Electron Capture into Different (n,l) States in Slow Collisions of C^{6+}, N^{6+}, O^{6+}, and Ne^{6+} Projectiles on He and H_2 Targets

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Absolute cross sections for electron capture into different nl states for C^{6+}, N^{6+}, O^{6+}, Ne^{6+}–He and N^{6+}, O^{6+}–H_2 collisions in the 0.15–0.5 a.u. velocity range have been measured. These cross sections strongly depend on the collision velocity, in contrast with the total capture cross sections and the cross sections for capture into different n states. Similarities in $\sigma_{nl}(v)$ dependences for different ions with the same ionic charge are found which are attributed to the hydrogenlike structure of the energy levels of these ions.

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Collisions of multiply charged ions with atoms and molecules in the relative velocity range $v \lesssim 1$ a.u. are of particular interest for such applications as controlled thermonuclear fusion, studies of astrophysical plasmas, and the search for soft x-ray lasers. From these applications there is a strong demand for cross sections for electron capture into specific nl states, σ_{nl}, because all radiative transitions are controlled by these processes. However, until now σ_{nl} capture cross sections neither have been measured nor can be calculated unambiguously.

We have measured absolute nl-state-resolved cross sections for electron capture in the processes

$$C^{6+}, N^{6+}, O^{6+}, Ne^{6+} + He \rightarrow A^{5+*}(nl) + He^{+}$$

and

$$N^{6+}, O^{6+} + H_2 \rightarrow A^{5+*}(nl) + H_2^{+}.$$

It is known (Refs. 1–3, and Ref. 4 and references therein) that in such systems electrons are captured into states with large n and that these transitions occur at large internuclear distances. This suggests that projectiles with different core but with the same ionic charge behave similarly in the charge-exchange process. The choice of the above mentioned systems enabled us to study the influence of the ionic core and of the target ionization potential on the capture process and to look for some systematics in the nl distribution.

The ion beams were produced by an electron cyclotron resonance source of the MINIMAFIOS type[5,6] which has recently been installed at the Kernfysisch Versneller Instituut, University of Groningen. The beam currents obtained in the collision chamber depended on the extraction voltage (1.5–20 kV) and the ion species. They varied between 1 nA of $^{13}C^{6+}$ at 9 keV and 5μA of O^{6+} at 120 keV.

The ions traversed a static gas target, under single-collision conditions ($p \leqslant 7\times10^{-4}$ mbar for He, $p \leqslant 3.5\times10^{-4}$ mbar for H_2, interaction length $\approx$ 6 cm). Vacuum-ultraviolet photon emission in the wavelength range 10–60 nm, resulting from the decay of the A^{5+*} ions, was observed perpendicular to the ion beam by a grazing-incidence spectrometer. This instrument has been absolutely calibrated on sensitivity, and is equipped with a position-sensitive microchannel plate, enabling simultaneous detection of a 20-nm wavelength range, with a resolution of 0.3–0.5 nm. The collision chamber, spectrometer, and calibration procedure have been described elsewhere.[7] The resolution was sufficient to resolve most of the lines corresponding to the transitions between different nl levels of the A^{5+*} ions; their identification in all cases was unambiguous. From our measurements we deduced absolute emission cross sections σ_{em} for the transitions between $2l$, $3l$, $4l$, and $5l$ levels, with an absolute uncertainty of about 30%, determined mainly by the calibration, and a relative error of 10%–25%, depending on signal-to-noise ratio and line separation. σ_{em} values and details of the experimental procedure will be published in a forthcoming article.

From the σ_{em} values we obtained absolute σ_{nl} cross sections, by taking into account all possible cascadings and using known branching ratios.[8,9] Furthermore, we obtained $\sigma_n = \sum_l \sigma_{nl}$ and $\sigma_t = \sum_{nl}\sigma_{nl}$. The results for the systems N^{6+}, O^{6+}, Ne^{+6}–He and O^{6+}-H_2 are shown in Fig. 1, as a function of the relative collision velocity. For C^{6+}-He we could not deduce σ_{nl} cross sections since C VI is hydrogenlike: the l sublevels are degenerate. In this case we measured σ_{em}(18.1 nm) and σ_{em}(13.5 nm) for $3\rightarrow2$ and $4\rightarrow2$ transi-

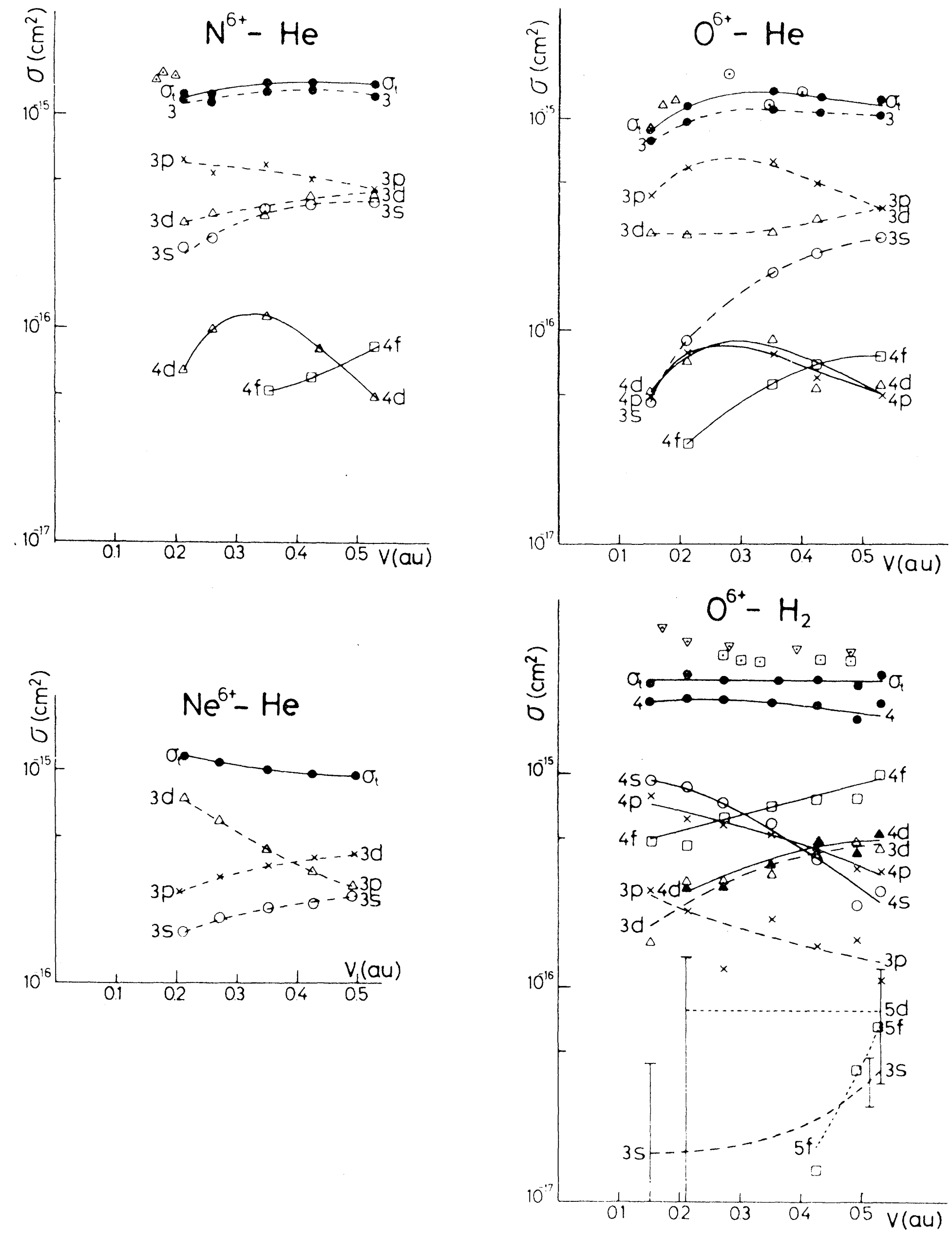

FIG. 1. σ_{nl} (indicated by nl), σ_n (indicated by n), and σ_t as a function of collision velocity for N^{6+}, O^{6+}, Ne^{6+}-He and O^{6+}-H_2. Measured points are shown except for σ_{3s} and σ_{5d} in the O^{6+}-H_2 case for which only error bars are given. Triangles with dot: σ_t from Ref. 10; circles with dot: σ_t from Ref. 11; squares with dot; σ_t from Ref. 12; inverted triangles with dot; σ_t from Ref. 13.

tions, respectively. The results will be discussed further on. In the O^{6+} and Ne^{6+} cases the electron is captured into a doublet state. However in the N^{6+} case it can enter singlet as well as triplet states. Figure 1 shows summed cross sections for capture into singlet and triplet states, the ratio between which was found to be statistical (1:3).

Also shown in Fig. 1 are published σ_t values for O^{6+}-He (Refs. 10 and 11), N^{6+}-He (Ref. 10), and O^{6+}-H_2.[12,13] In each case the agreement with our results is quite satisfactory, confirming the accuracy of our calibration method. To our knowledge there exist only two other experimental results which can be compared to our data. Baptist *et al.*[14] did a relative measurement of $4l$-$3l'$

emission for O^{6+}-H_2 at 0.4 a.u. collision velocity. Their relative intensities agree well with our emission cross sections for these lines. Ohtani *et al.*[3] showed that for C^{6+}-He around 0.15 a.u. collision velocity the electron is captured dominantly into the $n=3$ levels, which is in agreement with our results at this and higher velocities.

Both total-cross-section values and the dominance of $n=3$ and $n=4$ levels for He and H_2, respectively, are in accordance with a simple classical model for one-electron capture (Refs. 1 and 2; Ref. 4 and references therein).

It is remarkable that in all cases presented σ_t and σ_n do not show significant dependence on the collision velocity; in contrast σ_{nl} show a strong redistribution of the l-sublevel population over the studied velocity range. At present, theoretical calculations which can be compared directly with our measurements do not exist, the only available calculations dealing exclusively with bare-nuclei–atomic-H collisions (Ref. 15 and references therein). These theories predict more or less fixed l distributions over a wide velocity range. The observed strong redistribution is rather unexpected.

There are large similarities between O^{6+}-He and N^{6+}-He, both in the absolute values and in the velocity dependence of σ_{nl}, σ_n, and σ_t. Only the σ_{3s} values differ by a factor of 2. For Ne^{6+}-He σ_t is still about the same but the l-sublevel distribution clearly deviates from the N^{6+}, O^{6+}–He cases. This can be understood qualitatively from an inspection of the relevant nl energy levels of the three ions. For N VI and O VI these levels are almost the same as the hydrogenlike C VI levels; the deviations are less than 2 eV for all levels except 3s, implying that the influence of the core electrons is small except for the 3s levels. This is not the case for Ne VI where the deviations are much larger. This interpretation implies that σ_{nl} values for C^{6+}-He should be very similar to those for N^{6+}, O^{6+}–He. To check this we reconstructed the measured σ_{em}(18.1 nm) for $3\to2$ and σ_{em}(13.5 nm) for $4\to2$ transitions for C^{6+}-He from the σ_{nl} data of N^{6+}, O^{6+}–He, applying the (exact) branching ratios of C VI. The results for 18.1 nm shown in Fig. 2 confirm our assumption. The results for 13.5 nm are also identical within a somewhat larger error of 25%, but show no systematics because of larger scatter of the data points, due to much weaker signals.

Our conclusion is that indeed the influence of the ionic core on the capture process is small as long as the populated levels have hydrogenlike binding energies, a conclusion which is also confirmed by preliminary results for N^{6+}-H_2 which show that the nl distribution in this case is again quite similar to that of O^{6+}-H_2.

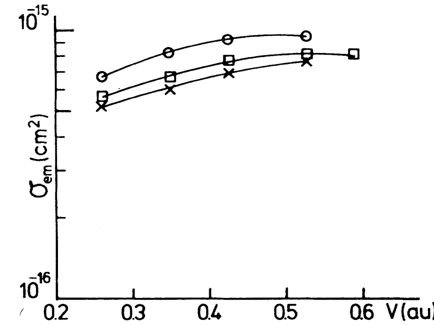

FIG. 2. Squares: σ_{em}(18.1 nm) as measured for C^{6+}–He, as a function of collision velocity. Circles: σ_{em}(18.1 nm) as calculated from σ_{nl} data for O^{6+}–He. Crosses: σ_{em}(18.1 nm) as calculated from σ_{nl} data for N^{6+}–He.

Our results imply that for certain practical needs one can use σ_{nl} data obtained for different systems. For instance, nl distributions for collisions involving O^{8+} ions should be identical to those for Ne^{8+} ions, which can be measured much more simply.

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