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COLLISIONS OF HIGHLY STRIPPED IONS AT MeV ENERGIES
IN GAS TARGETS: CHARGE TRANSFER AND IONIZATION

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Abstract

We have measured cross sections for charge transfer and ionization in H_2 and rare-gas targets by fast, highly ionized carbon, iron, niobium, and lead ions in charge states +3 to +59, with energies in the range 0.1-4.8 MeV/amu. Experimental results are compared with classical-trajectory calculations; agreement is generally good. For a given target, the cross curve when plotted as cross section divided by charge state versus energy per nucleon divided by charge state.

Introduction

Processes involving heavy, multi-charged ions in collision with target atoms¹ are of both basic and applied interest. Applications include accelerator design, beam transport, and neutral-beam heating of magnetically confined fusion plasmas.

Heavy, highly ionized impurity ions, such as Fe^{+25} , Mo^{+33} , and W^{+35} have been identified in magnetically confined hydrogen plasmas.² These 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 the highly stripped impurities.³ In order to estimate how large an effect an impurity ion could have in 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 atoms⁴ (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:

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

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

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

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:

$$\sigma_+ = \sum_j j \sigma_j \quad (3)$$

For a hydrogen target, we call this σ_{loss} .

Experimental Considerations

The apparatus we have used^{4,6-7} is shown in Fig. 1. A beam of ions from the LBL SuperHILAC heavy-ion linac was stripped in a carbon foil, producing a distribution of high-charge-state ions. A beam in a single charge state, after selection by the charge-selection magnet and after suitable collimation, 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 (for charge-transfer measurements) or a Faraday-cup array (for ionization measurements). We determined cross sections for ionization and charge transfer from the growth of the product-ion fluxes as the target-gas pressure was raised. We made suitable corrections for secondary-electron emission from the ion collector plate and for second-order processes. Typical uncertainties are of the order of 10-15%.

Fig. 1 Schematic diagram of the apparatus.

Charge Transfer and Ionization in H_2

Single-electron-capture cross sections⁶ $\sigma_{q,q-1}$ for Fe^{+q} in H_2 are shown in Fig. 2, along with theoretical calculations for $Fe^{+q} + H$. Modified OZK calculations by Rule and Omidvar⁸ and by Chan and Eichler⁹ are in good agreement

with experiment at higher energies; the results of Ryufuku and Watanabe¹⁰ are higher than experiment but have similar charge-state dependence; and the classical-trajectory Monte-Carlo (CTMC) calculations of Olson⁵ are in good agreement with experiment at lower energies.

Fig. 2 Single-electron-capture cross sections $\sigma_{q,q-1}$ for $\text{Fe}^{+q} + \text{H}_2$ (experiment, left ordinate) and $\text{Fe}^{+q} + \text{H}$ (theory, right ordinate). Lines are calculations by Olson⁵ (short-dash), Chan and Eichler⁹ (solid), Ryufuku and Watanabe¹⁰ (long-dash), and Rule and Omidvar⁸ (dash-dot-dash).

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:

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

where σ is in cm^2 and E is in keV/amu. Figure 3 shows experimental results^{6,11,12} 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 $\sigma_{q,q+1}$ for Fe^{+q} in H_2 are shown in Fig. 4, along with first-Born-approximation results of Rule and Omidvar,⁸ 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.

Fig. 3 Single-electron-capture cross sections $\sigma_{q,q-1}$ for $\text{Fe}^{+q} + \text{H}_2$ scaled by $q^{-3.15}$. ■ Berkner et al.⁶; ○ Meyer et al.¹²; ☆ Gardner et al.¹¹ The line is Eq. (4).

Fig. 4 Single-electron-loss cross sections $\sigma_{q,q+1}$ for $\text{Fe}^{+q} + \text{H}_2$ (experiment, left ordinate) and $\text{Fe}^{+q} + \text{H}$ (theory, right ordinate). Solid line: calculation by Rule and Omidvar. Dashed line for clarity.

Electron Loss in H_2

We have found⁵ that the cross sections for loss of an electron from a hydrogen target,

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

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:

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

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

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 measured⁷ the net ionization cross section σ_i 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 calculated⁴ cross sections σ_i 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.

Experimental and theoretical net-ionization cross sections σ_i for 1.1 MeV/amu ions in Ar are shown in Fig. 6. Also shown are experimental results of Cocke¹⁴ for 0.97 MeV/amu Cl^{+q} projectiles; we calculated $\frac{2}{3}\sigma_i$ from his σ_j results, adjusted by the ratio 0.97/1.1. 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 Cl projectiles 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.

Fig. 6 Net ionization cross sections σ_i for 1.1 MeV/amu projectiles in charge state q in He ($\bullet, \circ$), Ne ($\blacksquare, \square$), and Ar ($\blacktriangle, \triangle$) targets. Closed symbols: Schlachter et al.; open symbols: Cocke; lines are CTMC calculations.

We have found⁷ that the calculated net-ionization cross sections for a given rare-gas target reduce to a common curve when plotted as σ_i/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 predictions. 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 .

Summary

Extensive 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 sections 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, again based on Olson's CTMC calculations. Measurements are essentially consistent with the scaled cross sections.

Fig. 7 Reduced plot of net-ionization cross sections σ_+ for highly stripped ion in charge-state q in He($\bullet$), Ar($\blacktriangle$), Ne($\blacksquare$), and Xe($\blacktriangledown$) targets. Symbols are experimental results, lines are CTMC calculations.

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