Single electron capture by multiply charged ^{28}Si ions in atomic and molecular hydrogen

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Cross sections for single electron capture by Si^{q+} ($2 \leq q \leq 9$) incident on atomic and molecular hydrogen have been measured in the relative-collision-velocity range $(3.1\text{–}6.3) \times 10^8$ cm/s. All measured cross sections decrease monotonically with relative velocity and scale roughly as q^N. The values of N needed to fit the data range from ~ 2 to ~ 3 and increase with velocity. Cross sections averaged over incident charge states q for molecular hydrogen are larger than for atomic hydrogen, becoming twice as large for relative velocities greater than 4×10^8 cm/s. For the limited cases where comparison was possible, we found the classical-trajectory Monte Carlo calculation to give a good account of the experimental results.

INTRODUCTION

Earlier[1] we reported on the experimentally measured electron-capture cross sections $\sigma_{q,q-1}$ for multiply charged C, N, and O ions with energies 1.1–140 keV/nucleon and charge $q = 1\text{–}5$ incident on atomic and molecular hydrogen. The relative collision velocities v corresponding to these incident energies are $(0.3\text{–}5.2) \times 10^8$ cm/s and encompass the Bohr velocity ($\sim 2 \times 10^8$ cm/s) for the target electrons. The cross-section dependence on such collision parameters as incident ion species and charges and velocity indicated a complex relationship for velocities below the Bohr velocity, but exhibited a uniform behavior at higher velocities. The present report is a sequel: $\sigma_{q,q-1}$ for ^{28}Si ions with energies 51–204 keV/nucleon and $q = 2\text{–}9$ incident on the same atomic- and molecular-hydrogen targets as were previously investigated.[1] The corresponding relative velocity range is $v = (3.1\text{–}6.2) \times 10^8$ cm/s.

Such a cross-section investigation is of both basic and applied interest, especially for the heating and refueling of confined thermonuclear plasmas by neutral-deuterium-beam injection. The stripping of electrons from the injected deuterium beam caused by electron-capture collisions with multiply charged heavy impurity Si near the plasma boundary can seriously impair the intended plasma heating and refueling.[2] Electron-capture cross sections pertaining to this situation can be measured by bombarding an atomic-hydrogen target with multiply charged projectile ions having the velocity of the injected beam. Impurity ions ranging from He to Fe and even heavier have been found in varying amounts in a typical tokamak plasma,[3] but thus far the cross sections have been measured only for very light impurity ions (see Ref. 1). A systematic study of electron-capture cross sections for selected ion species would provide experimental bases with which other pertinent cross sections may be estimated through a suitable empirical or theoretical model. For the present investigation we chose Si ions, which are considerably heavier than C ions (a major impurity) and are an amenable projectile for a tandem Van de Graaff accelerator.

EXPERIMENTAL APPARATUS AND PROCEDURE

Except for the changes given below, the same apparatus and procedure as described before[1] were used and the details will not be repeated. The major experimental change for the present study is the use of the ORNL tandem accelerator for the incident ion beam rather than the simpler electrostatic accelerator. Figure 1 gives the experimental arrangement.

Negative Si ions extracted from a sputter source and accelerated to the injection energy were mass analyzed via a source magnet and injected into the tandem. The energetic negative ions go through the terminal stripper and emerge from the tandem as multiply charged positive ions with various charge states q. The 90° bending magnets selectively transmit either $q = 2$ or 3 ^{28}Si ions of desired energy. Higher-charge states were obtained by stripping on either argon or air in the postacceleration stripper, and subsequent magnetic analysis allowed selection of the desired incident charge state.

Sufficient pumping was provided to ensure that the pressure in the last magnet chamber and downstream did not exceed 2×10^{-7} torr. The maintaining of low pressure in this region of the beam line was necessary to reduce the background count to a tolerable level.

The ^{28}Si ions emerging from the H_2 target were charge dispersed by the pair of electrostatic deflector plates shown in Fig. 1 and detected by a (7×45)-mm solid-state position-sensitive detector[4] (PSD). Conventional electronics were used

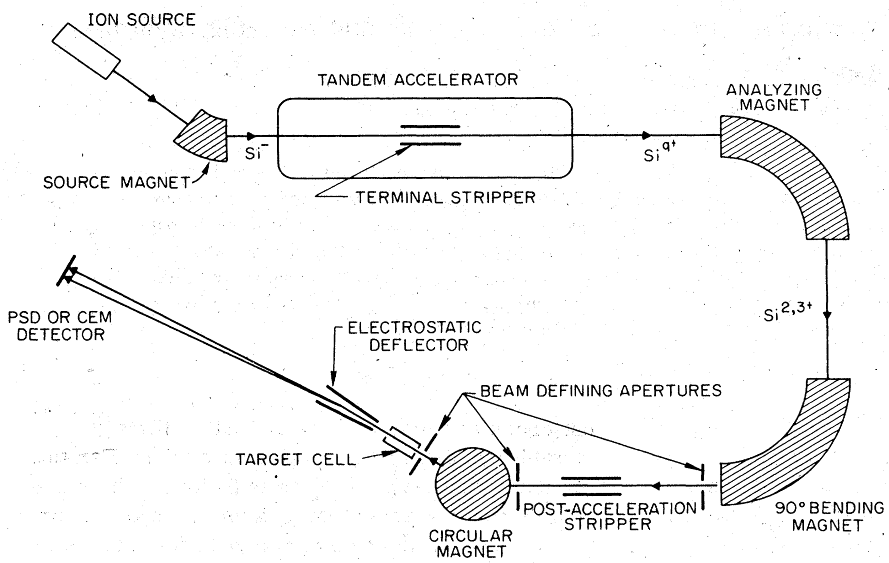

FIG. 1. Apparatus and experimental arrangement.

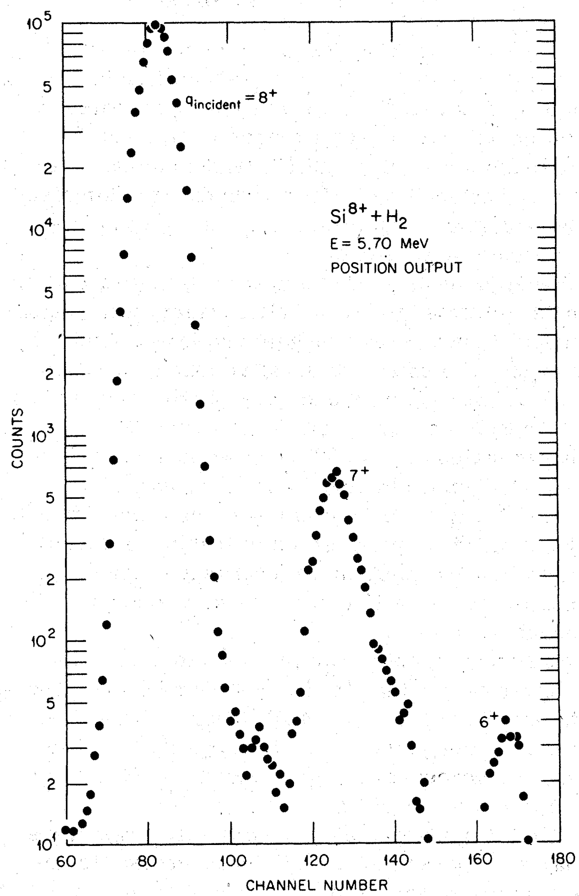

FIG. 2. A representative position spectrum obtained with a position-sensitive solid-state detector. Incident charge state is 8^+. The intensity of the 6^+ peak is consistent with its being entirely due to double single-capture events. See text for detail.

for processing and storing the position and energy information. Figure 2 shows a representative position spectrum obtained with this detector. The beam size that was deduced from this figure is consistent with the geometric beam divergence of the collimating apertures, shown in Fig. 1. A number of cross sections were also measured using channel electron multipliers (CEM) as described before.[1] These cross sections were found to agree well with those measured using the PSD. The atomic-hydrogen measurements were made using the CEM exclusively because the light from the high-temperature target cell that reached the PSD despite the interposed baffle created considerable noise.

Incident ions traversed at least 3 m at pressure lower than 5×10^{-7} torr prior to reaching the target cell. Thus ions with residual excitation (due to collisions in the stripper and upstream where the pressure was higher) had more than 5×10^{-7} s of collisionless flight period in which to decay. We assumed that this dissipation period was sufficient for the deexcitation of most excited incident ions before they reached the target.

RESULTS AND DISCUSSION

The cross sections presently measured are given in Figs. 3 and 4. Lines connect the data points for a visual guide. The combined statistical and systematic uncertainties are given by the error bars shown. A detailed analysis of these uncertainties was given in Ref. 1. The relative sparsity of and larger uncertainties for the H cross sections relative to those for H_2 apparent in these figures re-

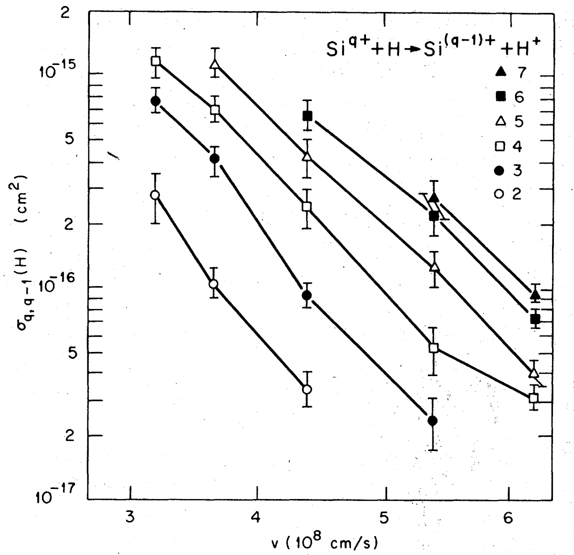

FIG. 3. Experimental cross sections for single-electron capture by Si^{q+} on atomic hydrogen. See text for detail.

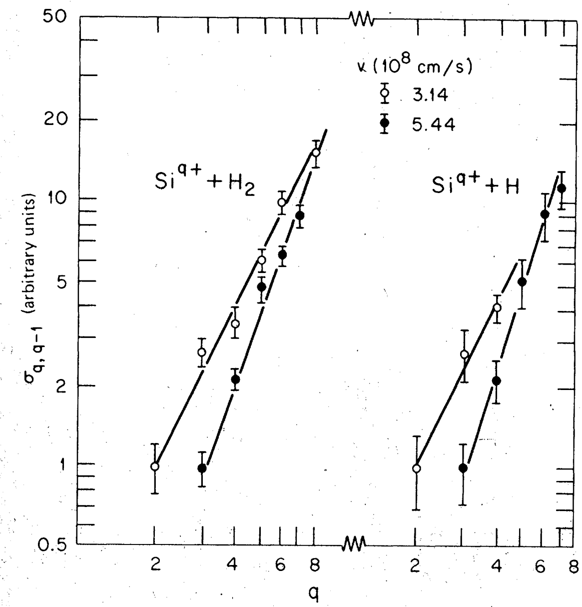

FIG. 5. Comparison of the experimental results to the $\sigma_{q,q-1} \propto q^N$ scaling law.

flect the experimental fact that the H measurements were more difficult.

Cross-section values are large ($>2\times10^{-16}$ cm²) at the lowest v, but decrease rapidly and monotonically with v for both H and H_2. This trend is consistent with our earlier results[1] for $v > 2\times10^8$ cm/s and with the electron-capture cross sections for various multiply charged ions on H_2 and rare gases measured by Betz *et al.*[5] and Nikolaev *et al.*[6] over a similar velocity range.

The cross section $\sigma_{q,q-1}$ increases with incident charge q at all velocities studied and, as indicated in Figs. 3 and 4, the amount of this increase seems to increase with v. To further elucidate this we compared the measured $\sigma_{q,q-1}$ to a

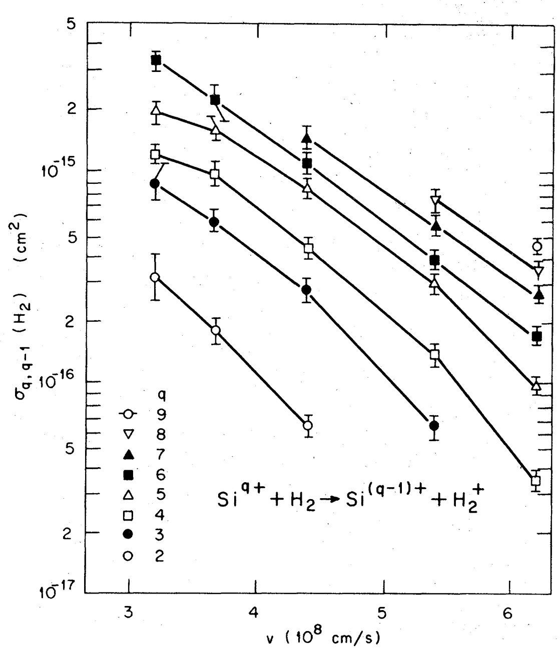

FIG. 4. Experimental cross sections for single-electron capture by Si^{q+} on molecular hydrogen. See text for detail.

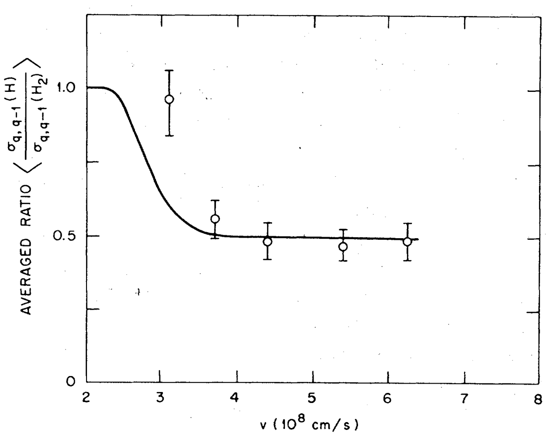

FIG. 6. Weighted-average values of the cross-section ratio $\sigma_{q,q-1}(H)/\sigma_{q,q-1}(H_2)$. The solid curve is the ratio for protons on atomic and molecular hydrogen. See text for detail.

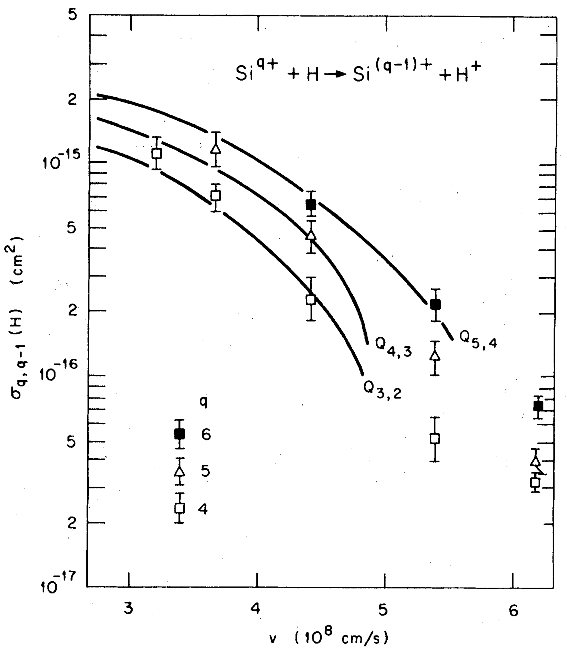

FIG. 7. Comparison of the experimental results to the theoretical results of Olson and Salop. Theoretical results are given by the solid curves.

simple power-law scaling, $\sigma_{q,q-1} \propto q^N$, with N as the free parameter. Typical comparisons are shown in Fig. 5. Such a scaling characterizes the data well, and N increases from 2.1 at $v=3.1 \times 10^8$ cm/s to 3.2 at $v=6.2 \times 10^8$ cm/s. Nikolaev *et al.*[6] reported a similar parametrization of their cross section for various multiply charged ions incident on rare gases for $3 \leq v \leq 8 \times 10^8$ cm/s.

The cross section $\sigma_{q,q-1}(H)$ is smaller in all cases than the corresponding $\sigma_{q,q-1}(H_2)$, and the ratios $R_q = \sigma_{q,q-1}(H)/\sigma_{q,q-1}(H_2)$ scatter around the value 0.5 except for the lowest v, where the ratio averages to about 0.9. However, the q-averaged values of the ratio are more stable and behave in a manner similar to the corresponding ratio for protons on H and H_2 for $v > 3.5 \times 10^8$ cm/s. This is clearly shown in Fig. 6 in which the weighted-average ratios $[\sum_q R_q(\Delta_q)^{-2}][\sum_q(\Delta_q)^{-2}]^{-1}$, where Δ_q is the experimental uncertainty for R_q, and the ratios for protons on H and H_2 obtained from the compilation of Barnett *et al.*[7] are plotted against v. Our earlier results[1] also showed a similar convergence of the cross-section ratios to the value of 0.5.

Using a Monte Carlo method for solving the classical trajectories of a bare nucleus incident on an atomic-hydrogen target with randomly oriented initial conditions, Olson and Salop[8] have recently calculated electron-capture cross sections $Q_{z,z-1}$ for projectiles ranging from $z=1$ to 36 and $v=2-6 \times 10^8$ cm/s. Only the Coulomb forces between the three bodies (proton, electron, and projectile) were considered in the calculation. They extended their calculation for partially stripped B, C, N, and O ions incident on H targets, assuming these ions to be equivalent to bare nuclei but endowed with appropriate effective charges q_{eff} which are related to the incident charges q and which take into account the screening effect by the remaining electrons. Their results agreed remarkably well with the experiments.[1,8] Effective charges for Si ions having $q=4$, 5, and 6 calculated according to the prescription given by Olson and Salop are 3.0, 4.1, and 5.1, respectively; since these values are not too different from the integer values, $z=3$, 4, and 5, we compare the measured $\sigma_{4,3}$, $\sigma_{5,4}$, and $\sigma_{6,5}$ to the calculated $Q_{3,2}$, $Q_{4,3}$, and $Q_{5,4}$ for fully stripped ions as shown in Fig. 7. The calculation predicts the cross sections fairly well, and this agreement, shown in Fig. 7, seems to justify the use of q_{eff}. For other charges, corresponding q_{eff} are too different from integers to warrant similar comparisons.

SUMMARY

The measured cross sections for Si ions with charge $q=2-5$ for electron capture from hydrogen atoms are large and scale roughly as q^2 near the planned Tokamak-Fusion-Test-Reactor[9] neutral-beam injection velocity ($v=3.4 \times 10^8$ cm/s). Using a q^2 scaling, we found the extrapolated value for bare Si nuclei from the measured values to be ~1×10^{-14} cm^2 at $v=3.4 \times 10^8$ cm/s, which is larger than the value of 0.6×10^{-14} cm^2 estimated from the theoretical results of Olson and Salop. The cross sections decrease rapidly and monotonically with v.

The qualitative v dependence of the molecular-hydrogen cross sections are similar to the atomic cross sections, but the corresponding cross-section values are larger for molecular hydrogen. For $v > 3.5 \times 10^8$ cm/s the cross-section ratio $R_q = \sigma_{q,q-1}(H)/\sigma_{q,q-1}(H_2)$ averaged over the incident charge q becomes $\frac{1}{2}$ and remains unchanged as v increases.

For the limited cases where the comparison was possible, the Monte Carlo calculations of Olson and Salop give a good account of the measured cross sections.

ACKNOWLEDGMENTS

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[1]R. A. Phaneuf, F. W. Meyer, and R. H. McKnight, Phys. Rev. A 17, 534 (1978).
[2]E. Hinnov, Phys. Rev. A 14, 1533 (1976); A. Salin, J. Phys. B 2, 631 (1969); A. Z. Msezane, Phys. Lett. 59A, 435 (1977).
[3]C. F. Barnett, in *Atomic Physics 5*, edited by R. Marrus, R. Prior, and H. Shugart (Plenum, New York, 1977), p. 375.
[4]*P* series ion-implanted detector supplied by ORTEC, Inc., Oak Ridge, Tenn.
[5]H. D. Betz, G. Ryding, and A. B. Wittkower, Phys. Rev. A 3, 197 (1970).
[6]V. S. Nikolaev, I. S. Dimitriev, L. N. Fateeva, and Ya. A. Teplova, Zh. Eksp. Teor. Fiz. 40, 989 (1961) [Sov. Phys.-JETP 13, 695 (1961)].
[7]C. F. Barnett, J. A. Ray, E. Ricci, M. I. Wilker, E. W. McDaniel, E. W. Thomas, and H. B. Gilbody, Atomic Data for Controlled Fusion Research, Oak Ridge National Laboratory Report ORNL-5206, II, 1977 (unpublished).
[8]R. E. Olson and A. Salop, Phys. Rev. A 16, 531 (1977).
[9]"Tokamak Fusion Test Reactor" Reference Design Report PPPL-1312, PH-R-004 (1976), Princeton Plasma Physics Laboratory, Princeton University, Princeton, N. J. (unpublished).