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Electron capture in very slow $C^{q+}+H$ collisions

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An expanding laser-produced plasma has been used as a source of a beam of slow, highly charged carbon ions. Bursts of collimated and energy-selected C^{q+} ions were directed through an atomic hydrogen gas target and charge analyzed by time-of-flight methods. Total electron-capture cross sections are reported for $C^{q+}+H$ collisions ($q=3,4,5,6$) at energies ranging from 11 to 387 eV/amu and are generally in accord with heretofore untested low-energy theoretical calculations.

At collision energies below several thousand eV/amu, collisions in which multiply charged ions capture electrons from neutral atoms can have large cross sections and thus play an important role in physical systems in which such ions occur. In the interstellar medium, charge exchange in slow collisions with hydrogen and helium is important in reducing the degree of ionization of highly charged ions.[1] Charge-changing collisions between highly ionized impurities and hydrogen isotopes influence impurity transport and the interpretation of diagnostic measurements in magnetically confined fusion plasmas.[2,3] Such collisions have proven difficult to treat theoretically since a quasimolecular description of the colliding system is required at low velocities.[4]

For many-electron systems, theories are generalized to give some average representation of the many potential energy curve crossings at which capture takes place. At keV energies, the predicted and measured cross sections are large, relatively independent of velocity, and increase smoothly with ionic charge.[5,6] The case of a highly stripped ion colliding with a one-electron atom presents quite a different situation; often few favorable curve crossings exist, and both the magnitude and velocity dependence of the cross section depend critically on the details of the potential-energy curves for that particular molecular system.[4] Thus measurements on nearly or fully stripped ions colliding with hydrogen atoms at low velocity are needed to test the perturbed-stationary-state calculations and the various approximations which have been applied. In this Communication, experimental total electron-capture cross sections are reported for $C^{q+}+H$ collisions ($q=3,4,5,6$) at energies ranging from 11 to 387 eV/amu. These data are believed to be the first reported cross-section measurements for nearly or fully stripped multiply charged ions colliding with atomic hydrogen in this energy range.

The arrangement of the time-of-flight apparatus is shown in Fig. 1. The technique is similar to that reported by Goldhar and co-workers,[7] and a more detailed account has been published elsewhere.[8] A 3-J pulse of 10.6-μm radiation 60 ns in duration from a TEA-CO_2 laser is focused onto a graphite target in

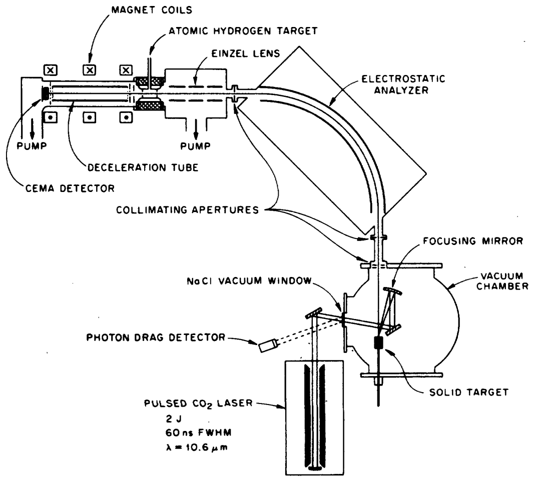

FIG. 1. Pulsed-laser ion source and time-of-flight electron-capture collision apparatus.

vacuum to a power density of $\sim 3\times 10^{10}$ W/cm^2. A series of apertures collimate a beam from the expanding plasma. A cylindrical electrostatic analyzer selects ions from this plasma having a fixed energy per charge which then pass through a differentially pumped atomic hydrogen gas target cell, a gridded deceleration tube, and are detected by a channel electron multiplier array (CEMA). Three coils provide an axial magnetic field which collimates the ion beam, offsetting beam blowup in the deceleration tube, and assuring detection of all ions which enter the hydrogen cell. The total path length from the laser target to the CEMA detector is 260 cm.

The separation of the various charges in the plasma by time-of-flight measurements is based on the fact that the plasma is short-lived relative to ion flight times in the apparatus and that an electrostatic analyzer selects ions having a fixed energy per charge E/q. Hence for a given analyzer voltage, each charge q will arrive at the detector at different time t, such that $t \propto (m/q)^{1/2}$. The deceleration charge-exchange analyzer takes advantage of the fact that an ion of a selected E/q that subsequently captures an electron has energy per charge $E/(q-1)$ and is thus retarded less by electrostatic deceleration. A digitized ion time-of-flight spectrum is shown in Fig. 2 for 278-eV/charge carbon ions passing through atomic hydrogen. The relative intensities are corrected for measured variations of ion detection efficiency with impact velocity and ionic charge. Under single-collision conditions, the variation of the net capture fraction with cell gas density is linear, and the slope is proportional to the total capture cross section. The atomic hydrogen target thickness calibration and the dissociation fraction (0.87 ± 0.03) were determined in an auxiliary experiment using a probe beam of 20-keV protons.[9] The ranges of energies for which measurements were made reflect the availability of adequate fluxes of ions of the various charges q from the laser-produced plasma, and uncertainties represent the quadrature combination of random uncertainties at 90% confidence level with systematic uncertainties ($\pm 22\%$) evaluated at a comparable level of confidence.

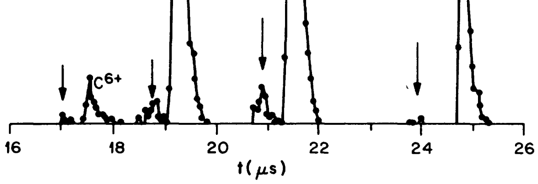

FIG. 2. Digitized time-of-flight spectrum for carbon ions at 278 eV/charge, with +190 V on deceleration charge analyzer. Ions indicated by arrows have captured an electron and are retarded less than the primary ions. Particle density in the atomic-hydrogen collision cell is 8×10^{12} cm^{-3}. The spectrum is an average over 50 laser shots.

The experimental cross sections for C^{6+} + H and C^{5+} + H are compared in Fig. 3 with theory,[10–16] and for C^{5+} + H, with higher-velocity experimental data.[14] The C^{6+} measurements each represent averages over several thousand laser shots at a repetition rate of 0.1 Hz, and their uncertainties are dominated by statistical fluctuations due to low ion fluxes. The C^{6+} data show the falloff with decreasing velocity predicted by perturbed-stationary-state (PSS) impact-parameter calculations of Salop and Olson,[10] of Vaaben and Briggs,[11] and of Green *et al.*[12] At $v = 2\times 10^7$ cm/s, the measurement exceeds the fully quantal 3-PSS calculation of Bottcher and Heil.[13] The distorted-wave calculation of Ryufuku and Watanabe[15] is not claimed to be reliable for $v < 6\times 10^7$ cm/s, and significantly exceeds the measurements. Present C^{5+} + H cross sections agree with the 5-PSS impact parameter calculation of Shipsey *et al.*,[16] and as predicted, become increasingly larger than the C^{6+} + H cross section with decreasing velocity below 2×10^7 cm/s.

Experiment and theory for C^{3+} + H and C^{4+} + H

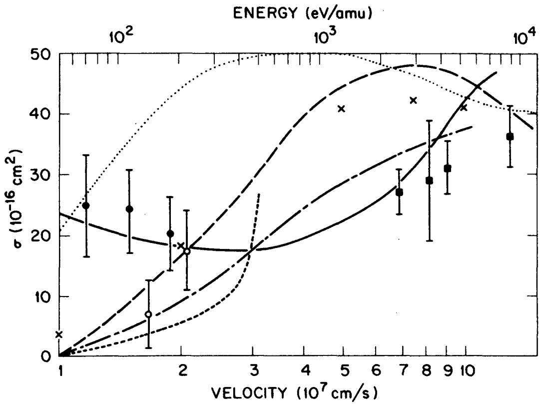

FIG. 3. Electron-capture cross sections for C^{5+} + H (solid points and solid curve) and C^{6+} + H (open points, crosses, and broken curves). Circles are present experimental results, and squares are data of Crandall *et al.* (Ref. 14). The solid curve is the 5-PSS calculation of Shipsey *et al.* (Ref. 16), the long-dashed curve is the 6-PSS of Salop and Olson (Ref. 10), the dash-dot curve is the 11-PSS of Vaaben and Briggs (Ref. 11), the short-dashed curve is the 3-PSS of Bottcher and Heil (Ref. 13), the dotted curve is the distorted-wave calculation of Ryufuku and Watanabe (Ref. 15), and the crosses are the 8-PSS and 10-PSS of Green *et al.* (Ref. 12).

are compared in Fig. 4. The present C^{3+} + H data substantiate both the magnitude of the cross section and the rise with decreasing velocity predicted by the 6-PSS quantal calculation of Bottcher and Heil.[13] The present C^{4+} + H results and those of Crandall *et al.*[14] are generally consistent with the velocity dependence predicted by the PSS impact-parameter calculation of Olson *et al.*,[17] and the quantal calculations of Bottcher and Heil[13] and of Gargaud *et al.*[18] The latter calculation also agrees well in magnitude with the present data. The C^{4+} + H measurements could be influenced by the presence of $C^{4+}(1s2s\,^3S_1)$ metastable ions in the beam, since capture by these metastables is predicted to have a negligible cross section.[20] A rough estimate of the metastable fraction may be made by assuming local thermodynamic equilibrium and using the measured relative concentrations of C^{4+} and C^{5+} in the expanding plasma to deduce an effective electron temperature. For the laser source, $N(C^{5+})/N(C^{4+}) \approx 0.13$, which yields $kT_{\text{eff}} \approx 165$ eV, and a 2^3S fraction in the neighborhood of 20%.

The laser source is convenient for producing very-low-energy, highly stripped ions of any element which exists as a solid or in a solid compound. Ions with charges of +9 and +16 have been detected in the present apparatus with aluminum and iron targets, respectively, and electron-capture measurements for O^{q+} + H and Fe^{q+} + H collisions are in progress. Improvements to increase the focused laser power density and ion acceleration are being considered in order to improve and extend the C^{6+} + H measurements to higher velocity, and thus provide a firmer basis for evaluation of theoretical methods for this simple one-electron case.

In summary, experimental cross sections for electron capture from atomic hydrogen by very-low-velocity, highly stripped carbon ions exhibit neither simple scalings with ionic charge nor uniform velocity dependences and are generally consistent with detailed perturbed-stationary-state calculations using accurate potential curves.

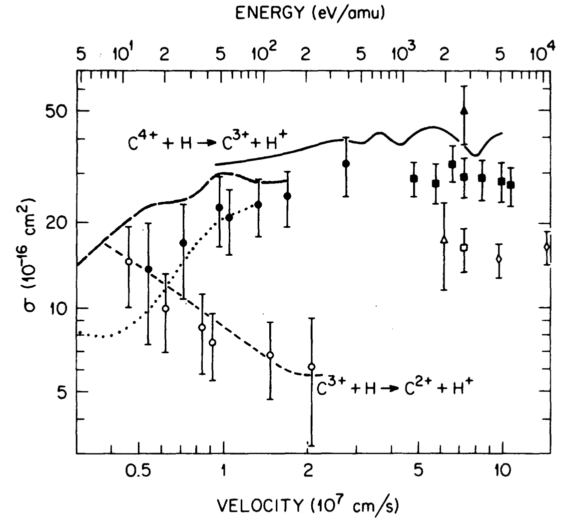

FIG. 4. Electron-capture cross sections for C^{3+} + H (open points and short-dashed curve) and C^{4+} + H (solid points and solid, long-dashed, and dotted curves). Circles are present experimental results, and squares, diamonds, and triangles are the measurements of Crandall *et al.* (Ref. 14), Phaneuf *et al.* (Ref. 9), and Gardner *et al.* (Ref. 19), respectively. Solid, dashed, and dotted curves are the PSS calculations of Olson *et al.* (Ref. 17), Bottcher and Heil (Ref. 13), and Gargaud *et al.* (Ref. 18), respectively.

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