# Total Capture and Line-Emission Cross Sections for $C^{6+}$-, $N^{7+}$-, $O^{8+}$-H Collisions in the Energy Range 3–7.5 keV/u

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We have measured total cross sections for single electron capture by fully stripped carbon, nitrogen, and oxygen ions from atomic hydrogen, in the energy range 3–7.5 keV/u. Some results for incompletely stripped ions are shown for comparison. For $C^{6+}$ and $N^{7+}$ we have also determined line-emission cross sections for several $\Delta n = 1,2$ transitions. All results are in excellent agreement with recent theoretical calculations.

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Charge-exchange reactions between slow ($v < 1$ a.u.) fully stripped ions and atomic hydrogen have been the subject of intensive theoretical study recently,[1–4] motivated by the importance of these processes in, e.g., astrophysical and fusion plasmas.[5] Experiments are hard to perform, because of the difficulties associated with the production of both slow, highly charged projectile ions and the atomic hydrogen target. Panov, Basalaev, and Lozhkin[6] measured total electron-capture cross sections, $\sigma_t$, for $C^{6+}$-, $N^{7+}$-, $O^{8+}$-, and $Ne^{10+}$-H in the impact energy range 0.5–8 keV/u, but their data scatter so much that they do not provide an accurate test for theoretical calculations. Phaneuf *et al.*[7] measured $\sigma_t$ for $C^{6+}$-H at very low energies; their data are in good agreement with recent calculations.[1,3] Recently, McCullough, Wilkie, and Gilbody[8] performed state-selective measurements for $C^{3+}$-H collisions, by means of energy-gain spectroscopy.

We have studied charge-exchange reactions in collisions between fully stripped carbon, nitrogen, and oxygen ions and hydrogen atoms, in the energy range 3–7.5 keV/u. For these systems we will present the first set of data including both $\sigma_t$ and line-emission cross sections $\sigma_{em}$ (for $\Delta n = 1,2$ transitions). The latter results provide a more detailed test of theoretical predictions, since they depend on the distribution of the captured electron over $nl$ sublevels.

The experimental setup used is basically the same as described in previous publications,[9,10] which dealt with collisions between highly charged ions and multielectron targets. We have recently constructed a high-density atomic-hydrogen-beam target, suitable for photon measurements, and a retarding-field analyzer, which enables a direct measurement of $\sigma_t$.

The ion beams were produced by an electron cyclotron resonance source of the Minimafios type.[11] Typical (electric) currents in the collision region were of the order 10 nA for $^{13}C^{6+}$ and $^{15}N^{7+}$ and 1 nA for $^{18}O^{8+}$. The use of isotopes prevented beam contamination (in particular by $H_2^+$). A radio-frequency discharge source, similar to sources described by other authors,[12] produced a partly dissociated hydrogen beam. The absolute density profiles in the collision region of the atomic and molecular components of the beam were determined via observation of electron-impact–produced atomic (Balmer-$\beta$) and molecular radiation with a monochromator. This instrument was equipped with an imaging system similar to that described by Kadota *et al.*,[13] which enabled the measurement of the target density as a function of position along the beam axis. The effective degree of dissociation in the collision center was about 70% and the target thickness was of the order $10^{13}$ $cm^{-2}$. The radiation emitted in the decay of the excited projectiles was observed with a grazing-incidence vacuum spectrometer, absolutely calibrated on sensitivity, and equipped with a position-sensitive microchannelplate detector. Because of the low ion-beam current, radiation measurements were not possible for $O^{8+}$-H, as a result of a constant background count rate apparently produced by neutral hydrogen atoms impinging on the channelplate.

A simple retarding-field analyzer, consisting of a transparent grid at high voltage between two grounded diaphragms, was placed in front of the Faraday cup collecting the ion beam. Each time the voltage on the grid reached a value $qV/(q-i)$, where $V$ is the acceleration voltage, $q$ the initial charge state, and $i = 0, 1, 2$, a sharp cutoff in the current (measured with an electrometer) was observed. For the total-cross-section measurements, the target-density calibration procedure described above was not adequate, since the entire target thickness traversed by the ions (also outside the collision center) contributed to the measured signal. Instead we used $\sigma_t$ data for $He^{2+}$-H,$H_2$ obtained by Shah and Gilbody[14] and for $N^{3+}$, $N^{4+}$-H,$H_2$ by Crandall, Phaneuf, and Meyer,[15] at a few different energies. The ratios of $\sigma_t$ for H and $H_2$ are sufficiently different for these systems, so that we could obtain both the target thickness and the composition from an (overdetermined) system of equations with two unknowns. The resulting effective degree of dissociation was about 56% in this case. This calibration method is somewhat similar to that used by Seim *et al.*,[16] and more details will be given elsewhere.[17]

 

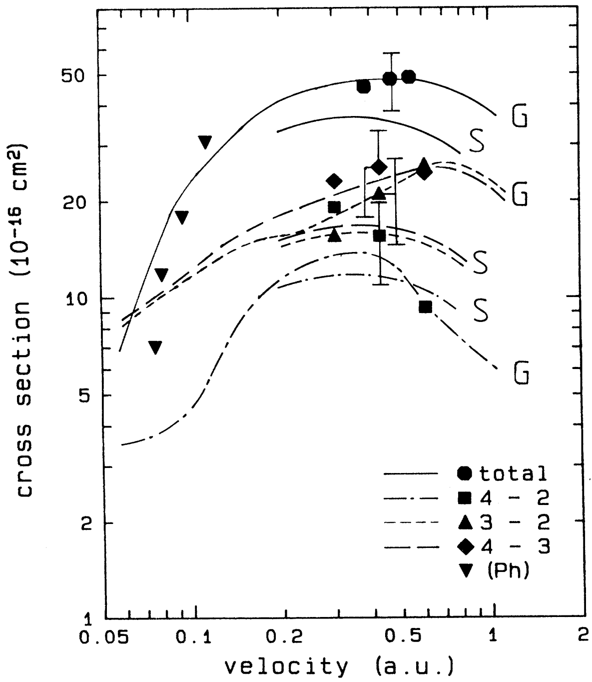


FIG. 1. Total capture cross section $\sigma_t$ and line-emission cross sections $\sigma_{em}(n\text{-}n')$ for $C^{6+}$-H as a function of collision velocity. Error bars indicate total uncertainties (cf. text). (Ph), $\sigma_t$ of Ref. 7; long curves indicated with *G*, theory of Ref. 1; short curves indicated with *S*, theory of Ref. 4.

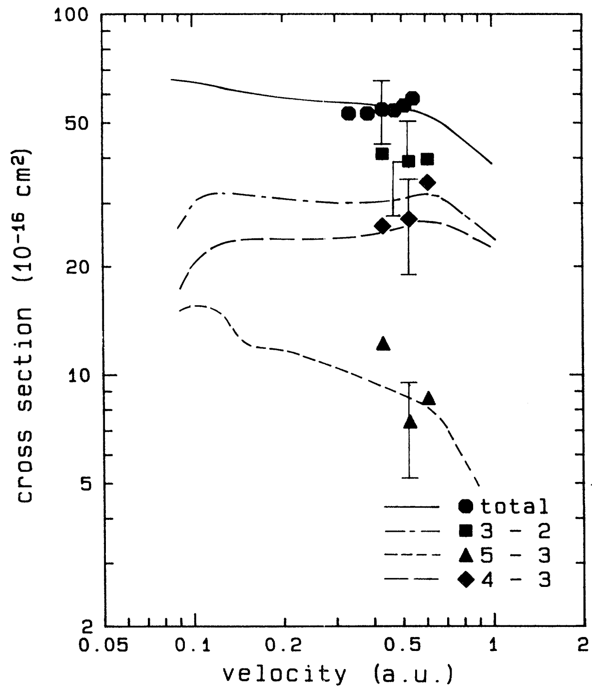


FIG. 2. $\sigma_t$ and $\sigma_{em}(n\text{-}n')$ for $N^{7+}$-H as a function of collision velocity. Curves, theory of Ref. 3.

Measurements were always first performed on a purely molecular target (discharge switched off) and then on the composite target (discharge on). Signals obtained from the latter measurements were corrected for the molecular contribution.

The optical measurements are subject to systematic errors of about 20% in the sensitivity calibration and 15% in the target thickness calibration. Summed quadratically with a statistical error (reproducibility) of about 20% this leads to a total uncertainty of 30%. The systematic error in the charge-state measurements is 15% (target thickness), and the statistical error is 10%, leading to a total uncertainty of about 20%.

To compare our experimental results for $\sigma_{em}(n\text{-}n')$ in $C^{6+}$,$N^{7+}$-H collisions with theory, we have constructed these emission cross sections from the calculated $\sigma_{nl}$ data, using known hydrogen branching ratios; for example,

$$\sigma_{em}(5\text{-}3) = 0.319\sigma_{5s} + 0.043\sigma_{5p} + 0.236\sigma_{5d} + 0.637\sigma_{5f}.$$

Results for $\sigma_t$ and for $\sigma_{em}(4\text{-}2)$, $\sigma_{em}(3\text{-}2)$, $\sigma_{em}(4\text{-}3)$ at 13.5, 18.2, and 52.0 nm, respectively, in $C^{6+}$-H collisions are shown in Fig. 1, with typical error bars which represent the total uncertainties discussed above. The data are compared with the predictions of a 33-state molecular-orbital (MO) calculation by Green, Shipsey, and Browne[1] and with the results of the so-called "complete *l*-mixing model" by Salin.[4] Also shown are the experimental results at low energy for $\sigma_t$ by Phaneuf *et al.*[7] Figure 2 shows our results for $\sigma_t$ and $\sigma_{em}(3\text{-}2)$, $\sigma_{em}(5\text{-}3)$, $\sigma_{em}(4\text{-}3)$ at 13.4, 26.2, and 38.3 nm, respectively, for $N^{7+}$-H, compared with theoretical results by Fritsch and Lin,[3] who used a 46-state atomic-orbital (AO) expansion. Their results for $C^{6+}$-H are not shown in Fig. 1 because they practically coincide with those of Ref. 1. Figure 3 shows $\sigma_t$ for $O^{8+}$-H compared with the 33-state MO calculation by Shipsey, Green, and Browne,[2] and with the 46-state AO calculation by Fritsch and Lin.[3] Again, results of both types of calculations agree very well with each other. Experimental results of Panov, Basalaev, and Lozhkin[6] for $\sigma_t$ (on the average of a factor of 2 below our data) have been omitted in these figures because of their large scatter. It is clear from the figures that the experimental $\sigma_t$ data are in excellent agreement with the theories of Refs. 1–3, considering the total uncertainty of 20%. The agreement of $\sigma_{em}$ data with the theoretical results of Refs. 1 and 3 for $C^{6+}$ and $N^{7+}$ is also quite good, in view of the additional experimental errors discussed above, leading to a total uncertainty of about 30%. We do observe a slightly different energy dependence for some of these cross sec-

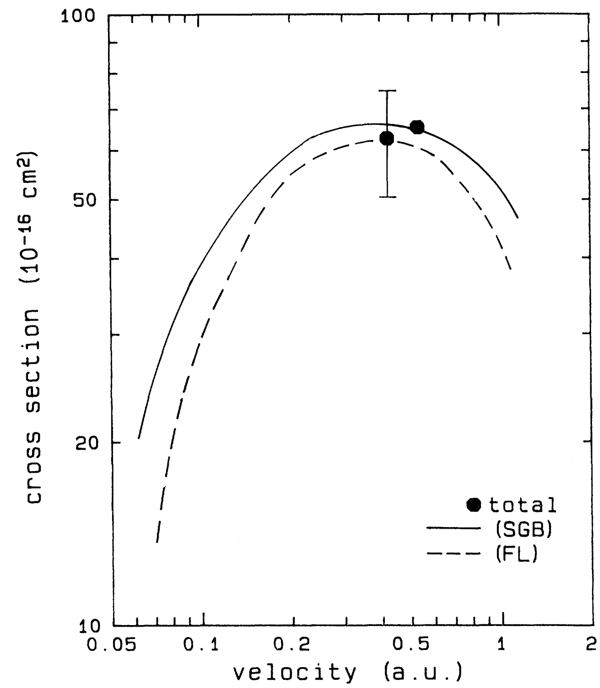


FIG. 3. $\sigma_t$ for $O^{8+}$-H as a function of collision velocity. (SGB), theory of Ref. 2; (FL), theory of Ref. 3.

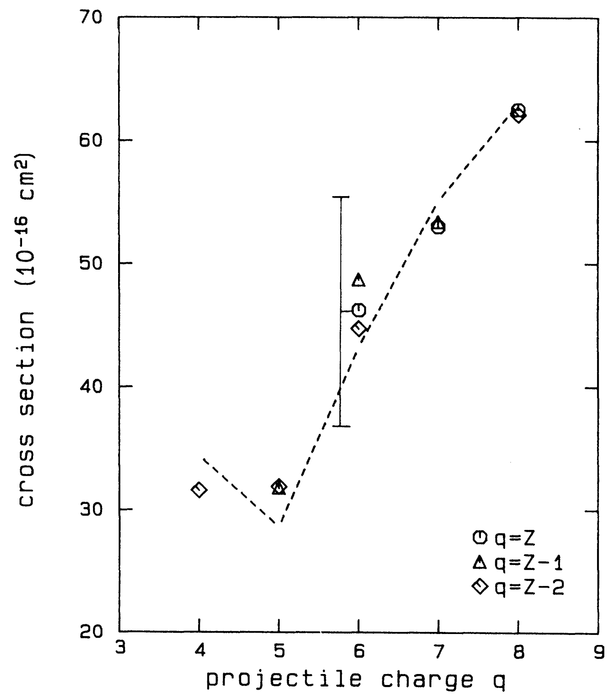


FIG. 4. $\sigma_t$ as a function of projectile charge at a fixed impact energy of 4 keV/u ($v = 0.4$ a.u.). Circles, triangles, and diamonds represent present results for fully stripped, hydrogenlike, and heliumlike ions, respectively. Broken line, theory of Ref. 3.

tions [$\sigma_{em}(4\text{-}2)$ for $C^{6+}$-H and $\sigma_{em}(4\text{-}3)$ for $N^{7+}$-H].

The agreement between our data for $C^{6+}$ with the theoretical results of Ref. 4 is less good. With regard to the absolute magnitudes, this is not so surprising since in these calculations only an 11-state MO expansion was used. However, the aim of the calculation was to obtain insight in the $l$ distribution rather than yielding very accurate absolute $\sigma_{nl}$ values. From a comparison of the experimental energy dependence of $\sigma_{em}(\lambda)$ with the dependencies of the two calculations we tentatively conclude that the $l$ distribution of Ref. 1 agrees better with the experiment.

Finally, in Fig. 4 we compare theoretical $\sigma_t$ data for fully stripped ions colliding with atomic hydrogen at 4 keV/u (Ref. 3) with our results for fully stripped, hydrogenlike, and heliumlike ions. It is clear from Fig. 4 that the total cross section is not very sensitive to the presence of projectile core electrons, as has been observed previously.[9,15] The anomalously low value of $\sigma_t$ for $q = 5$ is generally attributed to the fact that for these systems the crossing radius of the entrance channel with the manifolds of the $n = 3$ and $n = 4$ exit channels is too small, respectively too large, to maximize the transition probability. The dip at $q = 5$ becomes even more pronounced at lower impact energies, as will be shown in a forthcoming article,[17] which will contain more data obtained for collisions of incompletely stripped ions with atomic hydrogen, as well as the results for $H_2$ as a target.

In conclusion, we have shown that current state-of-the-art multichannel strong-coupling calculations, both of the AO and MO type, are capable of predicting accurate data, for total as well as partial capture cross sections, provided that a sufficiently large number of states is taken into account. Our data provide the first direct experimental evidence that the use of the results of such calculations in, e.g., plasma modeling and plasma diagnostics is indeed justified.

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