State-Resolved and Differential Cross Sections of Low and Intermediate Energy Ion/atom - He/H₂ Collisions

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Outline

- H2-molecule target
  Single electron capture in p – H$_2$
  Single electron capture C$^{5+}$-H$_2$
  Single electron capture Ne$^{9+}$-H$_2$

- Neutral H projectile
  H-He collisions, capture & ionization

- Ion-atom collisions
  He$^{+}$-He collision system
  p- He collision system

- Experiment at storage ring
National Laboratory of Heavy Ion Accelerator in Lanzhou

**SSC (K=450)**
100 AMeV (H.I.), 110 MeV (p)

**SFC (K=69)**
10 AMeV (H.I.), 17~35 MeV (p)

**CSRe**
1000 AMeV (H.I.), ≤ 2.8 GeV (p)

**RIBLL1**
RIBs at tens of AMeV

**RIBLL2**
RIBs at hundreds of AMeV

**CSRm**
Facility: 320 kV Platform

320kV Platform for Research with Highly-charged Heavy Ions

Energy range: (15-320)q keV

Five experimental terminals

Ion species: p, H$_2^+$, He$^{2+}$, Ar$^{12+}$, Xe$^{30+}$, Bi$^{35+}$, ……

Reaction Microscope, investigation of atomic collision dynamics.
Reaction Microscope in Lanzhou (ReMiLa)
Single electron capture in $p$-H$_2$ collisions

Single electron capture into ground state is dominant

$20\text{keV} \text{H}^-+\text{H}_2 \rightarrow \text{H}^0(n)+\text{H}_2^+$

$n=1$

FWHM=0.2 a.u.

$n=2, 3$

Single electron capture into ground state is dominant
Single electron capture in C\textsuperscript{5+}-H\textsubscript{2} collisions

C\textsuperscript{5+} + H\textsubscript{2} → C\textsuperscript{4+} \(1s_{nl}\) + H\textsuperscript{+} \(n=3\)

Q value (eV)

Counts

H\textsubscript{2} molecular target

Single electron capture into 4l states are dominant
Single electron capture of Ne$^{9+}$-H$_2$ collisions

Dominant reaction channel of single electron capture: n=5 or 6
H + He → H^+ + He^+ + 2e^-

The differential cross sections were measured for simultaneous projectile and target ionization from 70 to 300 keV/u by Reaction Microscope in Lanzhou.
Single electron capture

$H^0 + \text{He} \rightarrow H + \text{He}^+(nl)$ at 70 keV

\[ P_\perp, P_\parallel (\text{a.u.}) \]

$n=1, n=2$
Single electron capture

\[ \text{Cross sections}(10^{-17}\text{cm}^2) \]

| n=1     | 2.12(1\pm0.17) |
| n\geq2  | 0.05(1\pm0.22) |

\[ \sigma_{sc} = (2.17\pm0.37) \times 10^{-17}\text{cm}^2 \]
Simultaneous projectile and target ionization - cross sections differential on recoil ion longitudinal & transverse momentum.
State selective electron capture in slow He\(^+\)-He collisions

\[ \text{He}^+ + \text{He}(1s^2) \rightarrow \text{He}(1s\ nl) + \text{He}^+(n'l') \]
State-selective differential cross sections for single-electron capture

\[ p + \text{He}(1s^2) \rightarrow \text{H}(n) + \text{He}^+(n') \]

Recoil-ion longitudinal momentum distributions for single electron capture from He in collision with proton at (a) 50, (b) 75 and (c) 100 keV, respectively. Open circles: present measurements. Solid lines: Gaussian fittings.
Angular differential cross sections for single-transfer process as functions of laboratory scattering angle for (a) 50, (b) 75 and (c) 100 keV $p$-He collisions. Theory: TC-BGM calculations within one-active-electron model [2]; TC-BGM calculations within IEM [2]. Experiments: present measurements; Schulz et al. for 50 and 75 keV [1]; Schöffler for 100 keV [3].

Angular differential cross sections for transfer excitation process as functions of laboratory scattering angle for (a) 50, (b) 75 and (c) 100 keV \( p \)-He collisions. Theory: TC-BGM calculations within IEM for 50 and 75 keV [2]. Experiments: present measurements; Hasan et al. for 50 and 75 keV [1].

\[ p + \text{He}(1s^2) \rightarrow \text{H}(n) + \text{He}^{2+} + e \]

Angular differential cross sections for transfer ionization as functions of laboratory scattering angle for (a) 50, (b) 75 and (c) 100 keV \( p \)-He collisions.

\[ p + \text{He}(1s^2) \rightarrow \text{H}(n) + \text{He}^{2+} + e \]

Angular differential cross sections for transfer-ionization process as functions of laboratory scattering angle for (a) 50, (b) 75 and (c) 100 keV \( p \)-He collisions.
Single differential cross sections for transfer ionization as functions of recoil-ion longitudinal momentum for (a) 50, (b) 75 and (c) 100 keV $p$-He collisions.

$$p + \text{He}(1s^2) \rightarrow \text{H}(n) + \text{He}^{2+} + e$$

Single differential cross sections for transfer-ionization process as functions of recoil-ion longitudinal momentum for (a) 50, (b) 75 and (c) 100 keV $p$-He collisions.
Triple differential cross sections in transfer ionization process for 50 keV \( p \)-He collisions. The projectile scattering angles are showed in the figure.
Fully differential cross sections for electron with an energy of 5.0 eV ejected into the scattering plane for transfer ionization process for 50 keV \( p \)-He collisions. The emission angle \( \theta_e \) is the polar angle in the scattering plane. The transverse momentum transfers are showed in the figure. The lines are B-spline fits to guide the eye.

\[
\text{Counts}
\]

\[
\begin{align*}
q_\perp &= 0.4-0.6 \text{ a.u.} \\
q_\perp &= 0.6-0.8 \text{ a.u.} \\
q_\perp &= 0.8-1.0 \text{ a.u.} \\
q_\perp &= 1.0-1.2 \text{ a.u.} \\
q_\perp &= 1.2-1.4 \text{ a.u.}
\end{align*}
\]
Fig. 8 Fully differential cross sections for recoil ion with an momentum of 0.9 a.u. ejected into the scattering plane for transfer ionization process for 50 keV $p$-He collisions. The emission angle $\theta_r$ is the polar angle in the scattering plane. The transverse momentum transfers are showed in the figure. The lines are B-spline fits to guide the eye.
Dielectronic Recombination of Ni$^{19+}$

Experiment at CSR

Cooler Storage Ring
In Lanzhou

Dielectronic Recombination experiment
Dielectronic Recombination experiment at CSR

- High luminosity, 1000,000 times
- High detection efficiency, 100%
- High precision, meV
- Defined charge state
Summary

Molecular H2 target
state selective information have been obtained
20 keV $p$-H$_2$ single electron capture
C$^{5+}$-H$_2$ single electron capture 200-500 keV
Ne$^{9+}$-H$_2$ single electron capture 135-495 keV

Atom-atom collisions
H-He collisions: 70~300 keV, projectile-target mutual ionization;
comparison between theory and experimental results show that e-e interaction plays important role in the ionization.

Ion-atom collisions
He$^+$-He 10~20 keV, state selective cross sections are measured.
p + He, 50-100 keV, differential and fully diff. CS are obtained.

Dielectronic recombination
DR spectrum of P-like Sn35+ ion have been measured, obvious discrepancy between experiment and theory has been observed. To demonstrate the ability to perform DR/RR measurements.
Team of atomic physics

Guest, A. Voitkiv, Theory
Thank you for your attention

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