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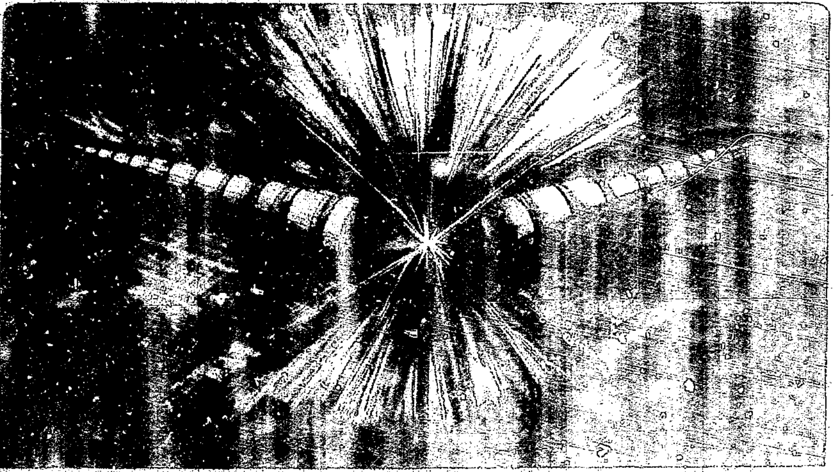

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COLLISIONS OF FAST MULTICHARGED IONS IN GAS TARGETS: CHARGE TRANSFER AND IONIZATION

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Collisions of fast multicharged ions with atoms are of fundamental interest. Important applications include fusion, accelerator design, and beam transport. We present electron-capture and ionization cross sections for multicharged ions colliding with H_2 and rare-gas targets. Projectile charge-states range from 3+ to 59+ and energies from 0.1-4.8 MeV/amu.

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Introduction

Processes involving heavy multi-charged ions in collision with target atoms[1,2] are of both basic and applied interest. Applications include accelerator design, beam transport, and neutral-beam heating of magnetically confined fusion plasmas.

Magnetically confined plasmas are often heated by injection of high-energy H or D atoms. The ionization (trapping) profile of the injected atoms can be altered by the presence of highly stripped impurities[3] which are present in the plasma. Heavy metal ions, such as Fe^{25+}, Mo^{33+}, and W^{35+} have been identified[4] in confined plasmas. In order to estimate how large an effect an impurity ion could have on the trapping profile, it is necessary to know the cross section for electron loss from the hydrogen atom. We have made measurements with a fast ion beam incident on a hydrogen target rather than a fast hydrogen beam incident on an ion target. It was also convenient to use a molecular rather than an atomic hydrogen target. For collisions at sufficiently high energies, a hydrogen molecule can be considered as two H atoms[5,6] (to within about 25%). We compare theoretical cross sections calculated for atomic hydrogen with cross sections measured in H_2 divided by 2.

The cross sections we have measured are single-electron capture:

$$\sigma_{q,q-1}: \; q + Y \rightarrow A^{(q-1)} \quad + Y^{+} \tag{1}$$

where Y is the target atom, and single-electron loss by the ion:

$$\sigma_{q,q+1}: \; A\,q^{+} + Y \rightarrow A^{(q+1)+} + Y + e^{-}. \tag{2}$$

These cross sections are determined experimentally by observing the change in charge state of the projectile after traversing the target. In addition, we have used the condenser-plate method, in which slow ions and electrons are collected in the target, to determine ionization in the target by passage of the fast projectile beam. If σ_j is the cross section for producing a target ion j-times ionized, then the net ionization cross section σ_+ is:

$$\sigma_+ = \Sigma\, j \;\; \sigma_j \; . \qquad (3)$$

For a hydrogen target we call this σ_{loss}. We have also made some measurements of the charge-state distribution of slow recoil ions created the passage of a fast heavy-ion beam through a gas target, using a time-of-flight coincidence technique. This measures relative values of σ_j.

Experimental Considerations

The apparatus we have used[5-8] is shown in Fig. 1. A beam of ions from the LBL SuperHILAC heavy-ion linac was stripped in a foil, producing a distribution of high-charge-state ions. A beam in a single charge state, after selection by the charge-selection

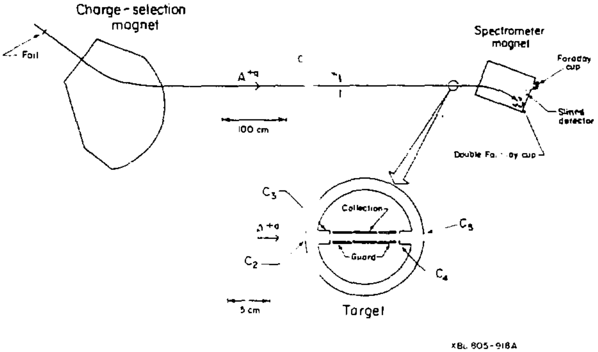

Fig. 1 Schematic diagram of the apparatus used by the LBL group.

magnet, passed through a gas target. Slow ions and electrons produced by ionization or charge transfer were swept from a well-defined length of the target by a weak electric field applied between two plates, and were collected on one of these plates. The spectrometer magnet located after the target deflected the beam onto either an array of solid-state detectors or a Faraday-cup array. We determined cross sections for ionization and charge transfer from the growth of the product-ion fluxes as the target gas pressure was raised. Typical uncertainties are of the order of 10-15%.

Charge transfer and Ionization in H_2

Single-electron-capture cross sections[7] $\sigma_{q,q-1}$ for Fe^{q+} in H_2 are shown in Fig. 2, along with theoretical calculations for Fe^{q+} + H. Modified OBK calculations by Rule and Omidvar[9] and by Chan and Eichler[10] are in good agreement with experiment at higher energies; the results of Ryufuku and Watanabe[11] are higher than experiment but have similar charge-state dependence ; and the classical-trajectory Monte-Carlo (CTMC) calculations of Olson[6] are in good agreement with experiment at lower energies.

In an attempt to find a general expression for the energy and charge-state dependence of $\sigma_{q,q-1}$ for Fe^{q+} in H_2, we fit our data to a power-law expression. For results at energies of 275 keV/amu and above, we found the following expression to fit the data very well:

$$\sigma_{q,q-1}\ (q,E) = (1.2 \times 10^{-8})q^{3.15}E^{-4.48} \qquad (4)$$

where σ is in cm^2 and E is in keV/amu.

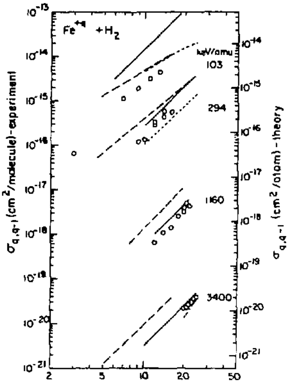

Fig. 2 Single-electron-capture cross sections[7] $\sigma_{q,q-1}$ for Fe^{q+} + H_2 (experiment, left ordinate) and Fe^{q+} + H (theory, right ordinate). Lines are calculations by Olson[6] (short-dash), Chan and Eichler[10] (solid), Ryufuku and Wantanabe[11] (long-dash), and Rule and Omidvar[9] (dash-dot-dash).

Figure 3 shows experimental results[7,12,13] for $\sigma_{q,q-1}$ scaled by $q^{-3.15}$. Cross sections at energies lower than 275 keV/amu deviate increasingly with decreasing energy.

Single-electron-loss cross sections [7,14] $\sigma_{q,q+1}$ for Fe^{+q} in H_2 are shown in Fig. 4, along with first-Born-approximation results of Rule and Omdivar,[9] which are in generally good agreement with experiment. The discontinuity in $\sigma_{q,q-1}$ between lithium-like projectiles (Fe^{+23}) and helium-like projectiles (Fe^{+24}) can be attributed to the shell structure of the iron ion; the s electrons are bound much more tightly than are the p electrons.

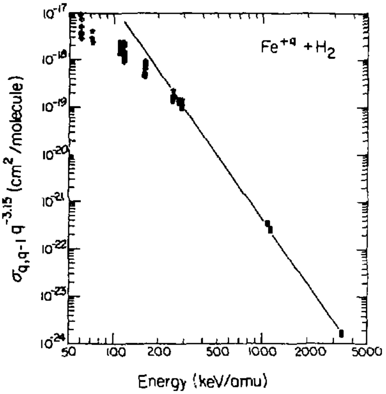

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Fig. 3 Single-electron-capture cross sections[7] $\sigma_{q,q-1}$ for $Fe^{q+}+H_2$ scaled by $q^{-3.15}$. ■, Berkner et al.[7]; ✧, Meyer et al.[13]; ☆, Gardner et al..[12] The line is Eq. (4).

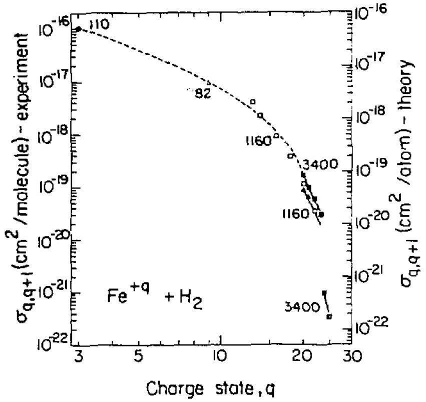

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Fig. 4 Single-electron-loss cross sections[7] $\sigma_{q,q+1}$ for $Fe^{q+}+H_2$ (experiment, left ordinate) and $Fe^{q+}+H$ (theory, right ordinate). Solid line: calculation by Rule and Omidvar.[9] Dashed line for clarity.

Electron loss in H_2

We have found[6,15] that the cross section for loss of an electron from a hydrogen target, σ_{loss}, can be combined into a universal scaling rule, applicable for a wide range of projectile energies and charge states. The scaled parameters are σ_{loss}/q and E/q (E is energy per nucleon). This scaling was based on CTMC calculations for an H target. We found that the results could be fitted to an analytic expression:

$$\sigma_{loss} = 4.6 \times q \times 10^{-16}\{(32q/E)\left[1-\exp(-E/32q)\right]\} , \qquad (5)$$

where σ_{loss} is in cm^2 and E is energy in keV/amu. This is valid for $1 \leq q \leq 50$ and for energies in the range 50 keV/amu to 5000 keV/amu.

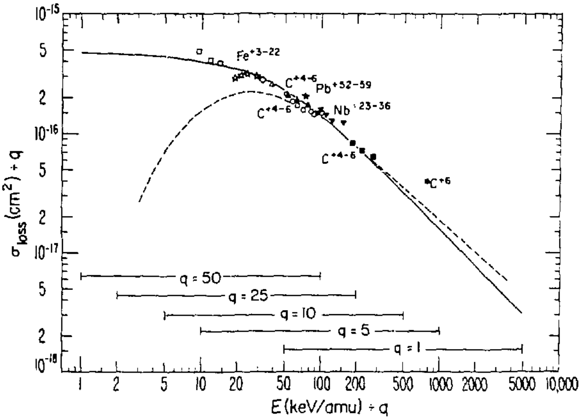

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Fig. 5 Hydrogen electron-loss cross section[6,15] σ_{loss}. Solid line: calculation for electron loss by atomic H in collision with an ion in charge state q; valid for $1 \leq q \leq 50$ and for energy range 50 to 5000 keV/amu. Dashed line: plane-wave Born approximation (ionization only).

The experimental cross sections (divided by 2 at all but the lowest energies) are compared with the theoretical expression and with the plane-wave Born approximation (ionization only) in Fig. 5.

Ionization of Rare-Gas Targets

We have measured[8] the net ionization cross section σ_+ for highly stripped carbon, iron, niobium, and lead ions in rare-gas targets; projectile charge states were in the range +4 to +54, and energies ranged from 300 keV/amu to 4.8 MeV/amu. Olson has calculcated[8] cross sections σ_j for the rare gases using the CTMC method and the independent-electron model for projectiles at collision energies of 1 MeV/amu to 5 MeV/amu with charge states +5 to +80.

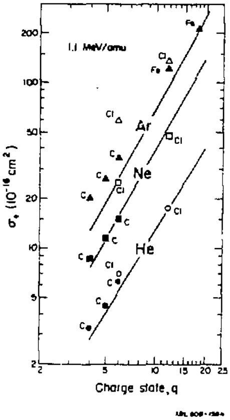

Fig. 6 Net ionization cross section[8] σ_+ for 1.1 MeV/amu projectiles in charge state q in He (●,O) Ne(■,□) and Ar (▲,△) targets. Closed symbols: Schlachter et al.[8]; open symbols: Cocke[16]; lines are CTMC calculations.

Experimental and theoretical net-ionization cross section σ_+ for 1.1 MeV/amu ions in Ar are shown in Fig. 6. Also shown are experimental results of Cocke[16] for Cl^{q+} projectiles; we calculated $\Sigma\, j\sigma_j$ from his σ_j results. Cocke's results for Cl^{6+} are almost a factor of 2 larger than our results, which we attribute to the lower state of ionization of the the Cl projectile relative to the fully stripped C projectile. His results for Cl^{12+} are in excellent agreement with the calculations and with our measurements for Fe^{12+} in Ar.

We have found[8] that the calculated net-ionization cross sections for a given rare-gas target reduce to a common curve when plotted as σ_+/q vs E/q, where E is energy per nucleon. Results are shown in Figs. 7a and 7b. The curves are proportional to q^2/E at the highest values of E/q. We also compare our experimental results to these calculations. The experimental data give credence to the scaling relationship and, in general, are within a factor of 2 of the theoretical prediction. However, the experimental results tend toward $q^{3/2}/E^{1/2}$, and thus are above the calculations, especially for large values of E/q.

Figure 8 shows the results of our calculations for highly stripped ions colliding with Ar at the energies studied. The calculations are most accurate for the prediction of low states of ionization of the target atom. For high states of ionization the calculated cross sections can only be considered qualitative and have uncertainties of at least a factor of 2 because of neglect of cascade effects and the breakdown of the sudden-impact approximation required for the independent electron model. As illustrated in Fig. 8, high states of ionization of the target are produced with sizable cross sections by the passage of an

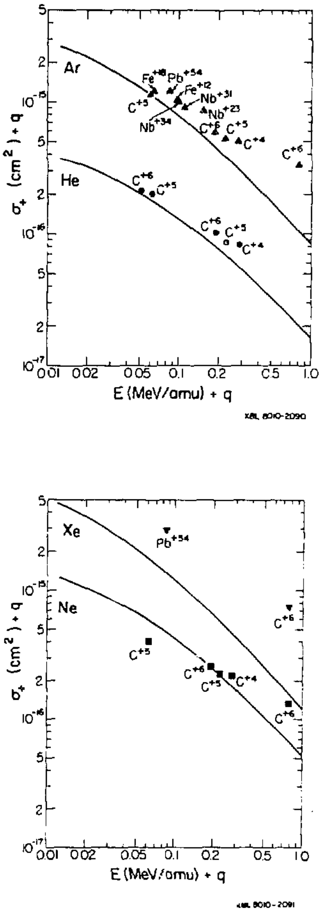

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Fig. 7 Reduced plot of net-ionization cross sections[8] σ_+ for highly stripped ion in charge-state q in He (●), Ar (▲), Ne (■), and Xe (▼) targets. Symbols are experimental results, lines are CTMC calculations.

energetic high-charge-state ion. Notable are the results for producing ten-times-ionized Ar, where cross sections approaching 10^{-15} cm^2 are predicted for projectile ions in charge states $q \gtrsim 40$.

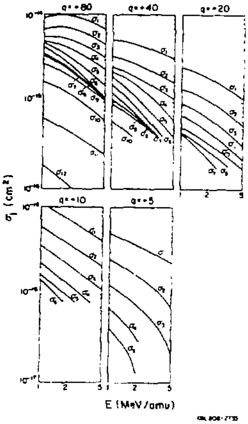

Fig. 8 Calculated cross sections σ_j for production of Ar recoil ions j-times ionized by incident 1-5 MeV/amu projectiles in charge states 80+, 40+, 20+, 10+, and 5+.

Beyer, Groh, Mann, Müller and Schlachter[17] have recently used a time-of-flight coincidence technique[18] to measure the charge-state distribution of slow recoil ions created in rare-gas targets by the passage of 1.4 MeV/amu Xe^{24+} ions from the UNILAC accelerator at GSI in Darmstadt. A recoil-ion charge-state spectrum in Ne is shown in Fig. 9. Recoil neon ions in charge states up to 8+ can be seen.

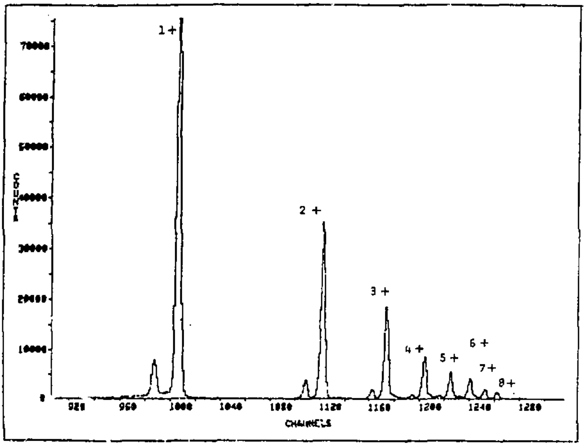

Fig. 9 Recoil-ion time-of-flight spectrum for 1.4 MeV/amu Xe^{24+} in Ne. The Ne recoil charge states 1+ to 8+ are identified. The small peaks to the left of the larger peaks are due to the ^{22}Ne isotope.

Summary

Measurements of cross sections for charge transfer and ionization of H_2 and rare-gas targets have been made with fast, highly stripped projectiles in charge states as high as 59+. We have found an empirical scaling rule for electron-capture cross section in H_2 valid at energies above 275 keV/amu. Similar scaling might exist for other target gases. Cross sections are generally in good agreement with theory. We have found a scaling rule for electron loss from H in collision with a fast highly stripped projectile, based on Olson's classical-trajectory Monte-Carlo calculations, and confirmed by measurements in an H_2 target. We have found a similar scaling rule for net ionization of rare-gas targets, based on Olson's CTMC calculations and the independent-electron model. Measurements are essentially consistent with the scaled cross sections. Calculations and measurements of recoil-ion charge-state spectra show large cross sections for the production of highly charged slow recoil ions.

Acknowledgments

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