Charge Exchange Collision Cross Sections of Tungsten Ions

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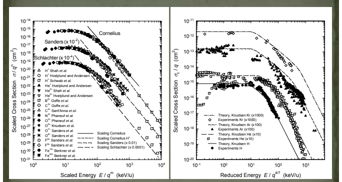
One of the urgent technical issues in materializing larger fusion devices is a need for using heavier elements in plasma-facing components. Tungsten element is attracting particular interests these days because of its specific aspects of high melting-point, good thermo-mechanical properties, low tritium-retention, low sputtering-rates, and so on. Since tungsten ions cause a serious problem of radiation power-loss brought by the high atomic number, charge-state resolved transport phenomena of tungsten ions in fusion plasma have become notably important feature in larger fusion devices. Use of tungsten impurities for diagnostics is also an important issue to be considered. To accomplish these issues, charge-exchange collision (electron-capture and loss) cross sections involving ions of tungsten become essential in both low-energy, up to 20 keV for tungsten projectile ions, and high-energy regions, up to 1 MeV projectile NBI hydrogen atoms colliding with tungsten ions at rest.

We have experimentally produced total electron-capture cross sections for low-q heavy-ions, Be^{q+}, B^{q+}, C^{q+}, Fe^{q+}, Ni^{q+}, and W^{q+} (q = 1,2), colliding with atomic and molecular gas targets of He, Ne, Ar, Kr, H_2, D_2, CH_4, C_2H_6, C_3H_8, CO, CO_2, and N_2 at collision energy between 4 and 25 keV, using the Van de Graaff accelerator facility in Kyoto University. For high-q projectile ions in low collision-energy range, the collision processes of which are exothermic, several scaling rules have been introduced to predict electron-capture cross sections, making use of initial charge state q of projectile ions and the ionization potential (IP) of target gas atoms/molecules. No such scaling behavior has been reported, however, for low-q projectile ions, for which the collision processes likely to expand into the endothermic region. A new attempt has been made to scale electron capture cross sections for such low-q projectile ions in low collision-energy range, using ΔIP, *i.e.*, the first ionization potential of target atoms/molecules subtracted by that of projectile ions after electron capture, which corresponds to the energy defect of the collision processes in a case all the involved projectile and target particles before and after the collision are in the ground states.

We are also performing charge-exchange cross section production at high-energy for diagnostic purposes, using the Tandem accelerator facility in Japan Atomic Energy Agency (JAEA). To produce cross sections of electron-loss and transfer processes for 1 MeV projectile NBI hydrogen beam by tungsten impurity ions, cross sections of equivalent electron-capture processes for 184 MeV (1 MeV/u) projectile tungsten ions from atomic hydrogen target will be measured. In this measurement, ionization cross section of tungsten ions by NBI hydrogen beam will be obtained at the same time, by analyzing the outgoing charge-states of the projectile tungsten ions. The target thickness will be normalized to existing well-resolved cross sections for iron projectile ions.

Existing scaling rules for electron-capture cross sections

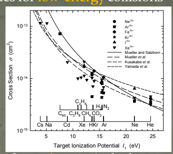
Scaling rules for high-energy collisions



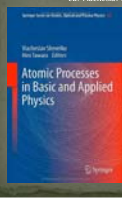
Single-electron-capture cross section scalings for A^{q+} + H2 collisions.

Single-electron-capture cross section for A^{q+} (q>=4) + H, He, Ar, Kr collisions.

Scaling rules for low-energy collisions



- Scaling law for exothermic single electron capture cross-sections (at low-energy limit)
  - by A. Müller and E. Salzborn (1977) $IP^{-2.76}$
  - by T. Kusakabe *et al.* (1986) $IP^{-2.0}$
  - by I. Yamada *et al.* (1999) $IP^{-1.59}$

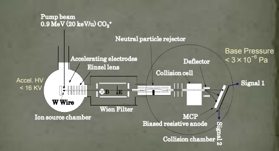


Springer Series on Atomic, Optical and Plasma Physics 68, ed. Viacheslav Shevelko and Hiro Tawara, Springer, June 7, 2012.

Chapter 17
Semiempirical Formulae for Inelastic Atomic and Molecular Collisions by M. Imai

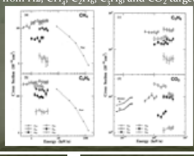
Production and Scaling of single-electron-capture cross sections for low-q heavy ions (incl. W^{q+}) at low energy

Experimental setup for cross section production for Be, B, C, Fe, Ni, W projectile ions

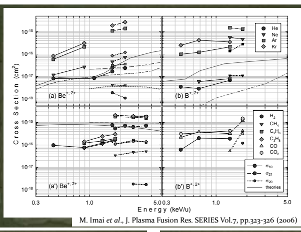


Experimental results

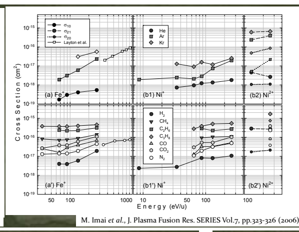
- Electron capture cross sections for C^{q+} ions (q=1–3) from H2, CH_4, C_2H_6, C_3H_8, and CO_2 targets



A. Itoh *et al.*, J. Phys. Soc. Jpn 64, 3255 (1995)

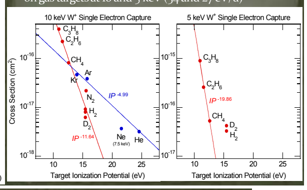


M. Imai *et al.*, J. Plasma Fusion Res. SERIES Vol.7, pp.323-326 (2006)

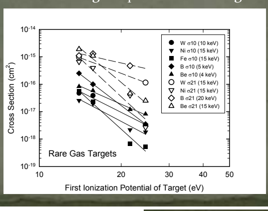


M. Imai *et al.*, J. Plasma Fusion Res. SERIES Vol.7, pp.323-326 (2006)

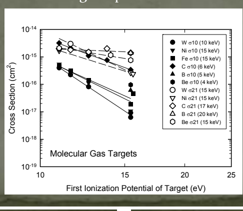
Single electron capture cross-sections for W^+ ions on gas targets at 10 and 5 keV (54 and 27 eV/u)



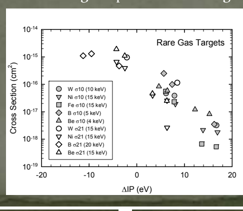
Discussion on target dependence for rare gas



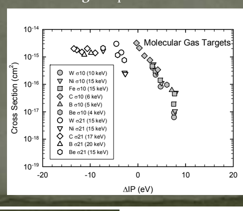
Discussion on target dependence for molecules



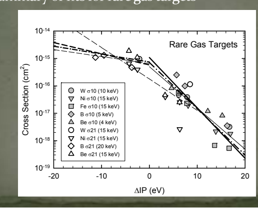
Discussion on target dependence for rare gas



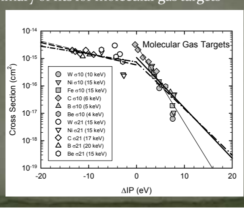
Discussion on target dependence for molecules



Summary of fits for rare gas targets



Summary of fits for molecular gas targets



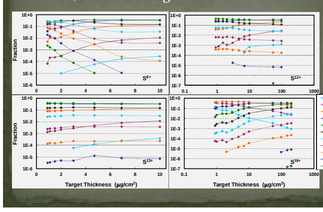
Summary of scaling formulae

Cross section	Target	Cross section scaling (cm^2)	Deviation range (order of mag.)	Δ*IP* region of interest
σ_{10}	A	$5.06 \times 10^{-16} \times 10^{-0.15 \Delta IP}$	−0.82 ~ 0.55	+ (endothermic)
σ_{21}	A	$1.78 \times 10^{-16} \times 10^{-0.11 \Delta IP}$	−1.10 ~ 0.78	± (exo- and endothermic)
σ_{21}	A	$6.53 \times 10^{-16} \times 10^{-0.025 \Delta IP}$	−0.28 ~ 0.35	− (exothermic)
σ_{10}	M	$3.07 \times 10^{-15} \times 10^{-0.28 \Delta IP}$	−0.55 ~ 0.45	+ (endothermic)
σ_{21}	M	$5.67 \times 10^{-16} \times 10^{-0.044 \Delta IP}$	−0.49 ~ 0.52	− (exothermic)
σ_{10}	A+M	$1.09 \times 10^{-15} \times 10^{-0.18 \Delta IP}$	−0.85 ~ 0.67	+ (endothermic)
σ_{21}	A+M	$5.82 \times 10^{-16} \times 10^{-0.041 \Delta IP}$	−0.50 ~ 0.52	− (exothermic)
$\sigma_{10} + \sigma_{21}$	A+M	$7.13 \times 10^{-16} \times 10^{-0.17 \Delta IP}$	−1.36 ~ 0.64	+ (endothermic)
$\sigma_{10} + \sigma_{21}$	A+M	$7.45 \times 10^{-16} \times 10^{-0.029 \Delta IP}$	−0.57 ~ 0.62	− (exothermic)

M. Imai *et al.*, Fusion Science Tech. 63, pp. 392-399 (2013)

Charge-exchange cross sections for H + W^{q+} collisions in high-energy region

Charge state distribution of 2.0 MeV/u S ions through C-foils



Our mission

- Electron loss (& transfer to the target) for H: $H + W^{q+} \rightarrow H^+ + W^{(q-1)+}$ for energy of H up to 1MeV.
- Equivalent to electron capture for W^{q+}: $W^{q+} + H \rightarrow W^{(q-1)+} + H^+$ for energy of W up to 184MeV.
- 184MeV W^{q+} is available at the JAEA tandem accelerator and projectile charge state after the collision can be measured with the present apparatus.
- All we need is atomic hydrogen source and TOF system for coincident recoil ion detection, but recoil ion detection might be skipped.
- *i*-th Ionization of W^{q+} by H: $H + W^{q+} \rightarrow H^+$ or $H + W^{(q+i)+}$ will be obtained at the same time.

Present status

- Hydrogen Atom Beam Source (Hydrogen Cracker) from MBE-Komponenten GmbH.
- Availability of the 184MeV W^{q+} (q=15, 30) beam was checked and charge state distribution after 4.6, 9.9, and 20 μg/cm² C-foil penetration was obtained.