Storage Ring Measurements for Dielectronic Recombination of Na-like Fe$^{15+}$

Wei-Qiang WEN （汶伟强）
Institute of Modern Physics, Chinese Academy of Sciences

The 14th International Colloquium on Atomic Spectra and Oscillator Strength for Astrophysical and Laboratory Plasmas (ASOS14)
Paris, July 10 - 14, 2023
IMP is founded in 1957, with ~1000 employees. With the quick expanding of the Lanzhou city with a population of ~3M, the site of IMP, the largest heavy-ion accelerator system in China becomes the city center.
Introduction to Institute of Modern Physics, CAS

Heavy Ion Research Facility in Lanzhou (HIRFL)

SSC (K=450)
100 AMeV (H.I.), 110 MeV (p)
1962

SFC (K=69)
10 AMeV (H.I.), 17~35 MeV (p)
1962

CSRe

RIBLL1
RIBs at tens of AMeV

CSR (Cooling Storage Ring)

CSRm
1000 AMeV (H.I.), ≤ 2.8 GeV (p)
1998
Approved
2000-2005
Construction
2006-2007
Commissioning
2008
Operation

We have
~ 1000 staff
~ 400 students
~ 1 billion ¥ /year

➢ Nuclear Physics
➢ Atomic Physics
➢ Quark Matter
➢ Materials
➢ Biomedical
➢ Nuclear Energy

➢ • • •
Introduce myself

Wei-Qiang WEN (汶伟强)

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My research focuses on the atomic physics with highly charged ions, including:

➢ Laser cooling and precision laser spectroscopy of highly charged heavy ions at storage rings;
➢ Dielectronic recombination spectroscopy of highly charged ions at heavy ion storage rings;
➢ Precision spectroscopy of highly charged ions at electron beam ion traps;

EMPLOYMENT

2021—now  Principal Investigator at Atomic Physics Group, IMP, CAS, Lanzhou, China.
2015—2021  associate scientist at Atomic Physics Group, IMP, CAS, Lanzhou, China.
2014—2015  Postdoc at Laser Particle Acceleration division, HZDR, Dresden, Germany
2013—2015  assistant scientist at Atomic Physics Group, IMP, CAS, Lanzhou, China.

EDUCATION

2007—2013  Ph.D, Atomic Physics Group, Institute of Modern Physics (IMP), CAS.
2009—2011  Joint PhD program of DAAD-CAS for PhD student at GSI & HZDR Germany.
2003—2007  Bachelor Degree, Dept. of Physics, Northwest University, Xi’an, China

My ResearchGate:
https://www.researchgate.net/profile/Weiqiang-Wen-2

My personal website:
https://people.ucas.ac.cn/~wenweiqiang?language=en
Outline

1. Motivation and introduction to DR experiment at CSR:
   — experimental method;

2. Plasma recombination rate coefficients of Fe\textsuperscript{15+}:
   — experimental results and theoretical calculation;

3. Precision DR spectroscopy of Ni\textsuperscript{19+}:
   — test high-order QED effect with highly charged ions;

4. Summary and outlook:
   — DR at storage ring: astrophysics & precision spectroscopy;
   — DR at storage ring: CSRm \rightarrow CSRe \rightarrow HIAF
Dielectronic recombination process

\[ \text{Dielectronic capture} \quad \text{Radiative stabilization} \quad \text{Dielectronic capture} \]

\[ A^{q+} + e^- \rightarrow [A^{(q-1)+}]^{**} \rightarrow A^{(q-1)+} + n \cdot \gamma \]

\[ E_{\text{exc}} = E_{\text{bind}} + E_{\text{res}} \]
Dielectronic recombination is an important atomic process governing the charge balance in astrophysical and fusion plasmas.

Schippers, JPCS 388, 012010 (2012)

Savin, JPCS 88, 012071 (2007)
Dielectronic Recombination Data for Astrophysical Applications: Plasma Rate-Coefficients for $\text{Fe}^{q+} (q = 7-10, 13-22)$ and $\text{Ni}^{25+}$ Ions from Storage-Ring Experiments

S. Schippers$^1$, M. Lestinsky$^{2,3}$, A. Müller$^1$, D.W. Savin$^3$, E.W. Schmidt$^1$ and A. Wolf$^2$

$^1$Institut für Atom- and Molekülphysik, Justus-Liebig-Universität Giessen, Leihgesterner Weg 217, 35392 Giessen, Germany.
DR of Astrophysically Relevant Iron Ions

publications from TSR

$\text{Fe}^{7+}$: E. W. Schmidt et al., A&A 492 (2008) 265
$\text{Fe}^{12+}$: M. Hahn et al., ApJ 788 (2014) 46
D. Bernhardt et al., PRA 90 (2014) 012702
$\text{Fe}^{15+}$: J. Linkemann et al., NIMB 98 (1995) 154
$\text{Fe}^{16+}$: E. W. Schmidt et al., JPCS 163 (2009) 012028
DR of Astrophysically Relevant Iron Ions
Next generation of X-ray telescopes

- X-ray Imaging and Spectroscopy Mission (XRISM) 2023
- Advanced Telescope High Energy Astrophysics (Athena) 2030
- Hot Universe Baryon Surveyor (HUBS) 2030
- The Lynx X-ray Surveyor (LynX) 2030

Collisional
- AtomDB
- Chianti
- SASAL
- SPEX
- ADAS (Fusion)

Photoionized
- Cloudy
- SPEX
- XSTAR
- Mocassin
- others

More accurate data from highly charged ions are needed for plasma modeling with high resolution X-ray astrophysics!
Electron-ion collision at storage-rings with electron coolers

ESR @ GSI/FAIR

CSRm & CSRe @ IMP Lanzhou

HIAF @ China

CRYRING @ GSI/FAIR

TSR @ MPIK

CSR @ MPIK

FAIR @ Germany

Electron - ion collision at storage-rings with electron coolers
Electron-ion recombination experiments at CSR
(2017—present, \(^{36}\text{Ar}^{15+}, \text{Ar}^{12+,13+,14+,15+},\)
\(^{40}\text{Ca}^{14+,16+,17+},\)
\(^{56}\text{Fe}^{15+,17+},\text{Ni}^{19+},\text{Kr}^{25+,30+},\text{Sn}^{35+}\)

Heavy Ion Research Facility in Lanzhou

- **DR @CSRm**
  - ion species: Si ~ Kr
  - cooling voltage: 2 ~ 30 kV
  - detuning voltage: ±3 kV
    (c.m. frame ~150 eV)

- **DR @CSRe**
  - ion species: Kr ~ U
  - cooling voltage: 10~300 kV
  - detuning voltage: ±15 kV
    (c.m. frame ~1.5 keV)
Electron-ion recombination experiments at CSR
Electron-ion recombination experiments at CSR
Electron-ion recombination experiments at CSR

\[ \alpha(E_{\text{rel}}) = \frac{R}{N_i n_e (1 - \beta_e \beta_i)} \times \frac{C}{L} \]

- **R**: counts of recombined ions
- **Ni**: stored ion beam in storage ring
- **n_e**: electron density
- **L**: effective interaction length (4.0 m)
- **C**: the circumstance of CSRm (161.0 m)
Advantages of DR experiments at heavy ion storage rings

- ultra-high precision (meV, even sub-meV)
- relative energy can be tuned precisely (meV ~ keV)
- ultra-high vacuum, long storage time (metastable state)
- absolute rate coefficients \( \rightarrow \) recombined ions can be detected \(~100\%\)
- only method to measure reaction rate at low energy
Electron-ion recombination experiments at CSR (2017–present, $^{36}$Ar$^{15+}$, $^{40}$Ar$^{12+,13+,14+,15+}$, $^{40}$Ca$^{14+,16+,17+}$, $^{56}$Fe$^{15+,17+}$, $^{58}$Ni$^{19+}$, $^{76}$Kr$^{25+,30+}$, $^{112}$Sn$^{35+}$)

Nadir Khan et al., *Chinese Physics C* 42, 064001 (2018)
Z. K. Huang et al., *X-Ray Spectrometry* 1, 5 (2019)

…….
Experimental result of Fe$^{15+}$: DR spectrum

$e^- + Fe^{15+}(2p^63s^2S_{1/2}) \rightarrow \begin{cases} Fe^{14+}(2p^63p^2[2P_{1/2,3/2}n_l])^{**}(n \geq 10) \\ Fe^{14+}(2p^63d^2[2D_{3/2,5/2}n_l])^{**}(n \geq 7) \end{cases}, \Delta n = 0$

$\alpha(E_{rel}) = \frac{R}{N_i n_e (1 - \beta_e \beta_i)} \frac{C}{L}$

$R$ : counts of recombined ions
$N_i$ : stored ion beam in storage ring
$n_e$ : electron density
$L$ : effective interaction length (4.0 m)
$C$ : the circumstance of CSRm(161.0 m)
Experimental and theoretical DR spectrum: Fe$^{15+}$

$e^- + Fe^{15+}(2p^63s[2S_{1/2}]) \rightarrow \begin{cases} Fe^{14+}(2p^63p[^2P_{1/2,3/2}nl])^{*\ast}(n \geq 10) \\ Fe^{14+}(2p^63d[^2D_{3/2,5/2}nl])^{*\ast}(n \geq 7), \Delta n = 0 \end{cases}$

![Graph showing DR rate coefficients vs electron-ion collision energy](graph.png)

**Preliminary**

DR rate coefficient of Na-like Fe$^{15+}$: experiment vs theory

- **Houke Huang, Zhongkui Huang & DR team:** Experiment
- **Chongyang Chen:** FAC calculation
- **Chunyu Zhang & Nigel Badnell:** AUTOSTRUCTURE calculation

H. K. Huang et al., *APJS*, in preparation
Experimental and theoretical DR spectrum: Fe$^{15+}$

\[ e^- + Fe^{15+}(2p^63s[2S_{1/2}]) \rightarrow \begin{cases} Fe^{14+}(2p^63p[2P_{1/2,3/2}nl])^{**}(n \geq 10) \\ Fe^{14+}(2p^63d[2D_{3/2,5/2}nl])^{**}(n \geq 7), \Delta n = 0 \end{cases} \]

Preliminary

DR rate coefficient of Na-like Fe$^{15+}$: experiment vs theory

H. K. Huang et al., APJS, in preparation
- Plasma recombination rates coefficients were deduced from the DR rate coefficients.
- We provide a benchmark data for plasma modelling with the ion of Fe$^{15+}$.

H. K. Huang et al., *APJS*, in preparation
Dielectronic recombination rate coefficients of fluorine-like nickel

Shu-Xing Wang¹, Zong-Kui Huang², Wei-Qiang Wen³, Chong-Yang Chen¹, Stefan Schippers⁵, Xin Xu¹,², Shahid Sardar¹,², Nadir Khan³, Han-Bing Wang³, Li-Jun Dou³, Sultan Mahmood¹,⁶, Dong-Mei Zhao¹, Xiao-Long Zhu³, Li-Jun Mao³, Xiao-Ming Ma³, Jie Li³, Mei-Tang Tang¹, Rui-Shi Mao³, Da-Yu Yin³, You-Jin Yuan³, Jian-Cheng Yang³, Ying-Long Shi³, Chen-Zhong Dong³, Xin-Wen Ma³, and Lin-Fan Zhu¹,²

Precision DR spectroscopy of Ni\textsuperscript{19+}: high-order QED

$58\text{Ni}^{19+} (2s^2 2p^5 [^2P_{3/2}]) + e^- 
\rightarrow \begin{cases} 
58\text{Ni}^{18+} (2s^2 2p^5 [^2P_{1/2}]nl) \quad ** \\
58\text{Ni}^{18+} (2s^2 2p^6 [^2S_{1/2}]nl) \quad ** 
\end{cases} 
\rightarrow 58\text{Ni}^{18+} + mhv$

Precision DR spectroscopy of Ni\(^{19+}\): high-order QED

\[ \Delta E_{core} = E_e + E_{bind} \]

\[ (2s^22p^6[^2S_{1/2}]6s)_{J=1} 86 \pm 4 \text{ meV} \]
1. Multi-Configurational Dirac-Hartree-Fock (MCDHF) theoretical calculation

\[ \Delta E_{\text{core}} = E_e + E_{\text{bind}} \]

MCDHF calculation: excitation energy of Ni$^{19+}$ and also bending energy of Ni$^{18+}$

<table>
<thead>
<tr>
<th>AO</th>
<th>(E(2s^22p^6[2S_{1/2}]))</th>
<th>(E(2s2p^6[2S_{1/2}]))</th>
<th>(\Delta E(2s2p^6[2S_{1/2}] \rightarrow 2s^22p^5[2P_{3/2}]))</th>
</tr>
</thead>
<tbody>
<tr>
<td>{3s, 3p, 3d}</td>
<td>-1292.583877</td>
<td>-1287.029907</td>
<td>151.118</td>
</tr>
<tr>
<td>{4s, 4p, 4d, 4f}</td>
<td>-1292.7902178</td>
<td>-1287.3083550</td>
<td>149.169</td>
</tr>
<tr>
<td>{5s, 5p, 5d, 5f, 5g}</td>
<td>-1292.834402</td>
<td>-1287.3745748</td>
<td>149.089</td>
</tr>
<tr>
<td>{6s, 6p, 6d, 6f, 6g, 6h}</td>
<td>-1292.8806642</td>
<td>-1287.4035955</td>
<td>149.039</td>
</tr>
<tr>
<td>{7s, 7p, 7d, 7f, 7g, 7h, 7i}</td>
<td>-1292.9096358</td>
<td>-1287.4331842</td>
<td>149.022</td>
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<tr>
<td>{8s, 8p, 8d, 8f, 8g, 8h, 8i, 8k}</td>
<td>-1292.9238447</td>
<td>-1287.4474401</td>
<td>149.020</td>
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<tr>
<td>{9s, 9p, 9d, 9f, 9g, 9h, 9i, 9k}</td>
<td>-1292.9295149</td>
<td>-1287.4531798</td>
<td>149.019</td>
</tr>
</tbody>
</table>

Ne-like Ni$^{18+}$ (MR = \{2s^2p^5s, 2s^2p^6s, 2s^2p^7s\})

<table>
<thead>
<tr>
<th>AO</th>
<th>(E(2s2p^6[2S_{1/2}][6s]_{f=1}))</th>
<th>(\Delta E(2s2p^6[2S_{1/2}][6s]<em>{f=1} \rightarrow 2s2p^5[2S</em>{1/2}][6s]_{f=1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>{8s, 8p, 8d, 8f, 8g, 8h, 8i, 8k}</td>
<td>-1292.8391704</td>
<td>158.08</td>
</tr>
<tr>
<td>{9s, 9p, 9d, 9f, 9g, 9h, 9i, 9k}</td>
<td>-1292.8712688</td>
<td>151.37</td>
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<tr>
<td>{10s, 10p, 10d, 10f, 10g, 10h, 10i, 10k}</td>
<td>-1292.8918299</td>
<td>150.13</td>
</tr>
<tr>
<td>{11s, 11p, 11d, 11f, 11g, 11h, 11i, 11k}</td>
<td>-1292.9022762</td>
<td>149.63</td>
</tr>
<tr>
<td>{12s, 12p, 12d, 12f, 12g, 12h, 12i, 12k}</td>
<td>-1292.9085850</td>
<td>148.99</td>
</tr>
<tr>
<td>{13s, 13p, 13d, 13f, 13g, 12h, 12i, 12k}</td>
<td>-1292.9165405</td>
<td>148.82</td>
</tr>
<tr>
<td>{14s, 14p, 14d, 14f, 14g, 12h, 12i, 12k}</td>
<td>-1292.9277362</td>
<td>148.97</td>
</tr>
</tbody>
</table>

\[ \Delta E_{\text{core}} = 149.019 \pm 0.010 \text{ eV} \]

\[ E_{\text{bind}} = 148.946 \pm 0.020 \text{ eV} \]
Precision DR spectroscopy of Ni$^{19+}$: high-order QED

\[ \Delta E_{\text{core}} = E_e + E_{\text{bind}} \]

2. *ab initio* theoretical calculation

➢ *ab initio* calculation of excitation energy of Ni$^{19+}$: $S_{1/2} \rightarrow 2P_{3/2}$

| TABLE V. Individual contributions to the transition $2s^22p^5 \ 2P_{3/2} \rightarrow 2s\ 2p^6 \ 2S_{1/2}$ energy in fluorine-like nickel ion (in eV). |
|-----------------|----------------|----------------|
| Contribution    | Core-Hartree  | Kohn-Sham      |
| Dirac           | 123.911       | 128.743        |
| Correlation (1) | 27.190        | 22.723         |
| Correlation (2) | −1.536        | −1.972         |
| Correlation (3) | 0.032(2)      | 0.102(2)       |
| QED (1)         | −0.506        | −0.510         |
| QED (2)         | −0.033(6)     | −0.028(6)      |
| Recoil          | −0.012(3)     | −0.012(3)      |
| Total           | 149.046(7)    | 149.046(7)     |

\[ \Delta E_{\text{core}} = E_e + E_{\text{bind}} \]

149.046 ± 0.007 eV

S.X. Wang et al., *PRA* 106 (2022) 042808
Precision DR spectroscopy of Ni$^{19+}$: high-order QED

Energy (eV)

- Present MCDHF calculation: 149.045
- Present experimental derived: 149.056±0.003
- Laser-produced plasma, 1991: 149.046±0.009
- Laser-produced plasma, 1974: 149.08±0.02
- SuperStructure, 2020: 149.24
- MCDHF, 2016: 149.05
- MBPT, 2016: 148.91
- CI+MBPT, 2005: 148.95
- CCSD(T), 2013: 149.51
- CI+MCDF, 2013: 149.08±0.03

Shuxing Wang, Zhongkui Huang & DR team: Experiment

Chunyu Zhang, Chongyang Chen FAC theory

Andrey Volotka, Yury Kozhedub ab initia theory

Kai Wang, Zhongwen Wu MCDHF theory
We will carry out more precision DR experiments with HCIs
We need more precision calculations.

Heavy Ion Research Facility in Lanzhou

DR @CSRm
- ion species: Si ~ Kr
- cooling voltage: 2 ~ 30 kV
- detuning voltage: ±3 kV (c.m. frame ~150 eV)

DR @CSRe
- ion species: Kr ~ U
- cooling voltage: 10~300 kV
- detuning voltage: ±15 kV (c.m. frame ~1.5 keV)
Future DR experiments: from CSR to HIAF

Heavier ions, Higher charge state, higher precision

HIRFL-CSR
Heavy Ion Research Facility in Lanzhou

HIRAF
(High Intensity heavy ion Accelerator Facility)

Heavier ions, Higher charge state, higher precision
The absolute DR rate coefficients of \( \text{Fe}^{15+} \) have been measured using the electron-ion merged-beam technique at the heavy ion storage ring CSR at IMP, Lanzhou.

The measurement covers most of the DR resonances associated with the \( 3s \rightarrow 3p \) and \( 3s \rightarrow 3d \) core excitations (\( \Delta N = 0 \)); compare with the AUTOSTRUCTURE, FAC and JAC calculations, and have a good agreement.

The temperature dependent plasma recombination rate coefficients are derived from the measured DR rate coefficients and provide a benchmark data.

Precision DR spectroscopy of \( \text{Ni}^{19+} \): test high-order QED effect with HCl.

We will perform more DR experiments to investigate on astrophysics & precision spectroscopy at storage rings: CSRm \( \rightarrow \) CSRe \( \rightarrow \) HIAF
<table>
<thead>
<tr>
<th>Institution</th>
<th>Members</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anhui Normal University</td>
<td>Kai Wang;</td>
</tr>
<tr>
<td>Uni. Giessen</td>
<td>Stefan Schippers;</td>
</tr>
<tr>
<td>GSI, Darmstadt</td>
<td>Th. Stöhlker, C. Brandau, A. Gumberidze, Yu. Litvinov;</td>
</tr>
<tr>
<td>Uni. Strathclyde, Glasgow</td>
<td>N.R. Badnell, Chunyu Zhang;</td>
</tr>
<tr>
<td>St. Petersburg State University</td>
<td>V.M. Shabaev, Yury Kozhedub, Andrey V. Volotka;</td>
</tr>
</tbody>
</table>
Thank you
for your attention!
Precision spectroscopy of HCI @CSRe

- First DR rate experiment of Na-like Kr\textsuperscript{25+} was performed at the CSRe
- The particle detectors and electron energy fast detuning system is proved to be feasible and performed excellently in the test experiment
- DR @CSRe open new possibility for investigate high precision experiments with heavy HCIs, to investigate strong field QED and nuclear properties

Z.K. Huang et al., NIMA, 1040 (2022) 167286