Low energy ionization, charge transfer and reactive collisions for ion source and edge plasma chemistry

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Experimentalists’ Network Meeting IAEA November 2018
Merged Ion Beams
Low temperature & high resolution
Diatom systems
Triatomic systems

Crossed Electron-Ion Beams
Animated beam method
Excited atoms
Molecular ions

Ion Beam Gas Target Measurements
Deceleration
Vibrational diagnostics
MERGED BEAMS SET-UP

- Adjustable geometry: broad mass ratio between beams
- Electrical bias: fine tuning of collision energy
- Long TOF: high resolution KER
- Simultaneous AI measurement: absolute overlap calibration

MERGED BEAM SET-UP: low collision energy, high resolution

\[
KER = \frac{E'}{4L^2} \left[ \Delta x^2 + v_{CM}^2 \Delta t^2 \right]
\]

\[L = 320 \pm 4(2) \text{ cm}\]

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(AN)ISOTROPY: The collision axis flips by $\pi$ when moving across zero detuning.

ENERGY RESOLUTION: Longitudinal and transverse temperature // e⁻-ion collisions

$$f(v_d, v) = \frac{m}{2\pi k T_\perp} \sqrt{\frac{m}{2\pi k T_\parallel}} \exp \left[ -\frac{m v_{\perp}^2}{2\pi k T_\perp} - \frac{m(v_{\parallel} - v_d)^2}{2\pi k T_\parallel} \right], v_{\parallel} \simeq |v|(1 \pm \Delta E/2E), v_{\perp} \simeq |v| \sin \theta$$

12 keV C⁺ and C⁻ beams, 5 eV dispersion, 1 mrad angular spread: $T_{\parallel} \simeq 8 K$, $T_{\perp} \simeq 70 K$
Low energy anion-cation reactions

\[ A^+ + B^- \rightarrow A^* + B \quad \text{Mutual Neutralization (MN)} \]
\[ \rightarrow A + B^+ + e \quad \text{Transfer Ionization (TI)} \]
\[ \rightarrow A^- + B^+ \quad \text{Charge Exchange} \]
\[ \rightarrow AB^+ + e \quad \text{Associative Ionization (AI)} \]

\[ e.g. \ H_2^+ + O^- \text{ Le Padellec et al., J. Chem. Phys. 124, 154304 2006} \]

Additional reactions in polyatomic systems

\[ AB^+ + C^- \rightarrow AC^* + B \quad \text{Reactive Neutralization} \]
\[ \rightarrow AC^+ + B + e \quad \text{Reactive Ionization (RI)} \]
\[ \rightarrow ABC + h\nu \quad \text{Radiative Association} \]
$A^+ + B^- \rightarrow A^* + B + \text{Kinetic Energy Release}$

$\rightarrow KER = [IP(A) - E_{\text{lev}}(A)] - EA(B)$
**KER SPECTRUM:** Partial cross sections  

\[ \text{e.g. } \text{He}^+ + \text{H}^- \rightarrow \text{He} \left(1s\text{n}\,{}^1\text{S} \right) + \text{H} \]

**kinetic energy release \( \rightarrow \) state identification**

**relative peak area \( \rightarrow \) branching ratio**

$E_{\text{level}} = IP(A) - EA(B) - KER$
Negative Ions in Earth’s ionosphere: UV tropical nightglow of O I (135 nm)

\[ \text{O}^+ + \text{O}^- \rightarrow \text{O} (^5\text{P}) + \text{O} \]


J. Qin et al. (2015) J. Geophys. Res. Space Physics, 120, 10116
Multistate Curve Crossing Model: electron ‘hops’ from B to A⁺

- Total transfer probability (Landau-Zener)
  \[ P \sim 2P(1 - P) \]
  \[ P \sim 1 - \exp \left\{ -\frac{2\pi H_{12}^2}{v_c a} \right\} \]

- \( H_{12} \) matrix element evaluated using Landau-Herring asymptotic method


→ transition probability window that mostly depends on covalent state potential energy
High energy neutral beams: negative ions preferred electron stripping $\gg$ electron capture at $E > 100$ keV

$D^-\text{ yield limited by volume recombination (MN) with } D^+/D_2^+$


Under test: SPIDER, Padua, Italy

MPI Plasmaphysik

ITER org

extraction area of $1.9 \times 0.9 \text{ m}^2$
ion current of 40 A, heating power 16.5 MW

ITER-NBI-Quelle

BATMAN

ELISE

$\times 4$

$\times 2$
NEGATIVE ION SOURCES: destruction of H\(^+\) by MN with parent cation

\[ \text{H}_2 + e^- \rightarrow \text{H}_2(B,C) + e^- \rightarrow \text{H}_2(v) + \text{photon} \]

\[ \text{H}_2(v) + e^- \rightarrow \text{H} + \text{H}^- \quad \text{dissociative electron attachment (DEA)} \]

\[ \text{H}_2^+ + \text{H}^- \rightarrow \text{H}_2(\ast) + \text{H}(\ast) \quad \text{mutual neutralization (MN) merged beams} \]

\[ \text{H}^+ + \text{H}^- \rightarrow \text{H} + \text{H}^\ast \]

DETACHED PLASMA: Molecular assisted recombination

\[ \text{H}_2(v) + \text{H}^+ \rightarrow \text{H}_2^+(v) + \text{H} \quad \text{charge transfer} \quad \text{decelerated beam} \]

Urbain et al. (2013) Phys. Rev. Letters 111, 203201 (H\(_2(v=0)\))

\[ \text{H}_2^+(v) + e^- \rightarrow \text{H} + \text{H}^\ast \quad \text{dissociative recombination} \quad \text{storage ring} \]

Calculations: Landau-Herring asymptotic method
Atom-like description: electron capture to Rydberg state of $H_2–$ diagonal FCF

Fantz & Wünderlich (2004) IAEA INDC(NDS)-457 report

⚠️ Restriction to $\Sigma_g$ for collinear geometry ($D_{\infty h}$) – $\Sigma_g$, $\Pi_u$, $\Delta_g$ for T-shape geometry ($C_{2v}$)

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\[ g \Sigma \]
Calculations under assumption: \( \text{H}_2^+ + \text{H}^- \rightarrow \text{H}_2 + \text{H}(n) \)

Phys. Rev. A 51, 3362

Predicted propensity towards \( n=5 \)

No evidence for direct atomic excitation in our data
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Electron impact ionization of excited helium atoms
How to get a pure He(1s2s 3S) beam?

1) He⁺ + Na → He⁻ (1s2s2p 4P)

2) He⁻(1s2s2p 4P) + hν → He (1s2s 3S) + e⁻: 50% efficiency!

Cross Section (Mb)

Photon Energy (eV)

CO₂ laser 10.6 μm
New beam line on crossed ion-electron beam setup

[Diagram of crossed ion-electron beam setup]

Animated electron beam
\[ \text{He}(1s2s \, ^3S) + e^- \rightarrow \text{He}^+ + 2 \, e^- \]

\[ \sigma \left(10^{-17} \text{cm}^2\right) \]

![Graph showing the cross-section \(\sigma\) for different states of \(\text{He}^+\) and \(\text{He}(2s)\) as a function of electron energy \(E_e\).](image)

Dissociative excitation and ionization of molecular helium ions by electron impact

Helium operation

*symmetric collisions: rapid thermalization*
\[ \text{He}^* + \text{He}^{++}/\text{He}^+/\text{He}/\text{He}^* \rightarrow \text{He}^* + \text{He}^{++}/\text{He}^+/\text{He}/\text{He}^* \]

*molecular ions (divertor region): well-known in technical plasmas*
\[ \text{He}^* + \text{He}^* \rightarrow \text{He}_2^+ + e^- \]
\[ \text{He} + \text{He} + \text{He}^+ \rightarrow \text{He}_2^+ + \text{He} \]

→ molecular ions appear in denser, colder regions

+ destruction mechanisms

  dissociative recombination with electrons

  \[ \text{He}_2^+ + e \rightarrow \text{He} + \text{He} \quad \text{extremely sensitive to plasma temperature and formation mechanism} \]


electron impact dissociation/ionization
\[ \text{He}_2^+ + e \rightarrow \text{He}^+ + \text{He} + e \quad \text{unknown} \]
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Vibrationally resolved charge transfer between slow ions and molecules

Merged Ion Beams

- Full resolution of initial and final states through 3D imaging
- Preliminary results of state-resolved differential cross sections
- Total cross sections measurements affected by excessive background

Crossed Electron-Ion Beams

- Animated beam method perfectly suited for absolute measurements
- Excited atoms from photodetachment (O(1D) in preparation)
- Molecular ions with known vibrational excitation needed

Ion Beam Gas Target Measurements

- Deceleration 10 eV and above (guided beams under study)
- Vibrational diagnostics: works for a few diatomics (H₂, O₂, HeH)
  more general if Rydberg target, as tested with CO and N₂
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