Photorecombination studies at Shanghai EBIT

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Outline

§ Introduction and Motivation
§ Experiment Setup at Shanghai-EBIT
§ Photorecombination studies for highly charged ions
  ➢ $KLL$ DR measurements for W ions
  ➢ $L$-shell DR measurements for W ions
  ➢ DR measurements for Ar and Xe ions
§ Summary
Introduction
Photorecombination (PR)

Dielectronic Recombination (DR)  Radiative Recombination (RR)

Interefering!
Introduction

Fano line profile

\[ |M_{jf}|^2 = \left( \frac{(Q + \epsilon)^2 + (B_Q - 1)^2}{1 + \epsilon^2} \right) \langle j | R | f \rangle^2 \]
Motivation

• Atomic structure and collision theory
  ➢ Energy levels, transitions, autoionization
  ➢ Interference effect
  ➢ QED
  ➢ Polarization effect

• Astrophysical and fusion plasma
  ➢ Charge state distribution balance
  ➢ Radiation energy loss
  ➢ Satellites for temperature diagnostics
Introduction

Electron Beam Ion trap (EBIT)

- Highly charged ions
- Monoenergetic electron beam
- Energy adjustable
- Atomic spectroscopy
  Structure
  Collision process
Experiment Setup on Shanghai-EBIT

Data acquisition system

- Collector
- charge breeding
- cooking
- Ar, Xe, W(CO)₆ gas
- Drift Tube
- E-Beam
- DT2
- HpGe
- PC Control and DAQ
- Cathode
Recent experiments at Shanghai-EBIT

$\kappa$-shell DR measurement for Ar

$\kappa$-shell DR measurement for Xe

$KL\ell$ DR measurement for Ba

$KL\ell$ DR measurement for W

$L$-shell DR measurement for W
Result

- *KLL* DR measurements for W ions
- *L*-shell DR measurements for W ions
- DR measurements for Ar and Xe ions
3D x-ray intensity spectrum

180 hours

KL\textsubscript{12}L\textsubscript{3}, KL\textsubscript{3}L\textsubscript{3}, KL\textsubscript{12}L\textsubscript{12}

<table>
<thead>
<tr>
<th>Expt. A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy scanned</td>
</tr>
<tr>
<td>Electron beam current</td>
</tr>
<tr>
<td>Gas injection pressure</td>
</tr>
<tr>
<td>Trapping potential</td>
</tr>
<tr>
<td>Electron energy spread</td>
</tr>
<tr>
<td>Charge state obtained</td>
</tr>
</tbody>
</table>
Excitation function

\[ C(q, E) = D(E) \sum_q f_q \left[ \frac{d\sigma_{\text{ex}}(q, E)}{d\Omega} + \sum_{ji} S_{ji} \times DR(q, E) \times W_{ji}(90^\circ) \right] \frac{1}{4\pi} \]
KLL DR resonance strengths

2D x-ray intensity spectrum

\[
\begin{align*}
KL_{12}L_3 \\
KL_{12}L_{12} \\
\text{He, Li, Be} \\
\text{He, Li, Be} \\
\text{Be}_1 \text{ Cut} \\
\text{Be}_2 \text{ Cut} \\
\text{Be}_4 \text{ Cut} \\
\text{RR} \rightarrow J = 3/2 \\
\text{RR} \rightarrow J = 1/2 \\
\end{align*}
\]

\[\sim 500 \text{ eV}\]
Interference effect

Fano Line Shape

\[ Q_{\text{meas}} = -12.3(1.9) \]

\[ \text{to} \]

\[ [1s^2s^22p_{1/2}^2]_{1/2} \]

\[ \text{Be}_1 \]

Electron beam energy (keV)
Interference effect

Q Factors

<table>
<thead>
<tr>
<th>Label</th>
<th>Initial state</th>
<th>Intermediate state</th>
<th>Final state</th>
<th>$Q_{meas}$</th>
<th>$Q_{cal}$</th>
<th>$Q_{aver}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>He(_1)</td>
<td>$[1s^2]_0$</td>
<td>$([\text{1s}2s]^0 \text{2p}<em>3/2^1/2]</em>{3/2}$</td>
<td>$[1s^22s_{1/2}]_{1/2}$</td>
<td>-12.3(1.8)</td>
<td>-13.2</td>
<td></td>
</tr>
<tr>
<td>Be(_1)</td>
<td>$[1s^22s^2]_0$</td>
<td>$[1s^22s^22p_{1/2}^2]_{1/2}$</td>
<td>$[1s^22s^22p_{1/2}]_{1/2}$</td>
<td>-12.3(1.9)</td>
<td>-13.3</td>
<td></td>
</tr>
<tr>
<td>Be(_2)</td>
<td>$[1s^22s^2]_0$</td>
<td>$([\text{1s}2s^22p_{1/2}]<em>{2}2p</em>{3/2}]<em>{0}2p</em>{3/2}^1/2]_{3/2}$</td>
<td>$[1s^22s^22p_{3/2}]_{3/2}$</td>
<td>12.7(1.7)</td>
<td>14.9</td>
<td></td>
</tr>
<tr>
<td>Be(_3)</td>
<td>$[1s^22s^2]_0$</td>
<td>$([\text{1s}2s^22p_{1/2}]<em>{0}2p</em>{3/2}]<em>{2}2p</em>{3/2}^1/2]_{3/2}$</td>
<td>$[1s^22s^22p_{1/2}^2]_{1/2}$</td>
<td>6.4(0.5)</td>
<td>6.6</td>
<td></td>
</tr>
<tr>
<td>Be(_4)</td>
<td>$[1s^22s^2]_0$</td>
<td>$[1s^22s^2(2p_{3/2})<em>{2}]</em>{5/2}$</td>
<td>$[1s^22s^22p_{3/2}]_{3/2}$</td>
<td>17.4(2.4)</td>
<td>15.2</td>
<td></td>
</tr>
<tr>
<td>B(_1)</td>
<td>$[1s^22s^22p_{1/2}^1]_{1/2}$</td>
<td>$[1s^22s^22p_{1/2}^1]<em>{2}2p</em>{3/2}^1/2]_{2}$</td>
<td>$[1s^22s^22p_{1/2}2p_{3/2}]_{1/2}$</td>
<td>26.5(6.8)</td>
<td>9.3</td>
<td>27.4*</td>
</tr>
<tr>
<td>C(_1)</td>
<td>$[1s^22s^22p_{1/2}^1]_{0}$</td>
<td>$[1s^22s^22p_{1/2}^1(2p_{3/2})<em>{2}]</em>{3/2}$</td>
<td>$[1s^22s^22p_{1/2}2p_{3/2}]_{3/2}$</td>
<td>4.4(0.4)</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>N(_1)</td>
<td>$[1s^22s^22p_{1/2}2p_{3/2}]_{3/2}$</td>
<td>$[1s^22s^22p_{1/2}2p_{3/2}]_{3/2}$</td>
<td>$[1s^22s^22p_{1/2}2p_{3/2}]_{2}$</td>
<td>13.4(2.1)</td>
<td>13.7</td>
<td></td>
</tr>
<tr>
<td>O(_1)</td>
<td>$[1s^22s^22p_{1/2}2p_{3/2}]_{2}$</td>
<td>$[1s^22s^22p_{1/2}2p_{3/2}]_{2}$</td>
<td>$[1s^22s^22p_{1/2}2p_{3/2}]_{1/2}$</td>
<td>11.8(1.6)</td>
<td>10.5</td>
<td></td>
</tr>
</tbody>
</table>

*Obtained by averaging the $Q$ values weighted with the branching ratios of the two transition channels.

Dual Fano and Lorentzian line profile properties of autoionizing states

360 hours

KL_3L_3 DR

Expt. B

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy scanned</td>
<td>42.5 – 44.1 keV</td>
</tr>
<tr>
<td>Electron beam current</td>
<td>140 mA</td>
</tr>
<tr>
<td>Gas injection pressure</td>
<td>2 × 10^{-7} Torr</td>
</tr>
<tr>
<td>Trapping potential</td>
<td>130 V</td>
</tr>
<tr>
<td>Electron energy spread</td>
<td>61 eV</td>
</tr>
<tr>
<td>Charge state obtained</td>
<td>Be- up to O-like</td>
</tr>
</tbody>
</table>
Dual Fano and Lorentzian line profile properties of autoionizing states
Dual Fano and Lorentzian line profile properties of autoionizing states

Different paths of radiation (or excitation) different line shapes

An autoionizing state can have both Fano and Lorentzian behavior.

Dielectronic satellite x-ray spectra of the 2-1 transitions
Dielectronic satellite x-ray spectra of the 2-1 transitions

Be-like: \[ \left[ \left( 1s^22s \right)_1 \right] \frac{2p_{3/2}}{2} = \frac{2p_{3/2}}{2} \]

\[ 1s^22s2p_{3/2} + \gamma(2p_{3/2} \rightarrow 1s) \]

\[ 1s^22s2p_{1/2} + \gamma(2p_{3/2} \rightarrow 1s) \]

\[ \sim 500 \text{ eV} \]

@60 keV
Dielectronic satellite x-ray spectra of the 2-1 transitions

36 transitions: RCI and MBPT calculations, Open-ADAS in wavelength

Mean difference between our measurements and calculations ~0.05%

Questionable data from transition rate comparison

<table>
<thead>
<tr>
<th>Middle States</th>
<th>Final States</th>
<th>$A_{rci}$</th>
<th>$A_{mbpt}$</th>
<th>$ADAS A_{lc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1s2s$^2$</td>
<td>1s$^2$ 2p$^{1/2}$</td>
<td>8.38E+14</td>
<td>9.02E+14</td>
<td>3.07E+10</td>
</tr>
</tbody>
</table>
Result

- *KLL* DR measurements for W ions
- *L*-shell DR measurements for W ions
- DR measurements for Ar and Xe ions
L-shell DR measurements for W ions

150 hours

11000
10000
9000
8000
7000
6000
Photon energy (eV)

n=4 RR
LMM - Cut
n=3 RR

6000
5000
4000
Electron beam energy (eV)

LMN
LMO, LMP...

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy scanned</td>
<td>7.84~3.26 keV</td>
</tr>
<tr>
<td>Cooking energy</td>
<td>7.84 keV</td>
</tr>
<tr>
<td>Electron beam current</td>
<td>20 mA</td>
</tr>
<tr>
<td>Gas injection pressure</td>
<td>1.7×10^{-7} torr</td>
</tr>
<tr>
<td>Trapping potential</td>
<td>80 V</td>
</tr>
<tr>
<td>Electron energy spread</td>
<td>43 eV</td>
</tr>
</tbody>
</table>
$LMM$ DR excitation function

![Graph showing the LMM DR excitation function.](image-url)
**LMM DR excitation function**

(c) 

- Meas.
- Fit with metastable state

Metastable DR peak

Electron energy (eV) vs Counts

- Counts
- Electron energy

 Lifetime $\sim 143$ years (cal.)

**Energy levels of Ti-like W**

- core$(3d^{8}$ $3d_{3/2}^{5})$
- core$(3d^{8}$ $3d_{5/2}^{5})$
- core$(3d^{8}$ $3d_{3/2}^{4}$ $3d_{5/2}^{4})$
- core$(3d^{8}$ $3d_{3/2}^{3}$ $3d_{5/2}^{4})$
- core$(3d^{8}$ $3d_{3/2}^{2}$ $3d_{5/2}^{4})$
- core$(3d^{8}$ $3d_{3/2}^{1}$ $3d_{5/2}^{4})$
- core$(3d^{8}$ $3d_{3/2}^{0}$ $3d_{5/2}^{4})$

- $A_{4} = 8.24 \times 10^{-14}$ s$^{-1}$
- $A_{4} = 2.36 \times 10^{-10}$ s$^{-1}$

**Angular momentum J**

- E4
- M3

Metastable state $\text{core}(3d_{3/2}^{3} 3d_{5/2}^{3})$

Lifetime $\sim 143$ years (cal.)

Ground state $\text{core}(3d_{3/2}^{4})$

2$s + e \rightarrow 3d_{3/2}^{5}$
## LMM DR resonance strengths

<table>
<thead>
<tr>
<th>Ion</th>
<th>Initial state</th>
<th>$\sum S_{i\delta /f}^{cal.}$</th>
<th>$\sum S_{i\delta /f}^{meas.}$</th>
<th>$\frac{\sum W_{i\delta /f} \times S_{i\delta /f}^{cal.}}{\sum S_{i\delta /f}^{cal.}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>core'</td>
<td>391</td>
<td>401(60)</td>
<td>1.13</td>
</tr>
<tr>
<td>K</td>
<td>core' $(3d_{3/2}^1)_{3/2}$</td>
<td>274</td>
<td>282(40)</td>
<td>1.02</td>
</tr>
<tr>
<td>Ca</td>
<td>core' $(3d_{5/2}^2)_{2}$</td>
<td>189</td>
<td>189(25)</td>
<td>0.99</td>
</tr>
<tr>
<td>Sc</td>
<td>core' $(3d_{3/2}^3)_{3/2}$</td>
<td>125</td>
<td>129(15)</td>
<td>1.04</td>
</tr>
<tr>
<td>Ti</td>
<td>core' $(3d_{3/2}^2)_{0}$</td>
<td>68.1</td>
<td>38.1(3.1) + 41.5(5.0)*</td>
<td>1.05</td>
</tr>
<tr>
<td>Ti*</td>
<td>core' $(3d_{3/2}^3)<em>{3d</em>{5/2}^4}$</td>
<td>90.3</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>core' $(3d_{3/2}^3)<em>{3d</em>{5/2}^5}^{5/2}$</td>
<td>40.5</td>
<td>40.6(3.9)</td>
<td>0.99</td>
</tr>
<tr>
<td>Cr</td>
<td>core' $(3d_{3/2}^2)<em>{3d</em>{5/2}^2}$</td>
<td>24.0</td>
<td>23.1(3.0)</td>
<td>1.00</td>
</tr>
<tr>
<td>Mn</td>
<td>core' $(3d_{3/2}^3)<em>{3d</em>{5/2}^5}^{9/2}$</td>
<td>11.3</td>
<td>11.2(2.5)</td>
<td>1.01</td>
</tr>
</tbody>
</table>

*core' represents $1s^22s^22p^63s^23p^6$

*represent the calculated and measured DR strength from the Ti-like metastable state.

**Ti* Extremely long-lived metastable state**
- Population ~45%
- Electron energy 7.9 keV
- Electron density $5 \times 10^{11}$ cm$^{-3}$
Collisional Radiative (CR)-model calculation

- Core states
  - \( \text{core}(3d_{3/2})_0 \)
  - \( \text{core}(3d_{3/2} 3d_{5/2})_2 \)
  - \( \text{core}(3d_{3/2} 3d_{5/2})_4 \)

- Short-lived m-states (<1ms)
  - \( \text{core}(3d_{3/2} 3d_{5/2})_2 \)
  - \( \text{core}(3d_{3/2} 3d_{5/2})_4 \)

- Long-lived metastable state
  - \( \text{core}(3d_{3/2}^3 3d_{5/2}^2) \) ~30%
  - \( \text{core}(3d_{3/2}^4) \) ~45%

Long-lived metastable state be considered as a second ground state, collision excitation and de-excitation, ionization, recombination, new transitions, resonances, indirect ionization processes.

Electron density cm\(^{-3}\)

- Ti-like
- B. Tu et al. submitted
- Pop. ~45% predicted in DR meas.
Result

- $KLL$ DR measurements for $W$ ions
- $L$-shell DR measurements for $W$ ions
- DR measurements for $Ar$ and $Xe$ ions
**K-shell DR measurements for Ar ions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy scanned</td>
<td>2.2~3.6 keV</td>
</tr>
<tr>
<td>Electron beam current</td>
<td>20 mA</td>
</tr>
<tr>
<td>Gas injection pressure</td>
<td>1×10⁻⁷ torr</td>
</tr>
<tr>
<td>Energy spread</td>
<td>20 eV</td>
</tr>
</tbody>
</table>

Data analysis
Ongoing...

By G. Xiong
K-shell DR measurements for Xe ions

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy scanned</td>
<td>19.8–30 keV</td>
</tr>
<tr>
<td>Electron beam current</td>
<td>75 mA</td>
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<tr>
<td>Gas injection pressure</td>
<td>2×10⁻⁷ torr</td>
</tr>
<tr>
<td>Energy spread</td>
<td>45 eV</td>
</tr>
</tbody>
</table>

Data analysis Ongoing...

By T. H. Xu
Summary

§  *KLL* DR measurements for W ions
  † Determine total *KLL* DR resonance strengths
  † Dual Fano and Lorentzian line profile properties
  † Satellite x-ray spectra of the 2-1 transitions

§  *L*-shell DR measurements for W ions
  † Determine total *LMM* DR resonance strengths
  † Observe an extremely long-lived metastable state of Ti-like W via DR experiment

§  DR measurements for Ar and Xe ions
  † Data analysis ongoing…
Thank You

for

Your Attention!
\[ |M_{jf}|^2 = \left[ \frac{(Q + \epsilon)^2 + (B_a - 1)^2}{1 + \epsilon^2} \right] \langle j|R|f \rangle^2, \]

\[ Q = \frac{2 \langle j|V|d \rangle \langle d|R|f \rangle}{\Gamma_d \langle j|R|f \rangle}, \]

\[ B_a = \frac{\Gamma_a}{\Gamma_d} \]

\[ DR_{Fano} = \int_{-\infty}^{+\infty} F(E') G(E' - E) dE' \]

\[ = \frac{2}{Q^2 \Gamma d \pi \sqrt{\pi}} \times \int_{-\infty}^{+\infty} \left[ \frac{(Qy + t - x)^2 + (B_a - 1)^2 y^2}{(t - x)^2 + y^2} - 1 \right] e^{-t^2} dt, \]