Experimental potentials for atomic data for fusion research and astrophysics at Lanzhou

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Motivation

HCI: Astrophysical plasma and Fusion Plasma

Collisionally ionized plasma formed in stars, supernova remnants, and galaxies

Photoionized plasmas formed in planetary nebulae, X-ray binaries, and AGN
1. Experimental facilities for atomic ions/molecular ions collisions.

2. Some typical results related to the atomic data for fusion research and astrophysics.

3. Near future working plans and collective action of data for fusion research and astrophysics.
Experiments of HCl @ Lanzhou

Heavy Ion Research Facility in Lanzhou (HIRFL)

Reaction Microscope

Ion-plasma int. at inter. E

CSR DR-spectroscopy

Reaction microscope

Ion-plasma int.

CSRe

CSRm

RIBLL2

SSC

ECR

e-cooler

e-cooler

CSRe X-ray spec.

CSRe Relativistic Reaction microscope
Experiments of HCIs @ Lanzhou

320 kV Platform for multi-disciplinary research with HCIs

- HCl-surface
- HCl-material Int.
- Reaction microscope
- Low Energy ion-plasma interaction
Experiments of HCIs @ Lanzhou

320kV platform for Multi-disciplinary Research with HCIs

Ion-plasma interaction

Reaction microscope
Experiments of HCIs @ Lanzhou

- Proton, 320keV, ~10µA
- He$^{1,2+}$, 640keV, ~5µA
- C$^{2-6+}$, 1.9MeV, ~2µA
- Ar$^{4-16+}$, 5MeV, ~0.5µA
- Xe$^{10-33+}$, 10MeV, ~0.2µA
Experiments of HCl @ Lanzhou

Very-low energy platform: EBIS-A facility

Dresden EBIS-A ion source
Kinetic Energy: $500q \cdot \text{eV} – 30q \cdot \text{keV}$

COTRIMS for Charge Exchange Experiments
Experiments of HCIs @ Lanzhou

COTRIMS/Reaction Microscopy @ EBIS

Electron capture:

\[
P_{\text{long}} = -\frac{Q}{v_p} - \frac{1}{2} \cdot n_c \cdot v_p
\]

\[
P_{\text{trans}} = p_0 \cdot \theta
\]
2. Some typical results related to the atomic data for fusion research and astrophysics

2.1 Charge exchange processes
The radial and rotational coupling effects played an important role.
State-resolved SEC in Ne^{9+}-He

\[ \text{Ne}^{9+}(1s) + \text{He}(1s^2) \rightarrow \text{Ne}^{8+}(1snl) + \text{He}^+ \]

The single electron capture into 4l and 5l states are dominant. Then contribution of 6l states have obvious contribution, while contribution of 3l state is rather small.

Relevant to Solar wind processes

J. B. Greenwood, PRA. 63 062707 (2001)
Phase information of ion-atom collisions

The phase factor in the probability amplitude contains important information of few-body few-body dynamics

\[ A_{Ne} = REAL \times \exp(i\phi) \]

\[ \text{Scattering phase of ion-atom collisions is obtained for the first time} \]

\[ \text{He}^{2+} + \text{CO} \rightarrow \text{He} + \text{C}^+ + \text{O}^+ \]

2018 PhysRevA.97.020701(R)
50, 75, 100 keV $H^+$ - He single capture

Ground state transfer

Excited-state transfer

Transfer excitation

The momentum transfer mediated by the electron is dominant in the single transfer because of the large contributions of small-angle scatterings.

The nucleus-nucleus interaction is more important in transfer excitation.

The electron-electron correlation effects, which can be neglected, may play a role in transfer excitation.

50, 75, 100 keV H⁺ - He single capture

![Graphs showing single-transfer and transfer-excitation for 75 keV, 50 keV, and 100 keV.](image)

- **Single-transfer**
  - 75 keV
  - 50 keV
  - 100 keV

- **Transfer-excitation**
  - 50 keV
  - 100 keV

Three graphs are shown, each comparing the present experiment (solid blue line), Schulz experiment (purple triangle line), Schoeffler experiment (pink triangle line), and theoretical predictions for TC-BGM-1e [Zapukhlyak et al] and TC-BGM-IEM [Zapukhlyak et al].
15, 30, 50 keV/u C^{4+} - He single capture

Angular differential cross sections \((n=2, n' = 1)\)

Theory: Two-active electrons AOCC by Gao et al.
State-selective electron capture in $\text{N}^{3+}$-He at 30 keV

\[ \text{N}^{3+} + \text{He} \rightarrow \text{N}^{2+}(nl) + \text{He}^{+}(n'l') \]

dominant channel G1: $\text{N}^{3+}(2s^2 \, ^1S) + \text{He}(^1S) \rightarrow \text{N}^{2+}(2s^2 \, 2p \, ^2P) + \text{He}^{+}(^2S)$

M3, M4, M5, G3 and G4 have a significant contribution
the contribution of other states is rather small.

Dissociation of \([\text{HCCH}]^{2+}\) to \(\text{H}_2^+\) and \(\text{C}_2^+\)

a benchmark reaction involving
H migration, H–H combination, and C–H bond cleavage

\[[\text{HCCH}]^{2+}\] dissociates into
\(\text{H}_2^+ + [\text{CC}]^{2+}\)
\(\text{H}^+ + [\text{CCH}]^+\)
\(\text{H}^+ + [\text{CC}]^+ + \text{H}\)

p-transfer dissociation in organic molecular dimer: C₂H₂-C₂H₂

Damaging Intermolecular Energy and Proton Transfer Processes in He²⁺-Irradiated Hydrogen-Bonded Systems

Alpha-particle radiation efficiently damages biologically relevant systems by initiating various intermolecular proton and energy transfer processes.

Angewandte Chemie international addition
https://doi.org/10.1002/anie.201808898
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Energy loss in Ion-Plasma Interaction

Experimental data:

- $E_0 = 100\,\text{keV}$, $P_0 = 3\,\text{mbar}$, $HV = 3\,\text{kV}$

Enhancement of E loss in plasma by a factor of $\sim 3$
2. Some typical results related to the atomic data for fusion research and astrophysics

2.2 Precision Spectroscopy of HCIs
Dielectronic Recombination experiment at CSRm
Advantages of DR experiments at heavy ion storage rings

- ultra-high precision (meV, even sub-meV)
- relative energy can be tuned precisely (meV ~ keV)
- recombined ions can be fully detected (100%)
- ultra-high vacuum, extremely low background
- absolute reaction rate can be measured
Results of Li-like argon ions experiment

![Graph showing DR Rate Coefficients vs Energy (eV)]

- DR Rate Coefficients (10^{-9} \text{ cm}^3 \text{s}^{-1})
- Energy (eV)
- Experiment Data
- FAC Calculation
Dielectronic Recombination of Be-like $^{40}$Ar$^{14+}$ at CSRm

Dielectronic Recombination of Be-like $^{40}\text{Ar}^{14+}$ at CSRm

$$e^- + \text{Ar}^{14+}(2s^2[1S_0]) \rightarrow \text{Ar}^{13+}(2p^2[3P_0]6f_J)$$

$$e^- + \text{Ar}^{14+}(2s^2[1S_0]) \rightarrow \text{Ar}^{13+}(2p^2[3P_0]6d_J)$$

$$e^- + \text{Ar}^{14+}(2s^2[1S_0]) \rightarrow \text{Ar}^{13+}(2p^2[3P_1]6p_J)$$

$$e^- + \text{Ar}^{14+}(2s^2[1S_0]) \rightarrow \text{Ar}^{13+}(2p^2[3P_2]6s_{1/2})$$

Dielectronic Recombination of Be-like $^{40}\text{Ar}^{14+}$ at CSRM

**Plasma rate coefficients** 

$$\alpha(T_e) = \int \alpha(E)f(E,T_e)dE$$

**Figure 3.** Plasma rate coefficients of Be-like Ar$^{14+}$ as a function of the electron temperature. The solid red line is the experimentally derived $\Delta N = 0$ DR and TR rate coefficients. The theoretical results derived from the AUTOSTRUCTURE code for $\Delta N = 0$ DR and for TR are shown as a dotted black line and a dashed-dotted blue line, respectively. The calculated sum of DR and TR is shown as a short-dashed red line. The experimentally derived field-ionization-free plasma rate coefficient is shown as a gray area. The approximate temperature ranges where Ar$^{14+}$ is expected to form in photoionized plasmas and collisionally ionized plasmas are indicated by vertical dashed bars and associated arrows (Kallman & Bautista 2001; Bryans et al. 2009).

**Figure 4.** Comparison of field-ionization-free resonant plasma recombination rate coefficients with theoretical calculated results for Be-like Ar. Full squares show rate coefficients by Colgan et al. (2003). Calculations by Gu (2003) and Mazzotta et al. (1998) are shown by full triangles and full circles, respectively. Rate coefficients of Romanik (1988) and Shull & Van Steeneberg (1982) are shown by full diamonds and stars, respectively. Temperature ranges where the Be-like Ar concentration is higher than 10% of its maximum abundance in photoionized and collisionally ionized plasmas are shown by vertical dashed bars, as in Figure 3 (Kallman & Bautista 2001; Bryans et al. 2009).

TR has important contr. At low electron tem.

Dielectronic Recombination of Be-like $^{40}$Ca$^{16+}$

- Experimental result
- TR contribution
- DR contribution
- Sum of DR and TR

Rate coefficient ($10^{-9}$ cm$^3$ s$^{-1}$)

Electron-ion collision energy (eV)

Dielectronic Recombination of Be-like $^{40}$Ca$^{16+}$

Electron-ion collision energy (eV)
Dielectric Recombination of Be-like $^{40}$Ca$^{16+}$

- DR in reasonable agreement with theoretical results
- TR obvious disagreements with theoretical results
- Metastable states contribute to DR at low energy

\[ e^- + Ca^{16+}(1s^22s^2[1S_0]) \rightarrow Ca^{15+}(1s^22p^2[1D_2]6l_j)^{**} \]
\[ e^- + Ca^{16+}(1s^22s^2[1S_0]) \rightarrow Ca^{15+}(1s^22s2p[3P_2]10l_j)^{**} \]

\[ e^- + Ca^{16+}(1s^22s2p[3P_0]) \rightarrow Ca^{15+}(1s^22p^2[3P_1]8l_j)^{**} \]

![Graph showing rate coefficients and experimental results](image-url)
Dielectronic Recombination of Be-like $^{40}\text{Ca}^{16+}$

\[
\alpha(T_e) = \int \alpha(E)f(E,T_e)\,dE
\]

E-ion recombination rates

\[
f(E,T_e) = \frac{2E^{1/2}}{\pi^{1/2}(k_B T_e)^{3/2}}\exp\left(-\frac{E}{k_B T_e}\right)
\]

**Plasma rate coefficient (10^{-9} \text{ cm}^3\text{s}^{-1})**

![Diagram showing temperature and plasma rate coefficient relationship]

**Temperature (K)**

- Experimental result
  - Jacobs (1980)
  - Badnell (1987)
  - Romanik (1988)
  - Gu (2003)
  - Colgan (2003)

Dielectronic Recombination of Be-like $^{40}\text{Ca}^{16+}$

Shu-Xing Wang et al. Astrophys. J. 862(2), 134
Experimental results: B-like Ar\textsuperscript{13+}

With upgrade of the HV system, higher resolution, \( \sim 0.03 \text{ eV} \)

The vertical bar indicated in the figure is estimated by Rydberg formula:

\[ E_{\text{res}} = E_{\text{exc}} - \frac{RZ_{\text{eff}}}{n^2} \]

- \( E_{\text{exc}} \) is the core excitation energy
- \( R \) is the Rydberg constant
- \( Z_{\text{eff}} \) is the charge of the target ion

\[ \Delta E = \sqrt{(\ln 2 \cdot k_B T_{\perp})^2 + 16 k_B T_{\parallel} \cdot E_{\text{rel}} \cdot \ln 2 + \Gamma^2} \]

\[ + \frac{\Delta p}{p} \cdot (\beta_i - \beta_e) \gamma_i \gamma_e \cdot m_e c^2 \]
3. Near future working plans and collective action of data for fusion research and astrophysics
Activities related to atomic data for Fusion and Astrophysics

1. DR rates for W/Au ions
2. Collective action on absolute cross section measurements with higher accuracy for ion-atom/molecules collision, Fudan Univ. + IMP
3. Dynamics of State resolved charge exchange processes
4. Energy loss: keV ion-plasma interaction
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Thank you for your attention

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