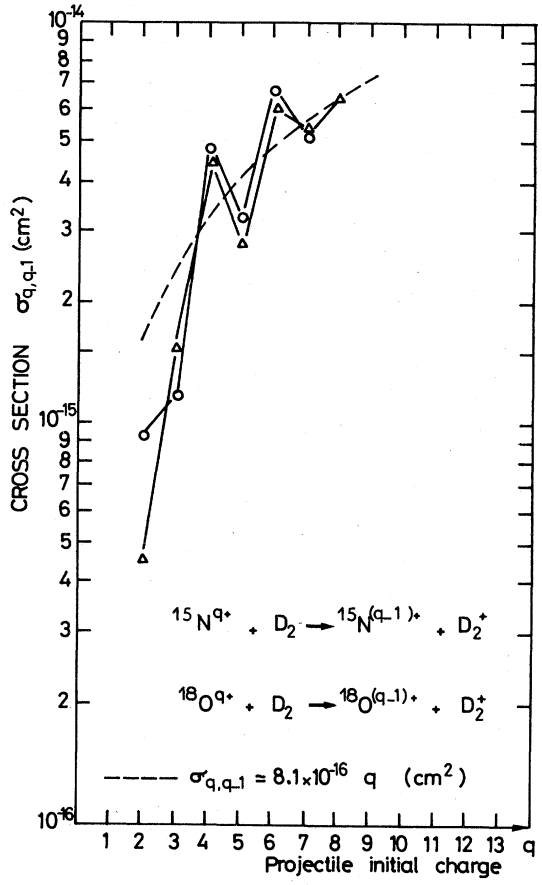

FIG. 4. One-electron transfer in collisions of nitrogen and oxygen ions on deuterium as function of initial charge: ○ [open circles—nitrogen ($2 \leq q \leq 7$)], △ [open triangles—oxygen ($2 \leq q \leq 8$)], Broken line experimental fit ($\sigma_{q,q-1} \approx 8.1\times10^{-16} q$ cm^2).

V. SUMMARY

The results presented fit with a semiempirical curve showing a linear dependence on q, incident ion charge. About this mean line, oscillations in the cross sections are observed which could tentatively be attributed to specific electronic structure of the incident ions (in the case of Ar^{8+} a Ne-like electronic closed shell giving a $\sigma_{8,7}$ associated with a relative minimum). The theoretical model to which comparison is best seems to be the electron tunneling approach.

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