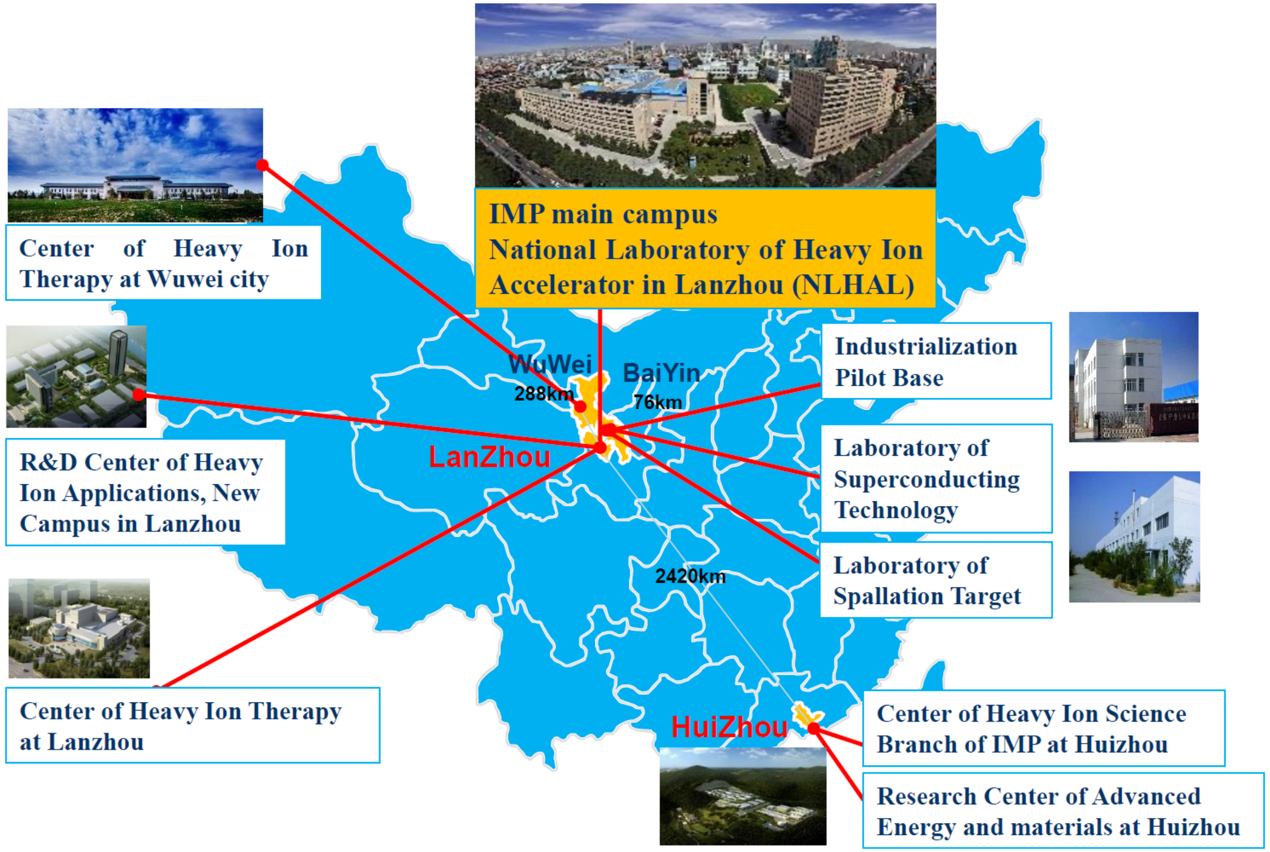
Storage Ring Measurements for Dielectronic Recombination of Na-like Fe^{15+}

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

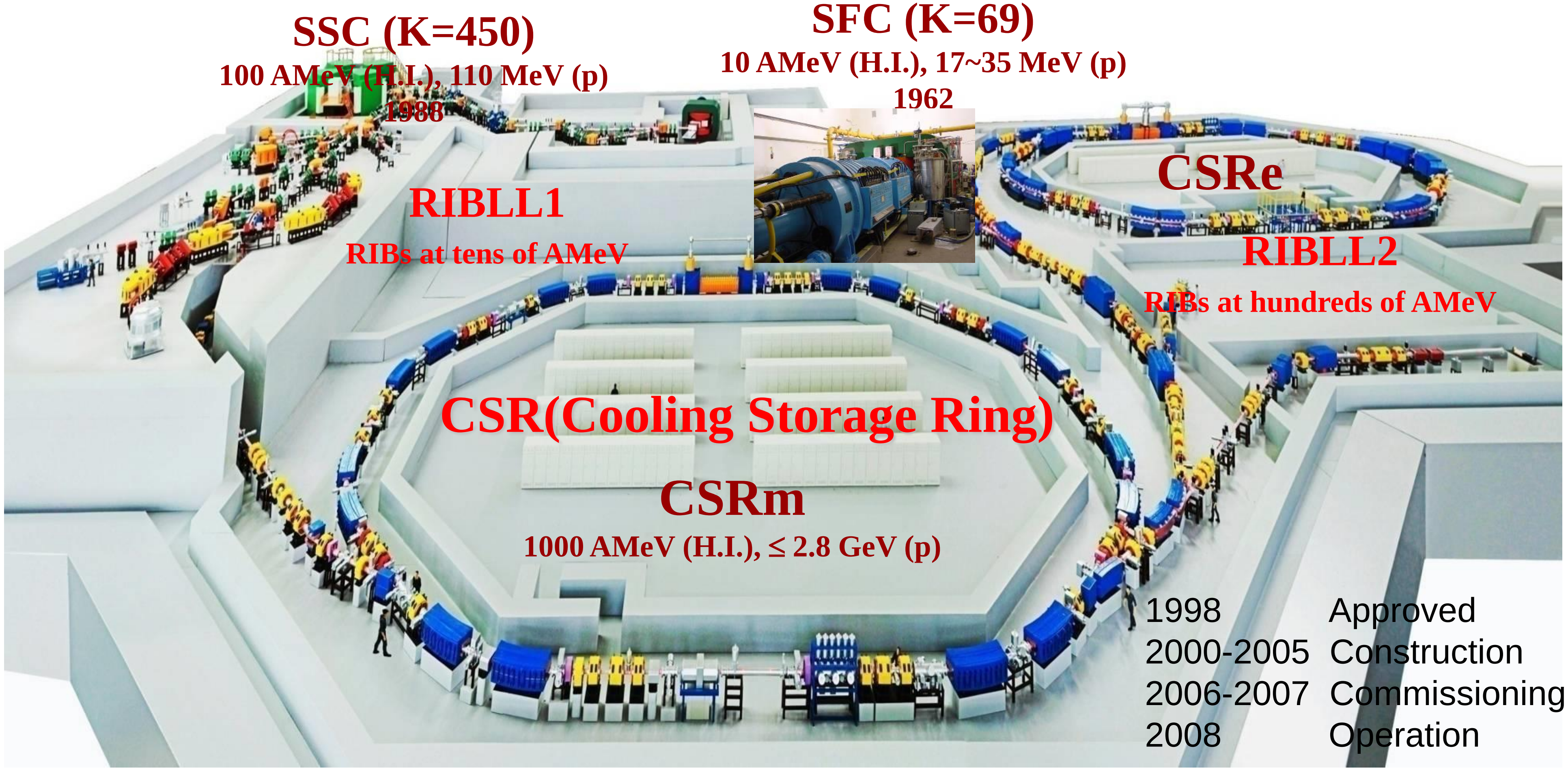
Introduction to Institute of Modern Physics, CAS



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)



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)

Atomic physics center, Institute of Modern Physics, Chinese Academy of Sciences.
509 Nanchang Rd., Lanzhou, China.
E-mail: wenweiqiang@impcas.ac.cn

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^{15+}:

— experimental results and theoretical calculation;

3. Precision DR spectroscopy of Ni^{19+}:

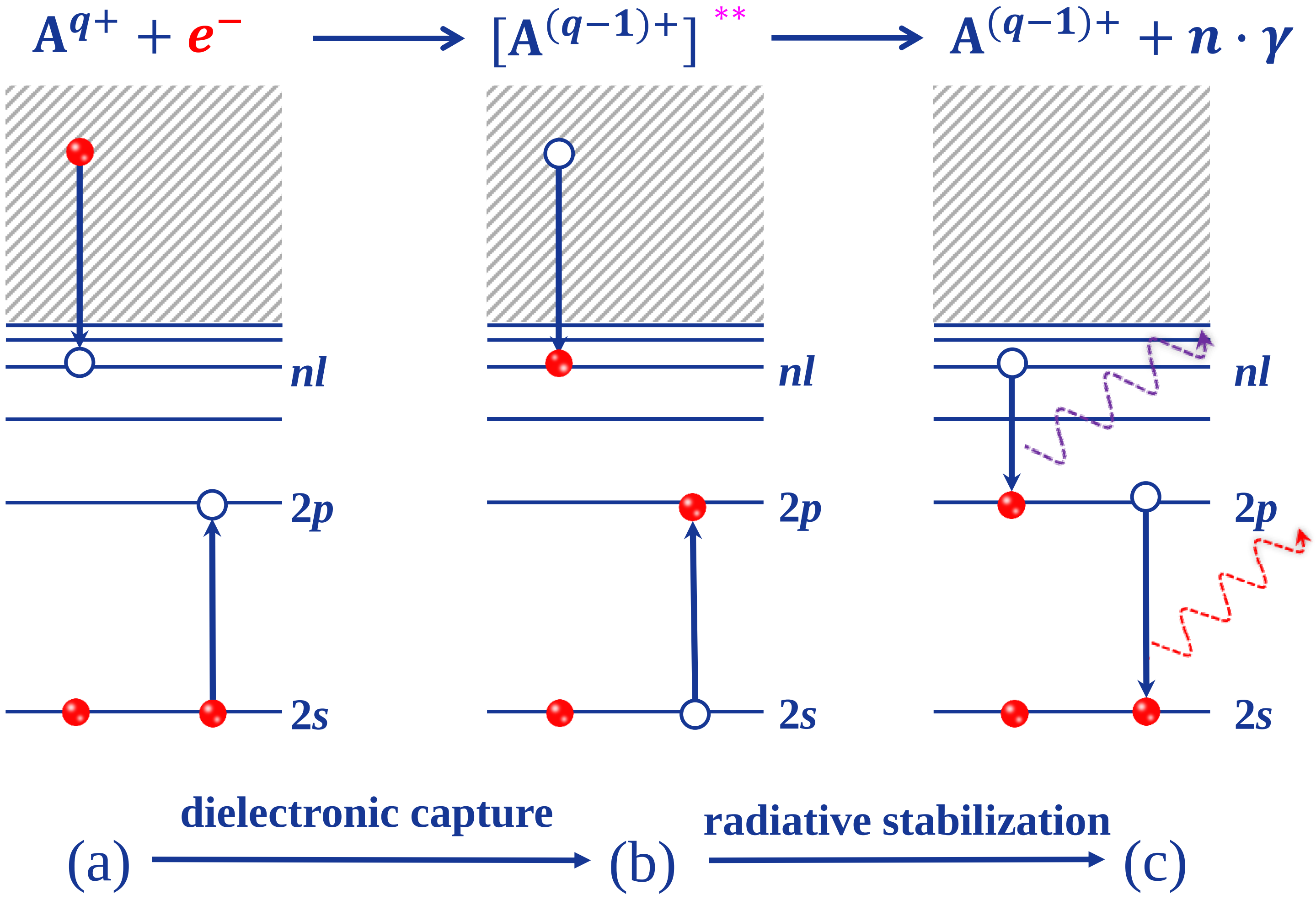
— test high-order QED effect with highly charged ions;

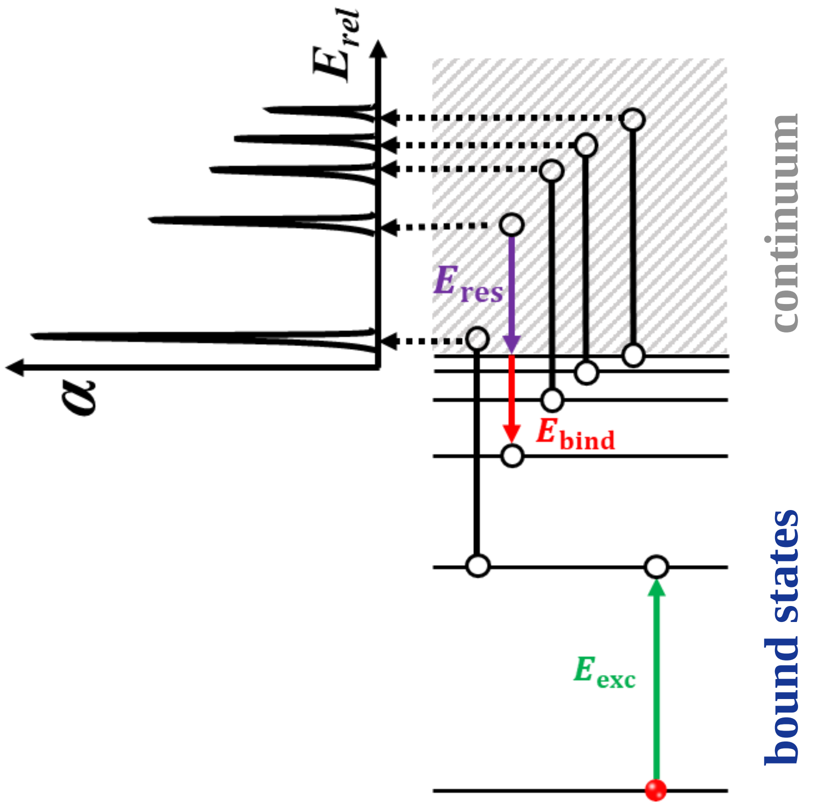
4. Summary and outlook:

— DR at storage ring: astrophysics & precision spectroscopy;

— DR at storage ring: CSRm → CSRe → HIAF

Dielectronic recombination process

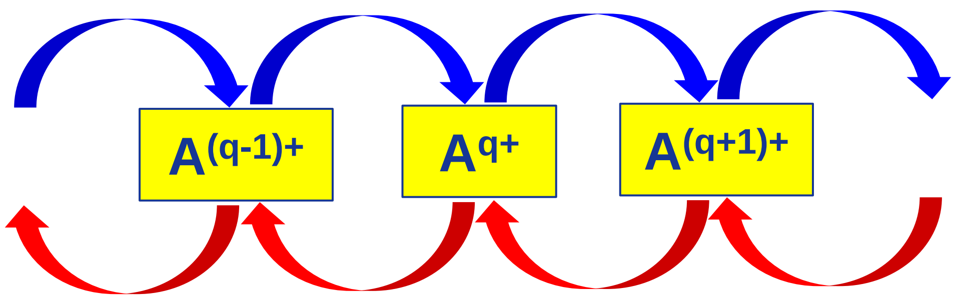


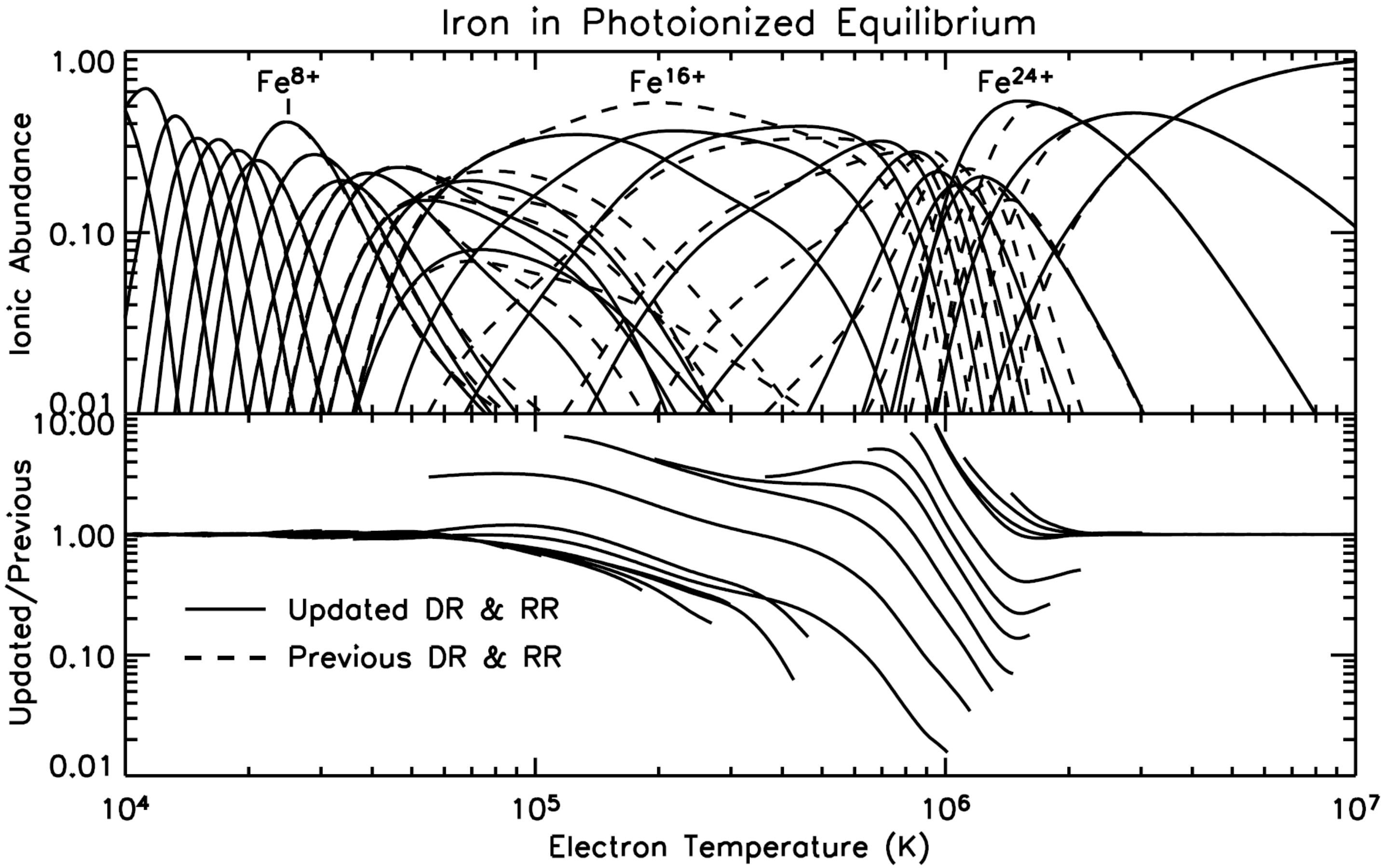


$$E_{exc} = E_{bind} + E_{res}$$

Dielectronic recombination in astrophysical plasmas

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)

DR of Astrophysically Relevant Iron Ions

INTERNATIONAL REVIEW OF ATOMIC AND MOLECULAR PHYSICS (IRAMP)
Volume 1, No. 2, July-December 2010, pp. 109-121, © *International Science Press, ISSN: 2229-3159*

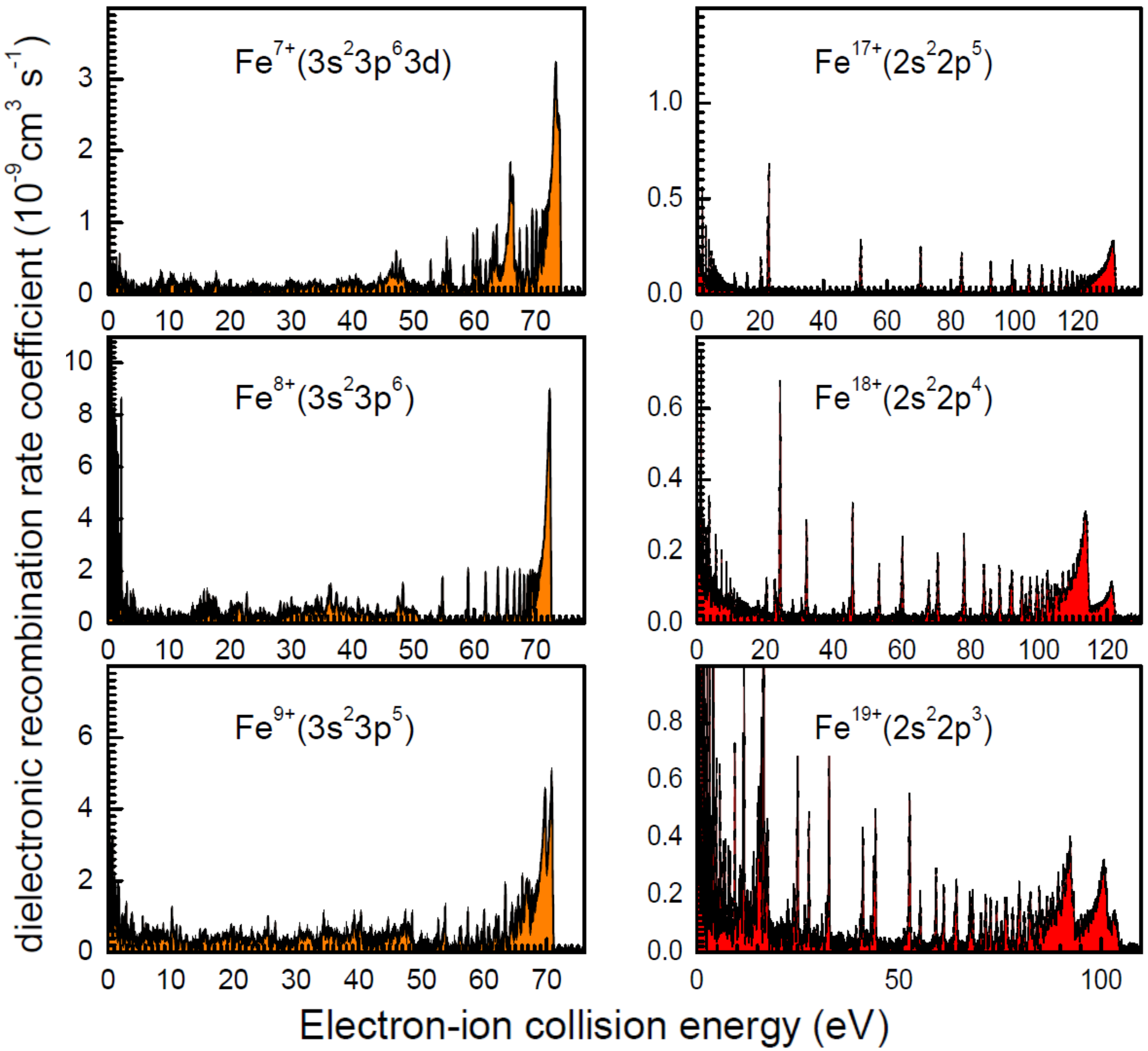
REVIEW ARTICLE

DIELECTRONIC RECOMBINATION DATA FOR ASTROPHYSICAL APPLICATIONS: PLASMA RATE-COEFFICIENTS FOR Fe^{q+} ($q = 7-10, 13-22$) AND 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- und Molekülphysik, Justus-Liebig-Universität Giessen, Leihgesterner Weg 217, 35392 Giessen, Germany.

DR of Astrophysically Relevant Iron Ions



publications from TSR

Fe^{7+}: E. W. Schmidt et al., A&A **492** (2008) 265

Fe^{8+}: E. W. Schmidt et al., A&A **492** (2008) 265

Fe^{9+}: M. Lestinsky et al., ApJ **698** (2009) 648

Fe^{10+}: M. Lestinsky et al., ApJ **698** (2009) 648

Fe^{11+}: O. Novotný et al., ApJ **753** (2012) 57

Fe^{12+}: M. Hahn et al., ApJ **788** (2014) 46

Fe^{13+}: E. W. Schmidt et al., ApJL **641** (2006) L157

Fe^{14+}: D. Lukić et al., ApJ **664** (2007) 124;
D. Bernhardt et al., PRA **90** (2014) 012702

Fe^{15+}: J. Linkemann et al., NIMB **98** (1995) 154

Fe^{16+}: E. W. Schmidt et al., JPCS **163** (2009) 012028

Fe^{17+}: D. W. Savin et al. ApJL **492** (1997) L115

Fe^{18+}: D. W. Savin et al., ApJS **123** (1999) 687

Fe^{19+}: D. W. Savin et al., ApJS **138** (2002) 337

Fe^{20+}: D. W. Savin et al., ApJS **147** (2003) 421

Fe^{21+}: D. W. Savin et al., ApJS **147** (2003) 421

Fe^{22+}: D. W. Savin et al. ApJ **642** (2006) 1275

DR of Astrophysically Relevant Iron Ions

INTERNATIONAL REVIEW OF ATOMIC AND MOLECULAR PHYSICS (IRAMP)
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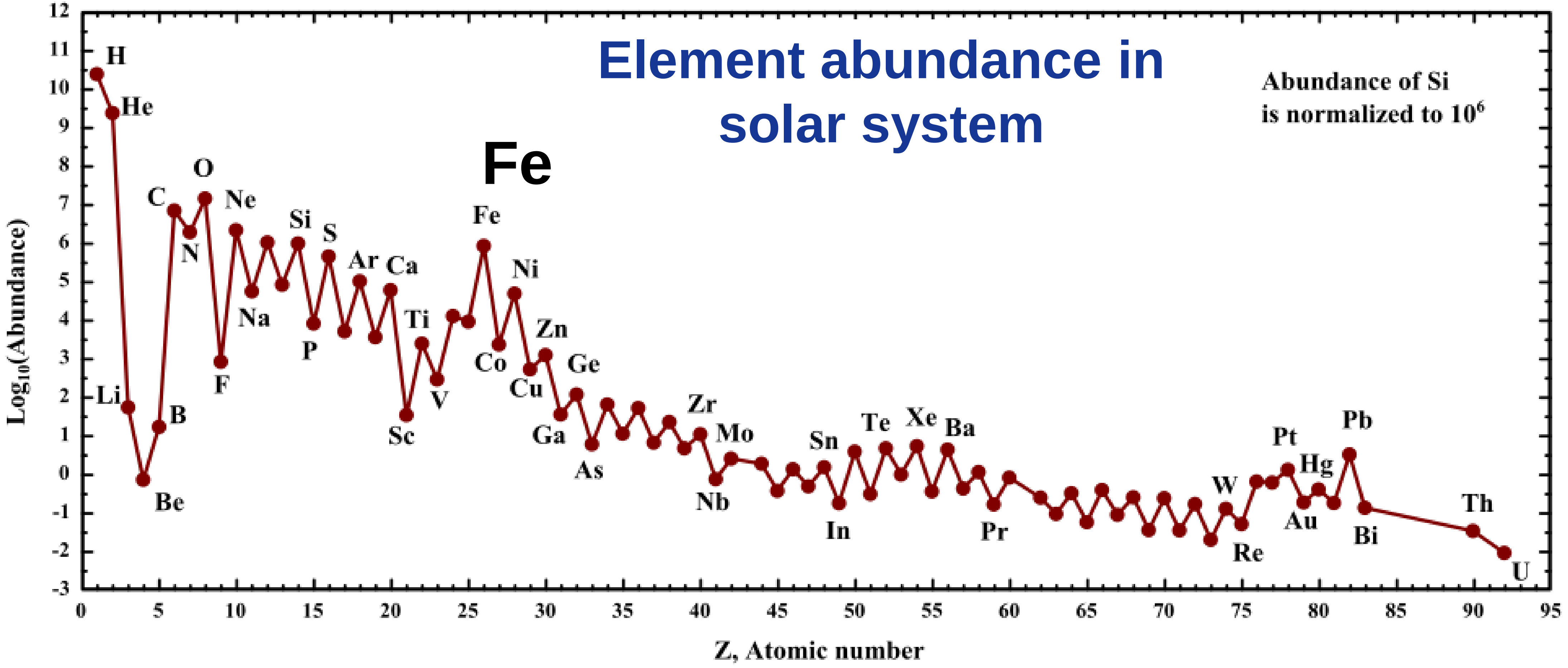
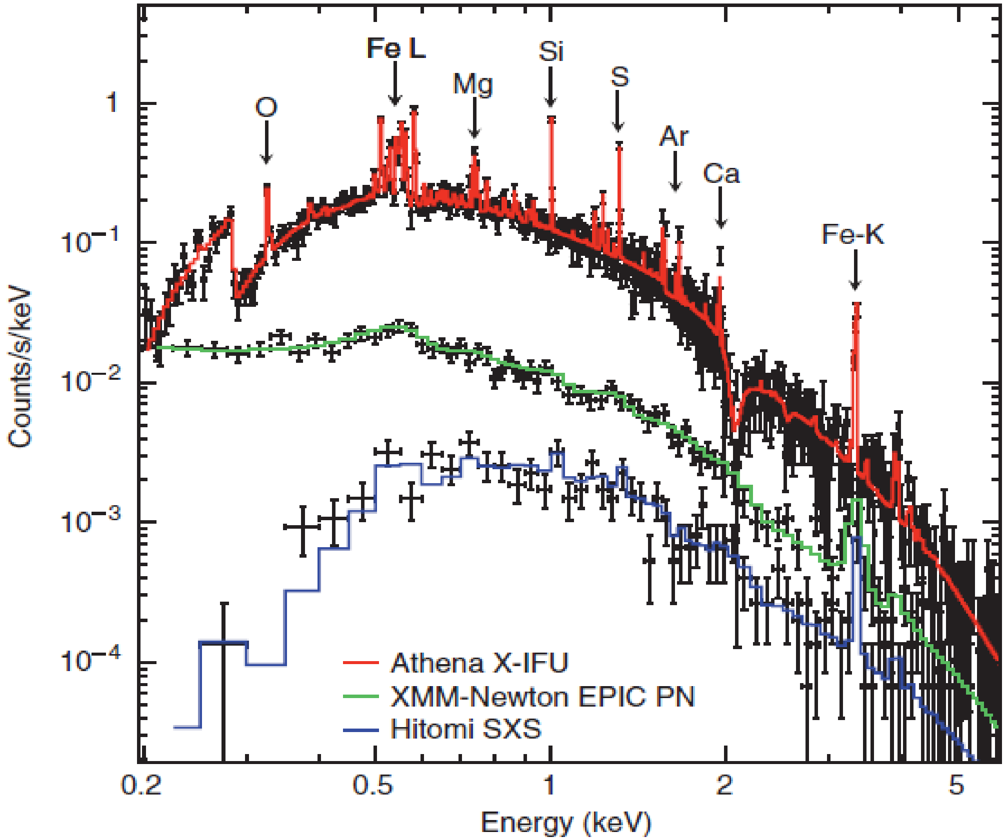
REVIEW ARTICLE



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

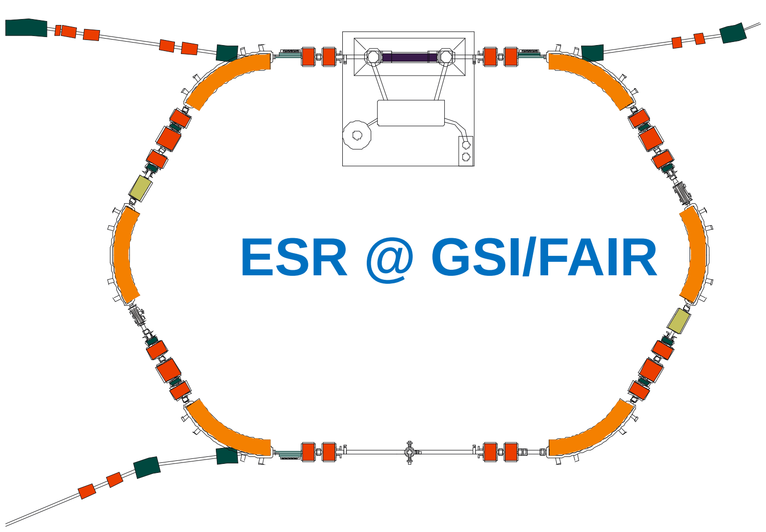


Collisional
- AtomDB
- Chianti
- SASAL
- SPEX
- ADAS (Fusion)

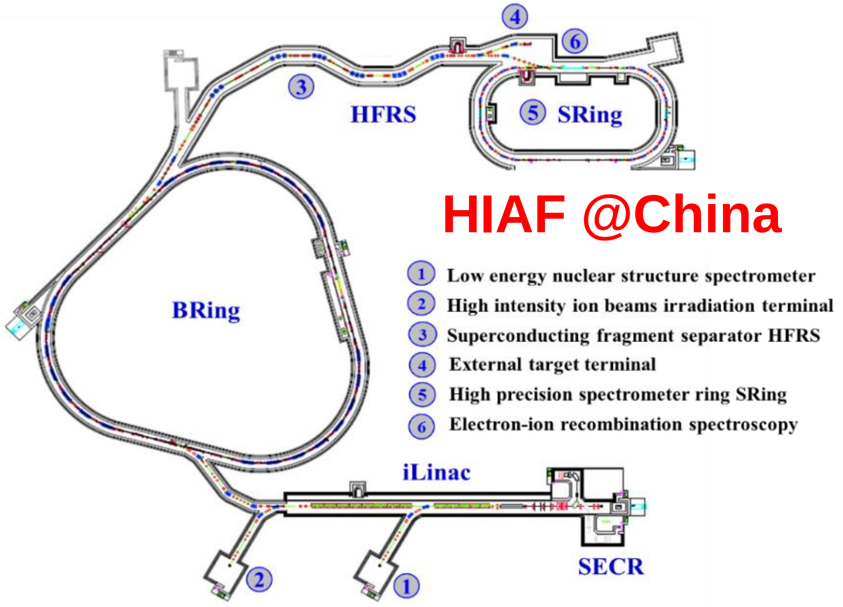
Photoionized
- Cloudy
- SPEX
- XSTAR
- Mocassin
- others

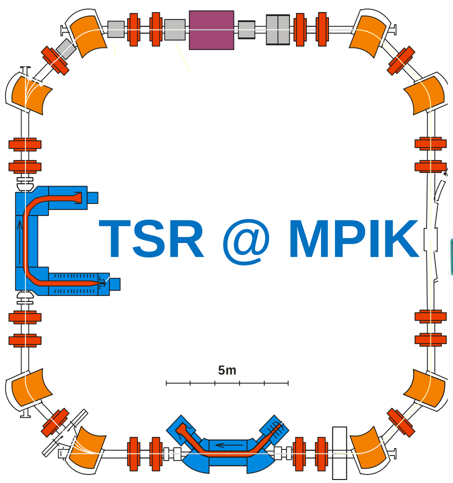
More accurate data from highly charged ions are needed for plasma modeling with high resolution X-ray astrophysics!

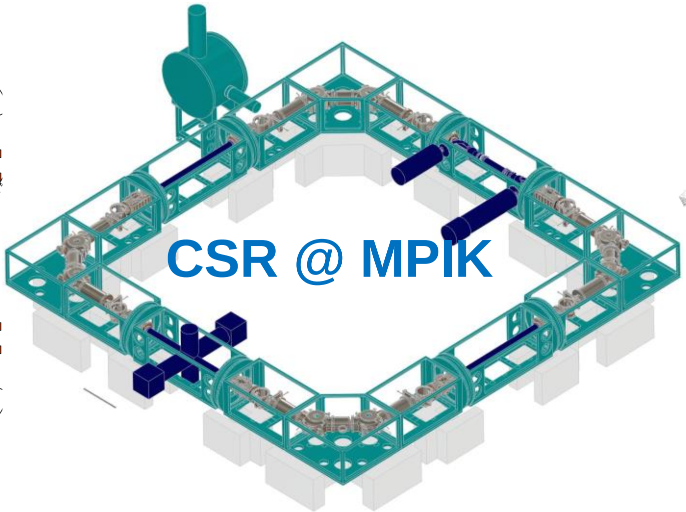
Electron-ion collision at storage-rings with electron coolers



CSRm & CSRe
@ IMP Lanzhou



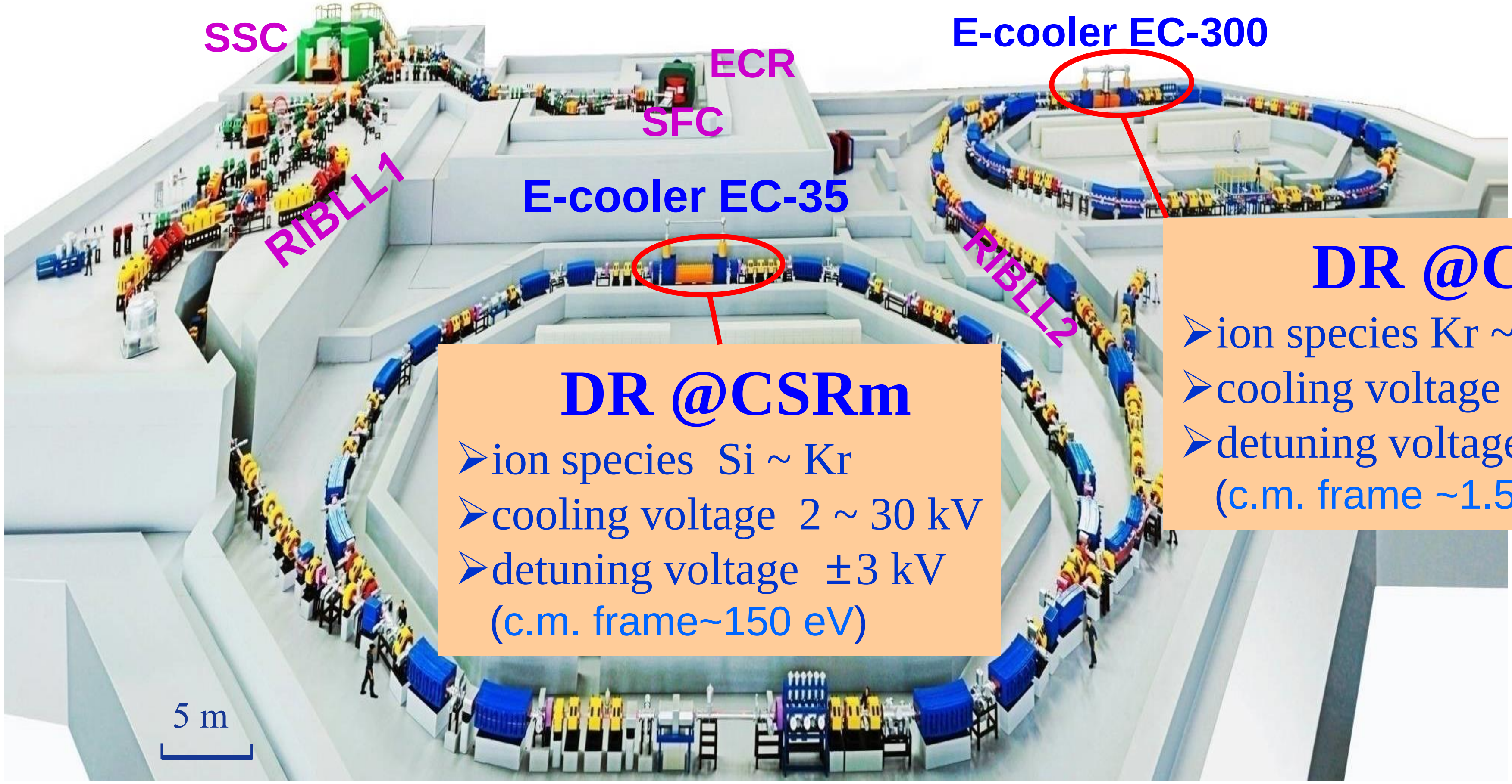




Electron-ion recombination experiments at CSR

(2017—present, $^{36}Ar^{15+}$, $^{40}Ar^{12+,13+,14+,15+}$, $^{40}Ca^{14+,16+,17+}$, $^{56}Fe^{15+,17+}$, $^{58}Ni^{19+}$, $^{76}Kr^{25+,30+}$, $^{112}Sn^{35+}$)

Heavy Ion Research Facility in Lanzhou



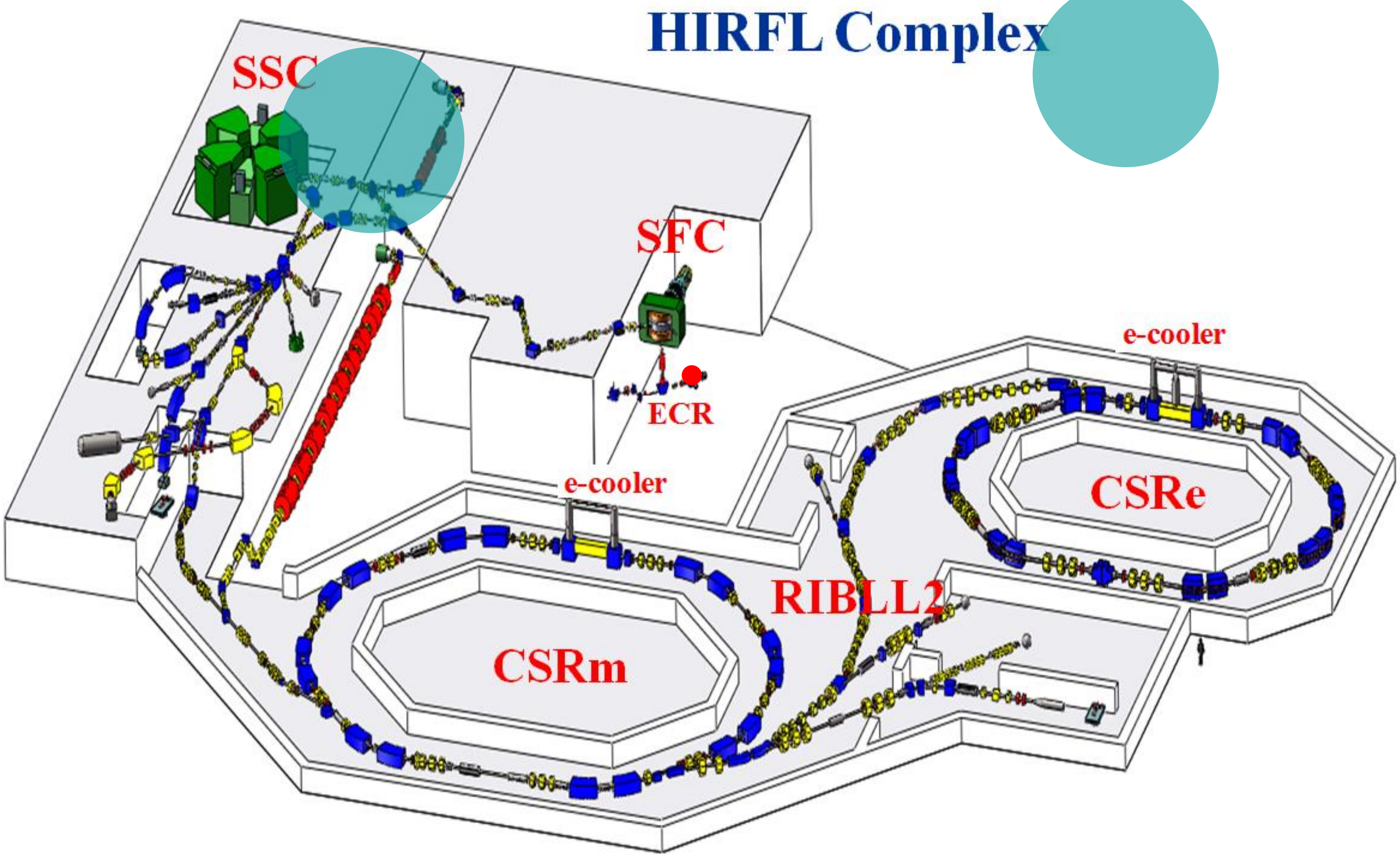
DR @CSRm

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

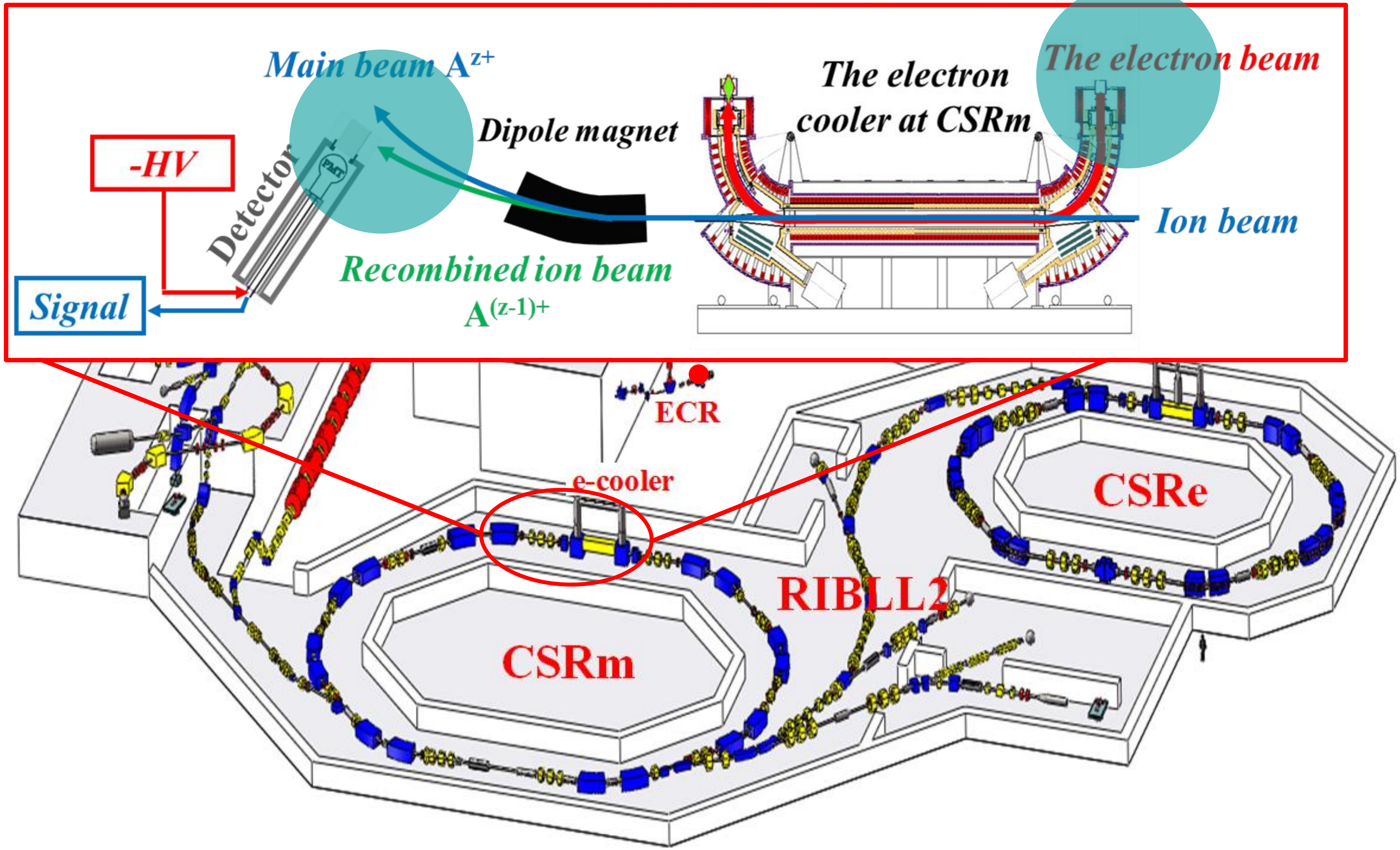
DR @CSRe

- ion species Kr ~ U
- cooling voltage 10~300 kV
- detuning voltage ±15 kV (c.m. frame ~1.5 keV)

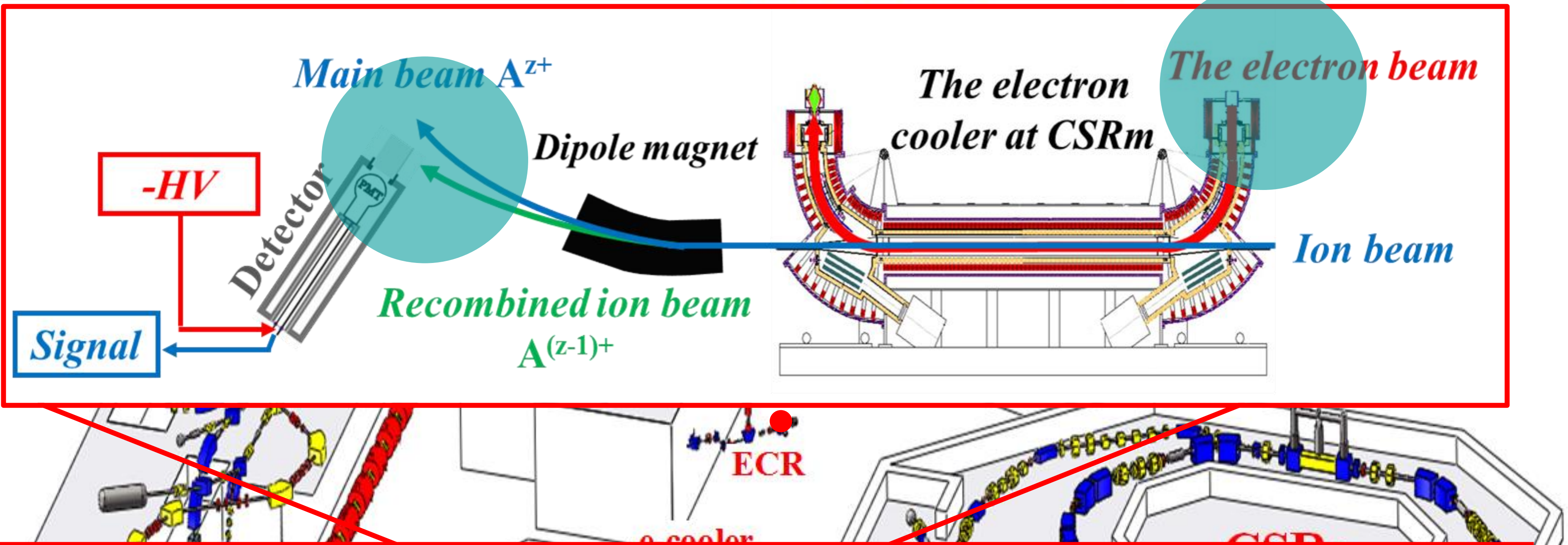
Electron-ion recombination experiments at CSR



Electron-ion recombination experiments at CSR



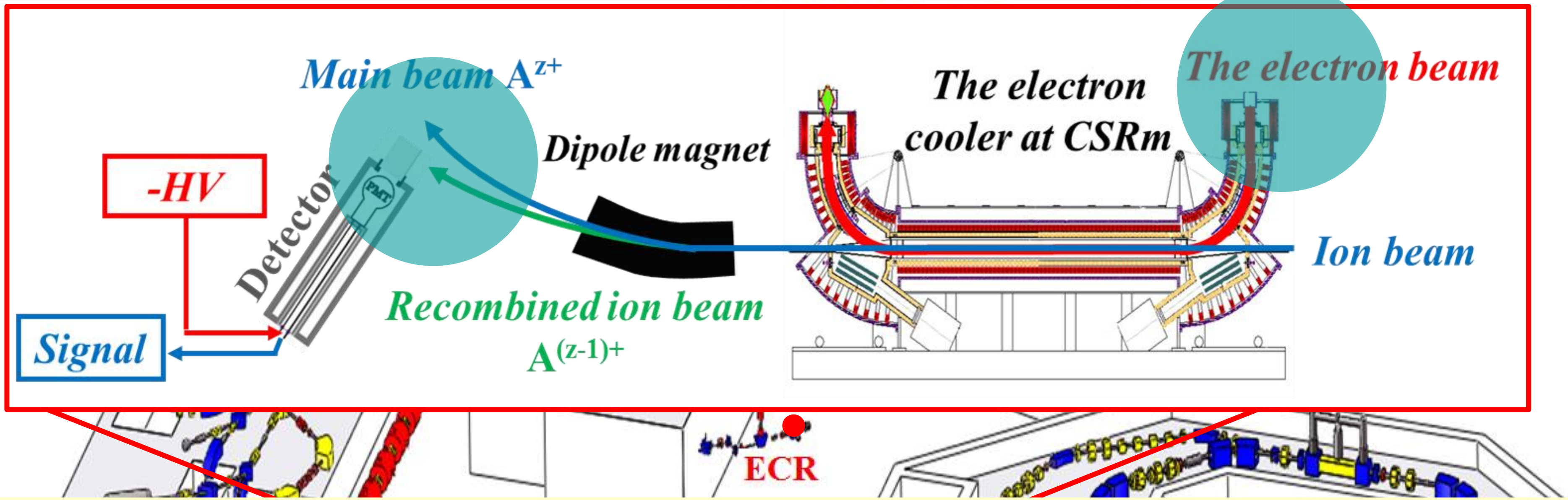
Electron-ion recombination experiments at CSR



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

- R : counts of recombined ions
- Ni : strored ion beam in storage ring
- n_e : electron density
- L : effective interaction length (4.0 m)
- C: the circumstance of CSRm(161.0 m)

Electron-ion recombination experiments at CSR



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 →recombined ions can be detected ~100%
- only method to measure reaction rate at low energy

Electron-ion recombination experiments at CSR

(2017—present, $^{36}Ar^{15+}$, $^{40}Ar^{12+,13+,14+,15+}$, $^{40}Ca^{14+,16+,17+}$, $^{56}Fe^{15+,17+}$, $^{58}Ni^{19+}$, $^{76}Kr^{25+,30+}$, $^{112}Sn^{35+}$)

Z. K. Huang *et al*., ***The Astrophysical Journal Supplement Series*** 235, 2 (2018)

S.X. Wang *et al*., ***The Astrophysical Journal*** 862, 134 (2018)

Nadir Khan *et al*., ***Chinese Physics C*** 42, 064001 (2018)

Z. K. Huang *et al*., ***X-Ray Spectrometry*** 1, 5 (2019)

S.X. Wang *et al*., ***Astronomy & Astrophysics***, 627, A171 (2019)

S. Mahmood *et al*., ***J. Phys. B: At. Mol. Opt. Phys.*** 53, 085004 (2020)

Z. K. Huang *et al*., ***Phys. Rev. A*** 102, 062823 (2020)

W. Q. Wen *et al*., ***The Astrophysical Journal*** 905, 36 (2020)

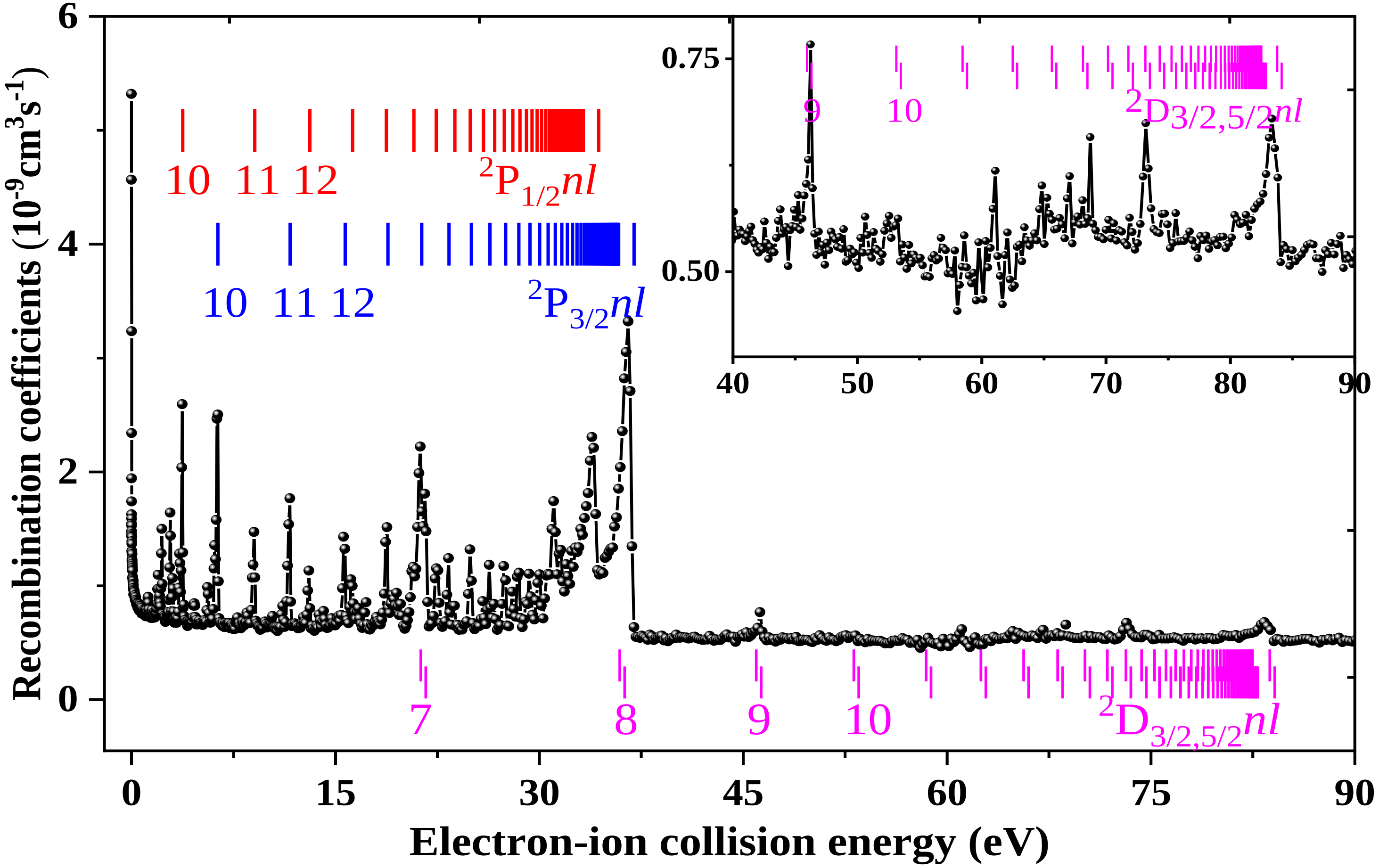
Nadir Khan *et al*., ***J. Phys. B: At. Mol. Opt. Phys.*** 55, 035001 (2022)

S.X. Wang *et al*., ***Phys. Rev. A*** 106, 042808 (2022)

……

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

$$e^- + Fe^{15+}(2p^6 3s[^2S_{1/2}]) \rightarrow \begin{cases} Fe^{14+}(2p^6 3p[^2P_{1/2,3/2} nl])^{**}(n \geq 10) \\ Fe^{14+}(2p^6 3d[^2D_{3/2,5/2} nl])^{**}(n \geq 7) \end{cases}, \Delta n = 0$$



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

R : counts of recombined ions

N_i : strored ion beam in storage ring

n_e : electron density

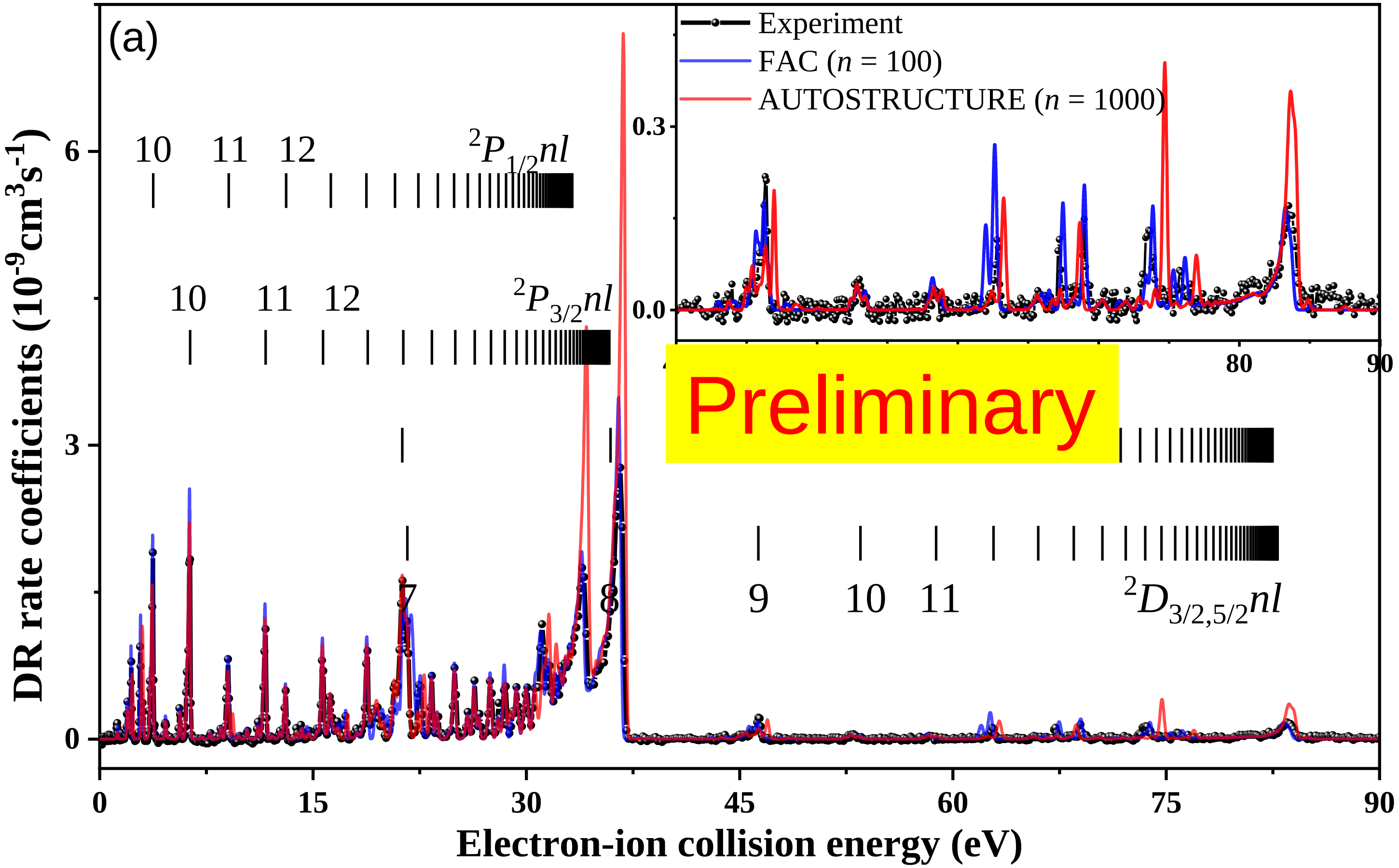
L : effective interaction length (4.0 m)

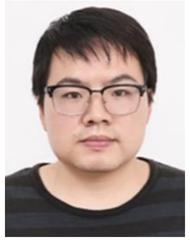
C: the circumstance of CSRm(161.0 m)

RR & DR & background

Experimental and theoretical DR spectrum: Fe^{15+}

$$e^- + Fe^{15+}(2p^6 3s[^2S_{1/2}]) \rightarrow \begin{cases} Fe^{14+}(2p^6 3p[^2P_{1/2,3/2} nl])^{**} (n \geq 10) \\ Fe^{14+}(2p^6 3d[^2D_{3/2,5/2} nl])^{**} (n \geq 7) \end{cases}, \Delta n = 0$$





Houke Huang, Zhongkui Huang & DR team: **Experiment**

Chongyang Chen: **FAC** calculation

Chunyu Zhang & Nigel Badnell **AUTOSTRUCTURE** calculation

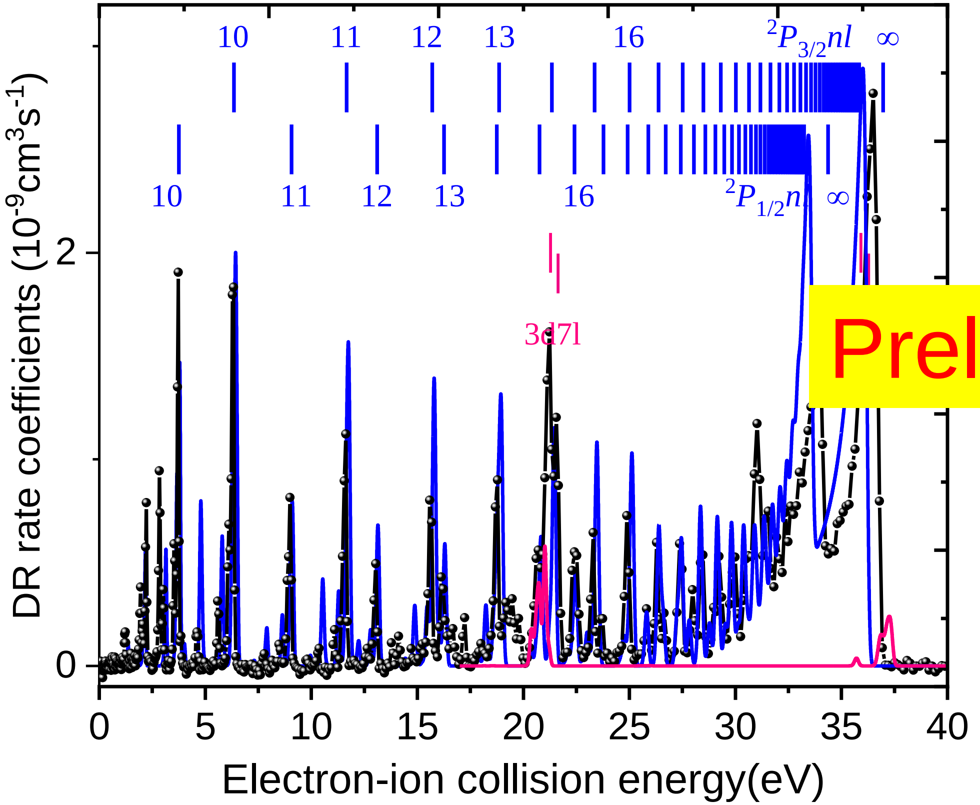
DR rate coefficient of Na-like Fe^{15+}: experiment vs theory

H. K. Huang *et al.*, ***APJS***, in preparation

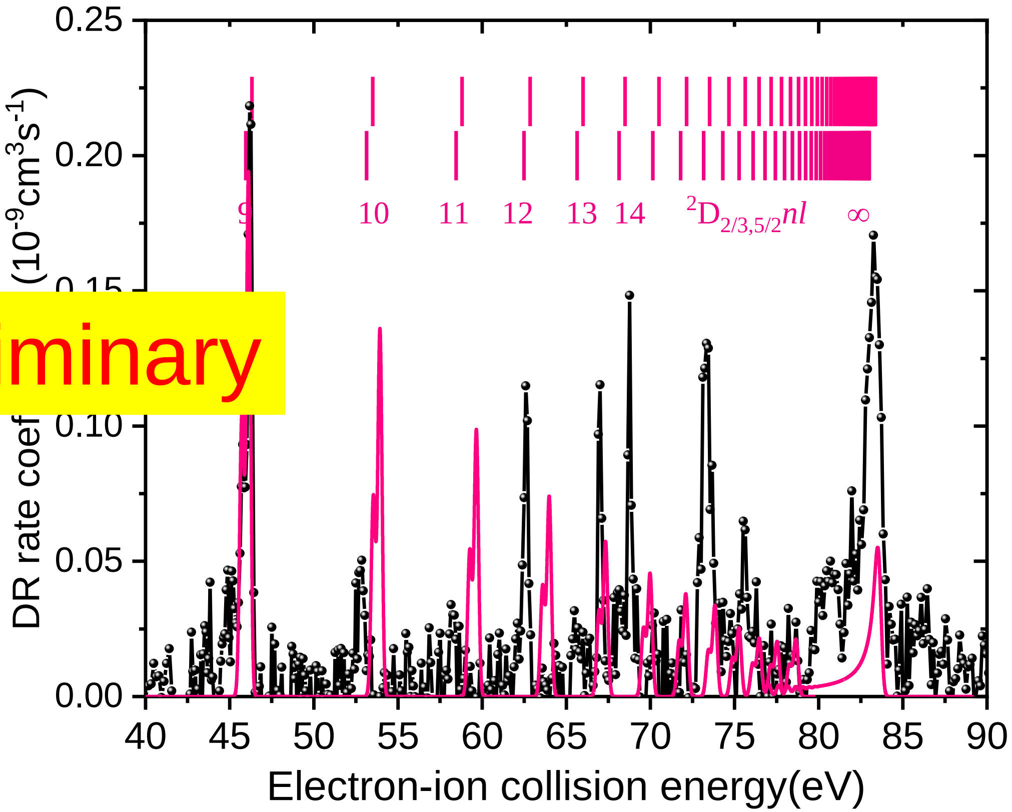
Experimental and theoretical DR spectrum: Fe^{15+}

$$e^- + Fe^{15+}(2p^6 3s[^2S_{1/2}]) \to \begin{cases} Fe^{14+}(2p^6 3p[^2P_{1/2,3/2}nl])^{**}(n \ge 10) \\ Fe^{14+}(2p^6 3d[^2D_{3/2,5/2}nl])^{**}(n \ge 7) \end{cases}, \Delta n = 0$$

Jena Atomic Calculator (JAC)



Preliminary



Stephan Fritzsche

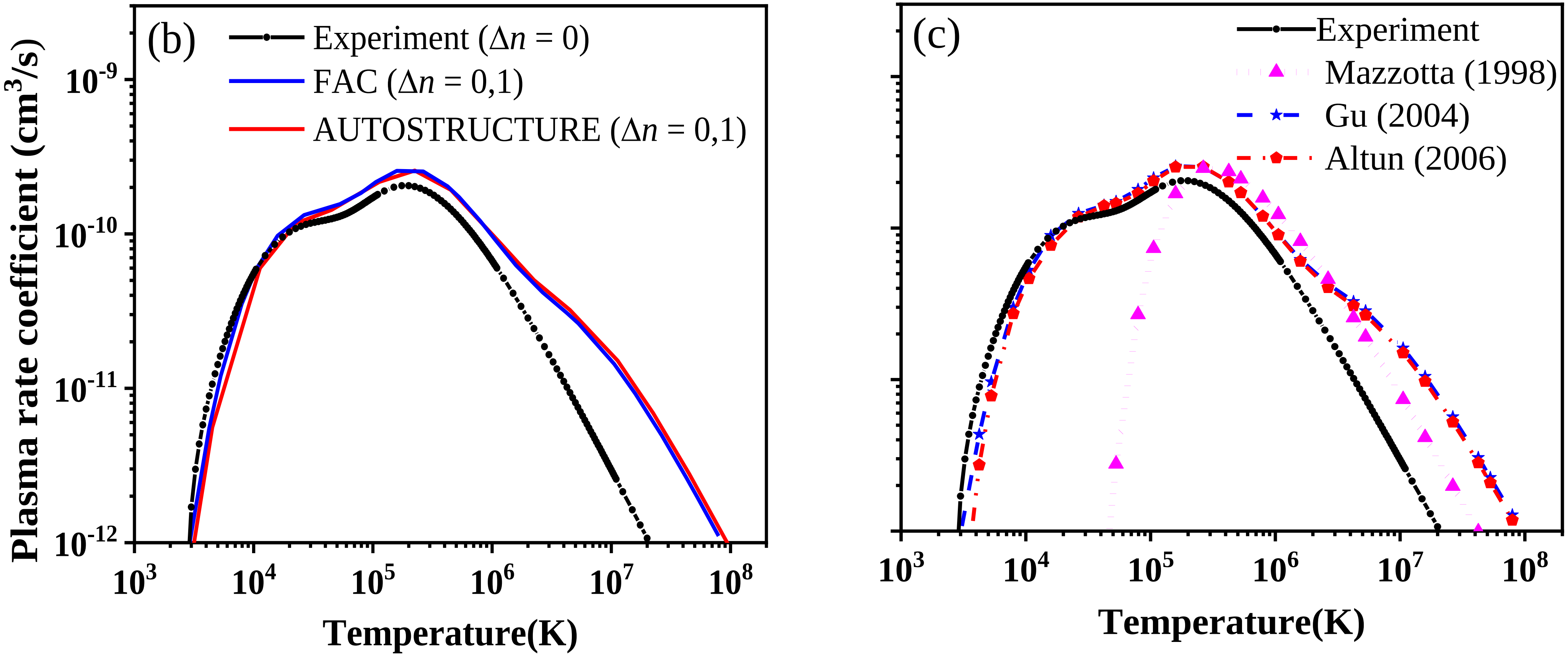
Houke Huang

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

H. K. Huang *et al.*, ***APJS***, in preparation

Experimental and theoretical plasma rate coeff.: Fe^{15+}

- 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

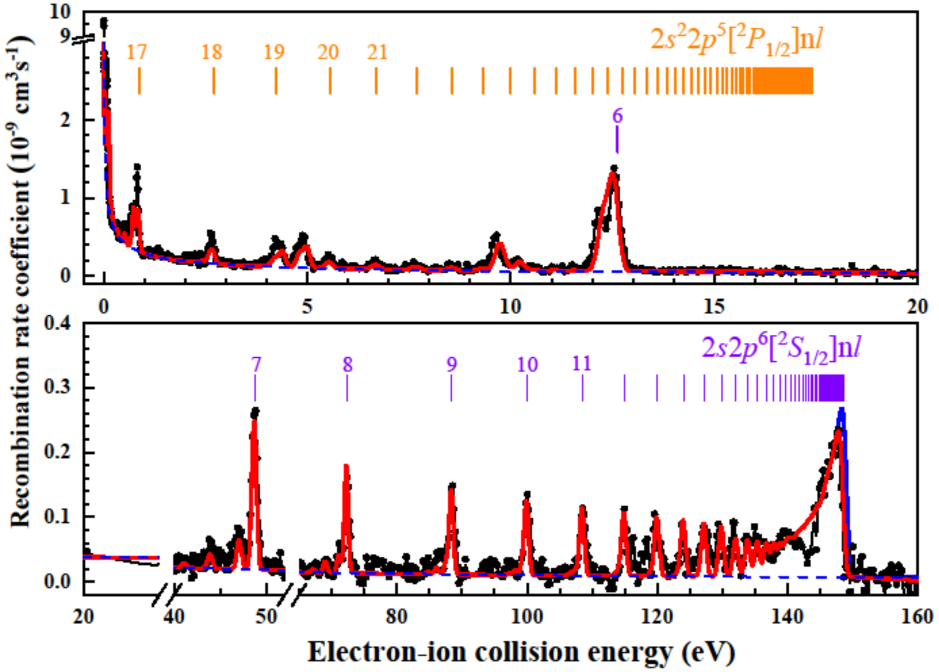
DR of F-like Ni^{19+} @CSRm

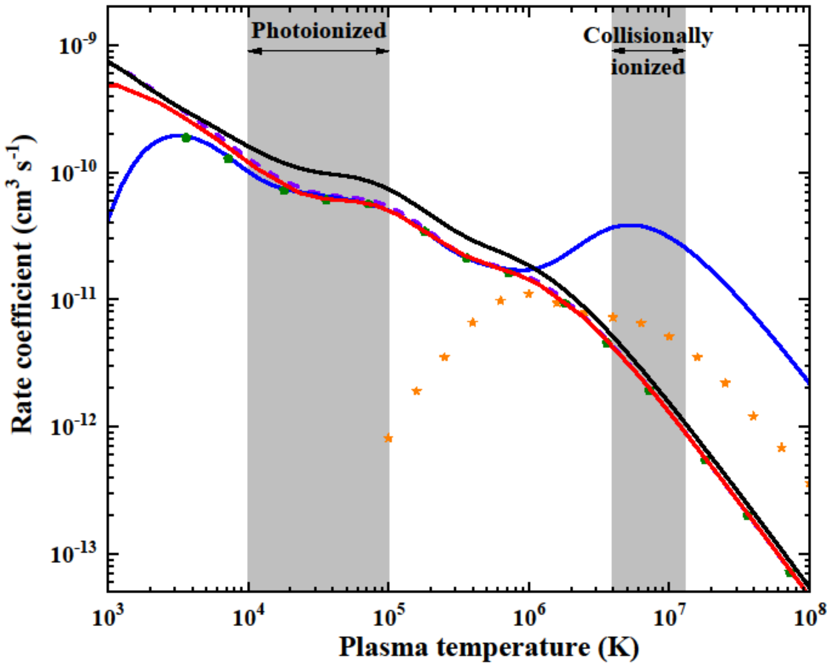
A&A 627, A171 (2019)
https://doi.org/10.1051/0004-6361/201935648

Astronomy & Astrophysics

Dielectronic recombination rate coefficients of fluorine-like nickel

Shu-Xing Wang[1,2], Zhong-Kui Huang[3], Wei-Qiang Wen[3], Chong-Yang Chen[4], Stefan Schippers[5], Xin Xu[1,2], Shahid Sardar[1,2], Nadir Khan[3], Han-Bing Wang[3], Li-Jun Dou[3], Sultan Mahmood[3,6], Dong-Mei Zhao[3], Xiao-Long Zhu[3], Li-Jun Mao[3], Xiao-Ming Ma[3], Jie Li[3], Mei-Tang Tang[3], Rui-Shi Mao[3], Da-Yu Yin[3], You-Jin Yuan[3], Jian-Cheng Yang[3], Ying-Long Shi[7], Chen-Zhong Dong[8], Xin-Wen Ma[3], and Lin-Fan Zhu[1,2]

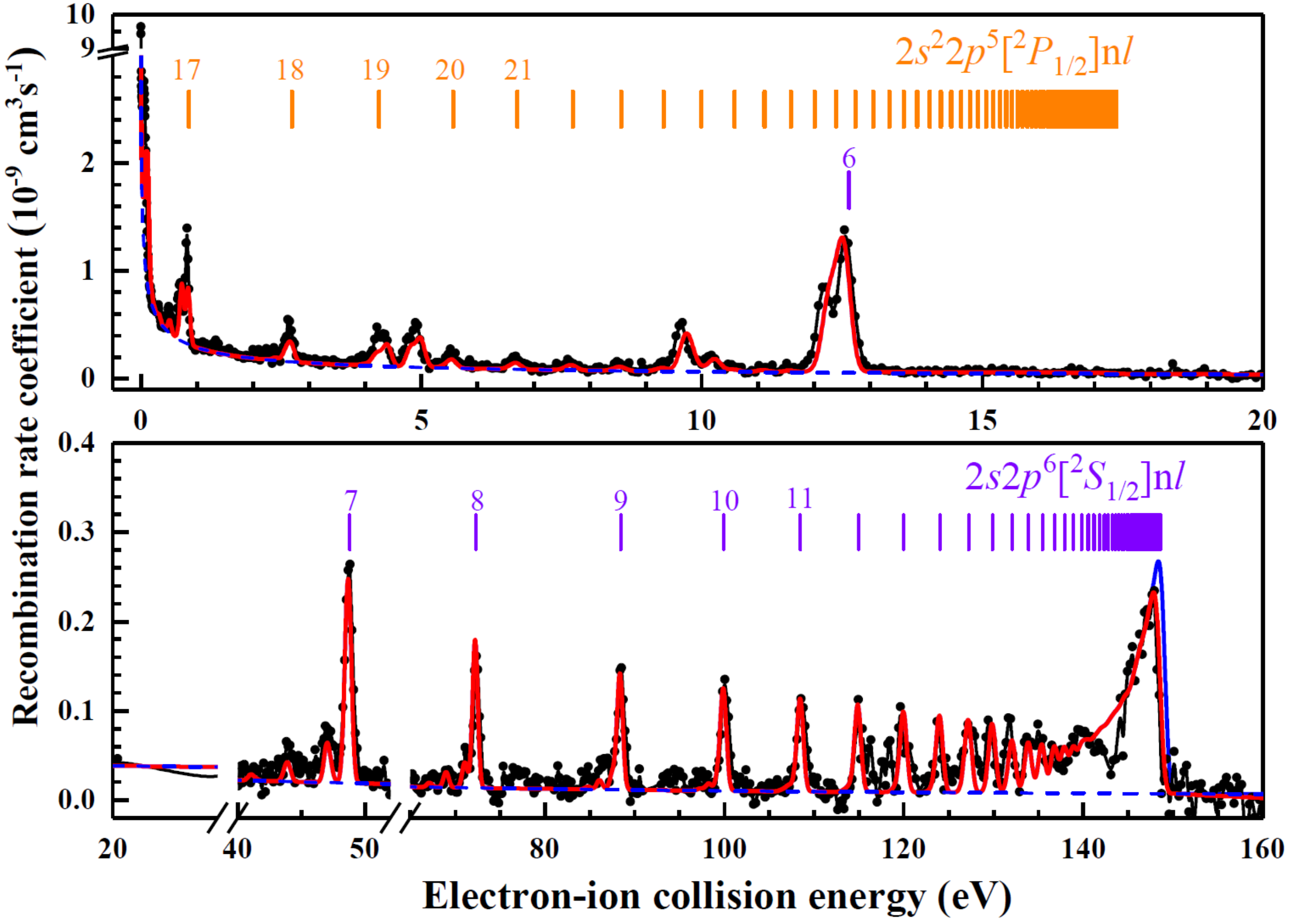




S.X. Wang et al., Astronomy & Astrophysics, 627, A171 (2019)

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

➢ 类氟Ni^{19+}离子的双电子复合精密谱

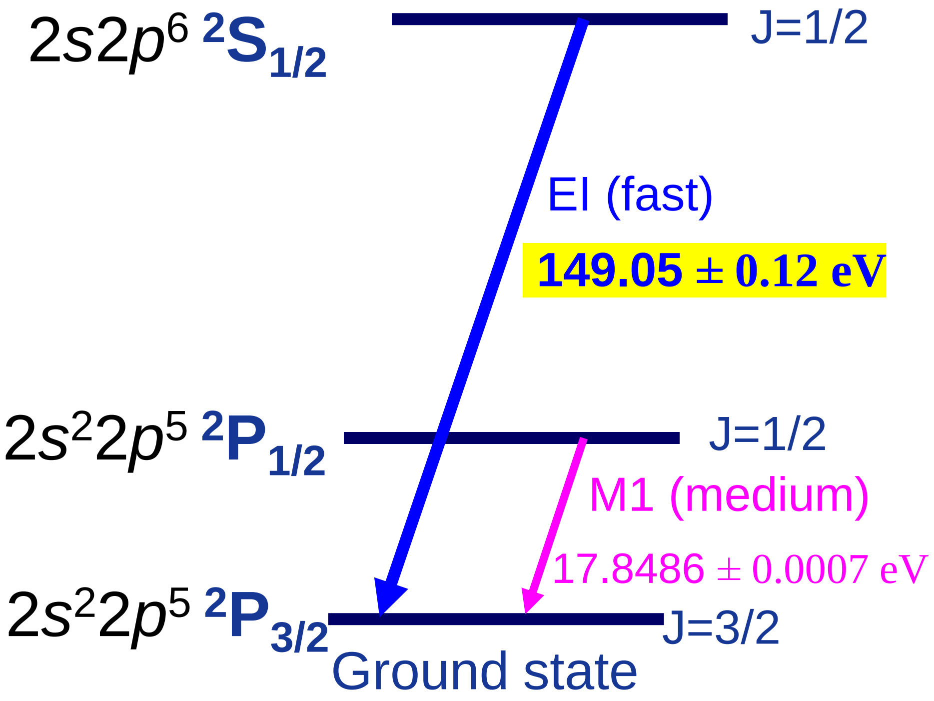


S.X. Wang et al., Astronomy & Astrophysics, 627, A171 (2019)

$$^{58}\mathrm{Ni}^{19+}(2s^2 2p^5[^2\mathrm{P}_{3/2}]) + e^-$$

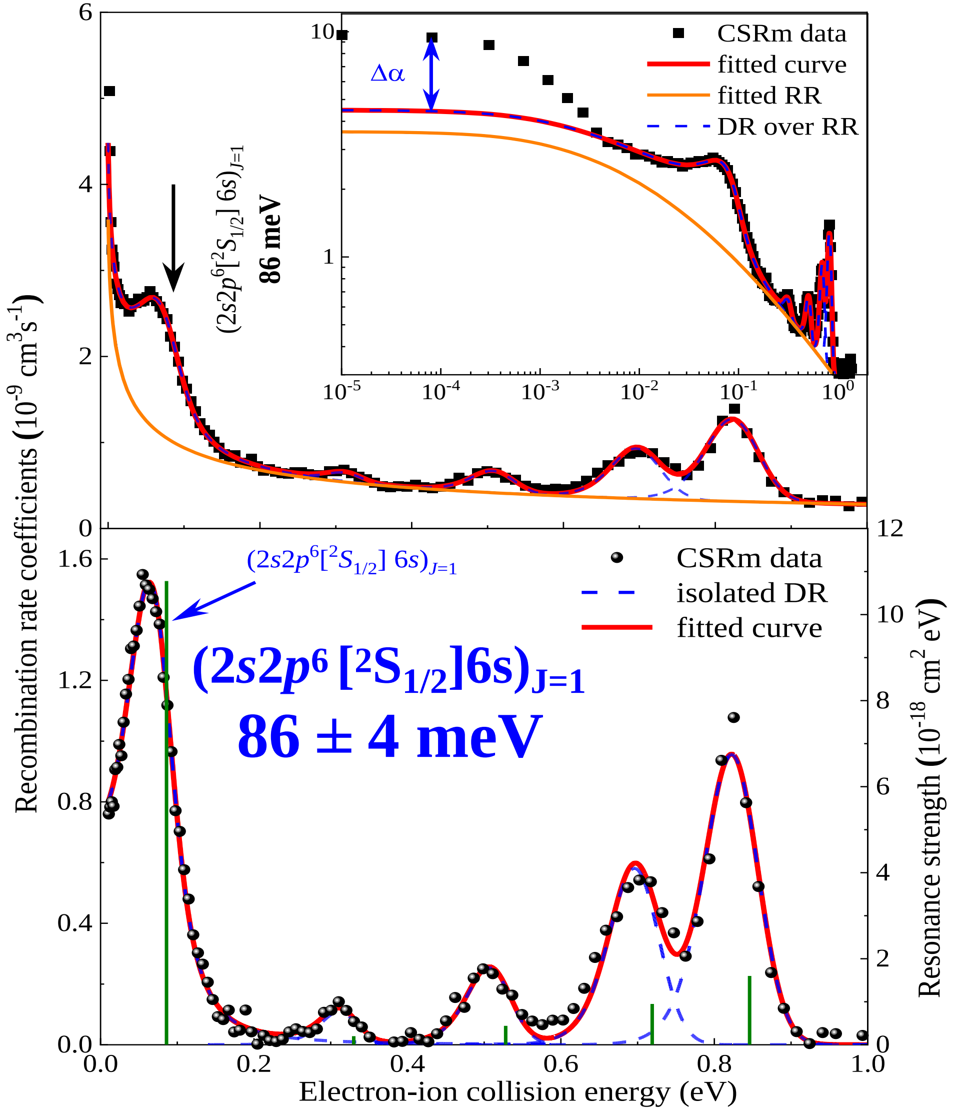
$$\rightarrow \begin{cases} ^{58}\mathrm{Ni}^{18+}(2s^2 2p^5[^2\mathrm{P}_{1/2}]nl)^{**} \\ ^{58}\mathrm{Ni}^{18+}(2s\ 2p^6[^2S_{1/2}]nl)^{**} \end{cases}$$

$$\rightarrow {}^{58}\mathrm{Ni}^{18+} + mh\nu$$



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

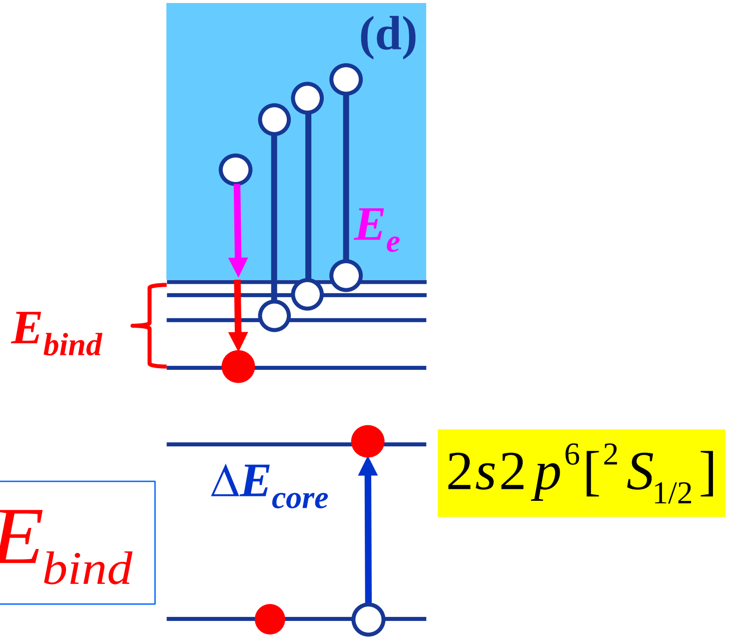
➢ Precison DR spectrum of Ni^{19+}



$$^{58}\mathrm{Ni}^{19+}(2s^2 2p^5[^2\mathrm{P}_{3/2}]) + e^-$$

$$\rightarrow \begin{cases} ^{58}\mathrm{Ni}^{18+}(2s^2 2p^5[^2\mathrm{P}_{1/2}]nl)^{**} \\ ^{58}\mathrm{Ni}^{18+}(2s\ 2p^6[^2S_{1/2}]nl)^{**} \end{cases}$$

$$\rightarrow {}^{58}\mathrm{Ni}^{18+} + mh\nu$$



$$\Delta E_{core} = \mathbf{E_e} + E_{bind}$$

S.X. Wang et al., ***PRA*** 106 (2022) 042808

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

$$\Delta E_{core} = \mathbf{E_e} + E_{bind}$$

1. **Multi-Configurational Dirac-Hartree-Fock (MCDHF) theoretical calculation**

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

AO	$E\ (2s^22p^5\ [^2P_{3/2}])$	$E\ (2s2p^6\ [^2S_{1/2}])$	$\Delta E(2s2p^6\ [^2S_{1/2}] \rightarrow 2s^22p^5\ [^2P_{3/2}])$
F-like Ni^{19+} (MR = $\{2s^22p^5, 2s2p^6, 2s^22p^43p, 2s2p^53p\}$)			
$\{3s, 3p, 3d\}$	−1292.5833877	−1287.0299079	151.118
$\{4s, 4p, 4d, 4f\}$	−1292.7902178	−1287.3083550	149.169
$\{5s, 5p, 5d, 5f, 5g\}$	−1292.8534402	−1287.3745748	149.088
$\{6s, 6p, 6d, 6f, 6g, 6h\}$	−1292.8806642	−1287.4035955	149.039
$\{7s, 7p, 7d, 7f, 7g, 7h, 7i\}$	−1292.9096358	−1287.4331842	149.022
$\{8s, 8p, 8d, 8f, 8g, 8h, 8i, 8k\}$	−1292.9238447	−1287.4474401	149.020
$\{9s, 9p, 9d, 9f, 9g, 9h, 9i, 9k\}$	−1292.9295149	−1287.4531798	149.019

ΔE_{core} = 149.019 ± 0.010 eV

AO		$E[(2s2p^6[^2S_{1/2}]6s)_{J=1}]$	$\Delta E[(2s2p^6[^2S_{1/2}]6s)_{J=1} \rightarrow 2s2p^6\ [^2S_{1/2}$
Ne-like Ni^{18+} (MR = $\{2s2p^65s, 2s2p^66s, 2s2p^67s\}$)			
$\{8s, 8p, 8d, 8f, 8g, 8h, 8i, 8k\}$		−1292.8391704	158.08
$\{9s, 9p, 9d, 9f, 9g, 9h, 9i, 9k\}$		−1292.8712688	151.37
$\{10s, 10p, 10d, 10f, 10g, 10h, 10i, 10k\}$		−1292.8918299	150.13
$\{11s, 11p, 11d, 11f, 11g, 11h, 11i, 10k\}$		−1292.9022762	149.63
$\{12s, 12p, 12d, 12f, 12g, 12h, 11i, 10k\}$		−1292.9085850	148.99
$\{13s, 13p, 13d, 13f, 13g, 12h, 11i, 10k\}$		−1292.9165405	148.82
$\{14s, 14p, 14d, 14f, 13g, 12h, 11i, 10k\}$		−1292.9277362	148.97

E_{bind} = 148.946 ± 0.020 eV

S.X. Wang et al., ***PRA*** 106 (2022) 042808

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

$$\Delta E_{core} = \mathbf{E_e} + E_{bind}$$

2. ***ab initio*** theoretical calcuation

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

TABLE V. Individual contributions to the transition $2s^2 2p^5\ {}^2P_{3/2} \rightarrow 2s\,2p^6\ {}^2S_{1/2}$ energy in fluorine-like nickel ion (in eV).

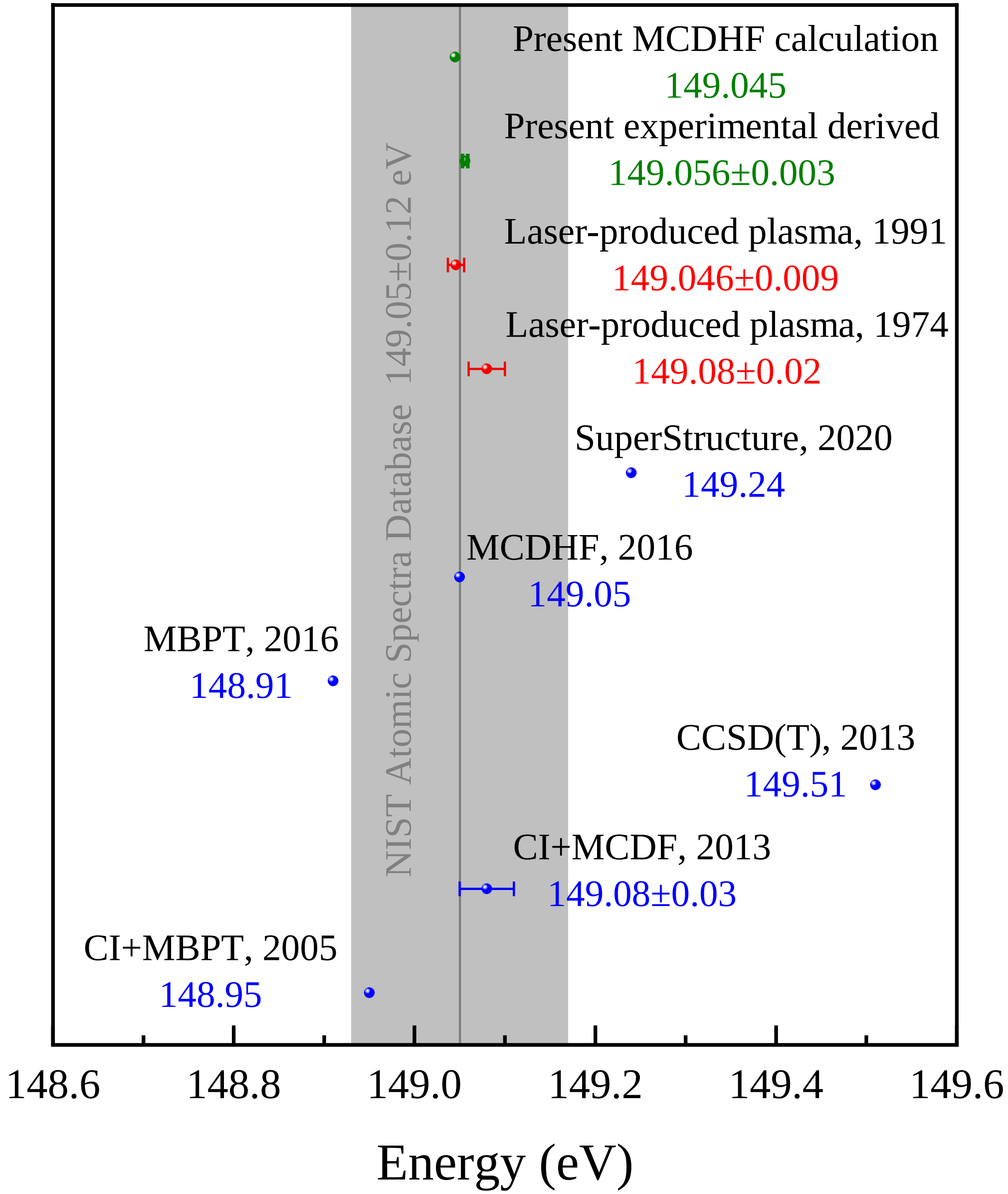
Contribution	Core-Hartree	Kohn-Sham
Dirac	123.911	128.743
Correlation (1)	27.190	22.723
Correlation (2)	−1.536	−1.972
Correlation (3)	0.032(2)	0.102(2)
QED (1)	−0.506	−0.510
QED (2)	−0.033(6)	−0.028(6)
Recoil	−0.012(3)	−0.012(3)
Total	149.046(7)	149.046(7)

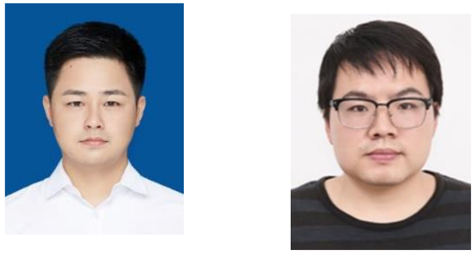
$$\Delta E_{core} = \mathbf{E_e} + E_{bind}$$

149.046 ± 0.007 eV **148.946 ± 0.006 eV**

S.X. Wang et al., ***PRA*** 106 (2022) 042808

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





Shuxing Wang, Zhongkui Huang

& DR team: **Experiment**

Chunyu Zhang, Chongyang Chen

FAC theory

Andrey Volotka, Yury Kozhedub

ab initia theory

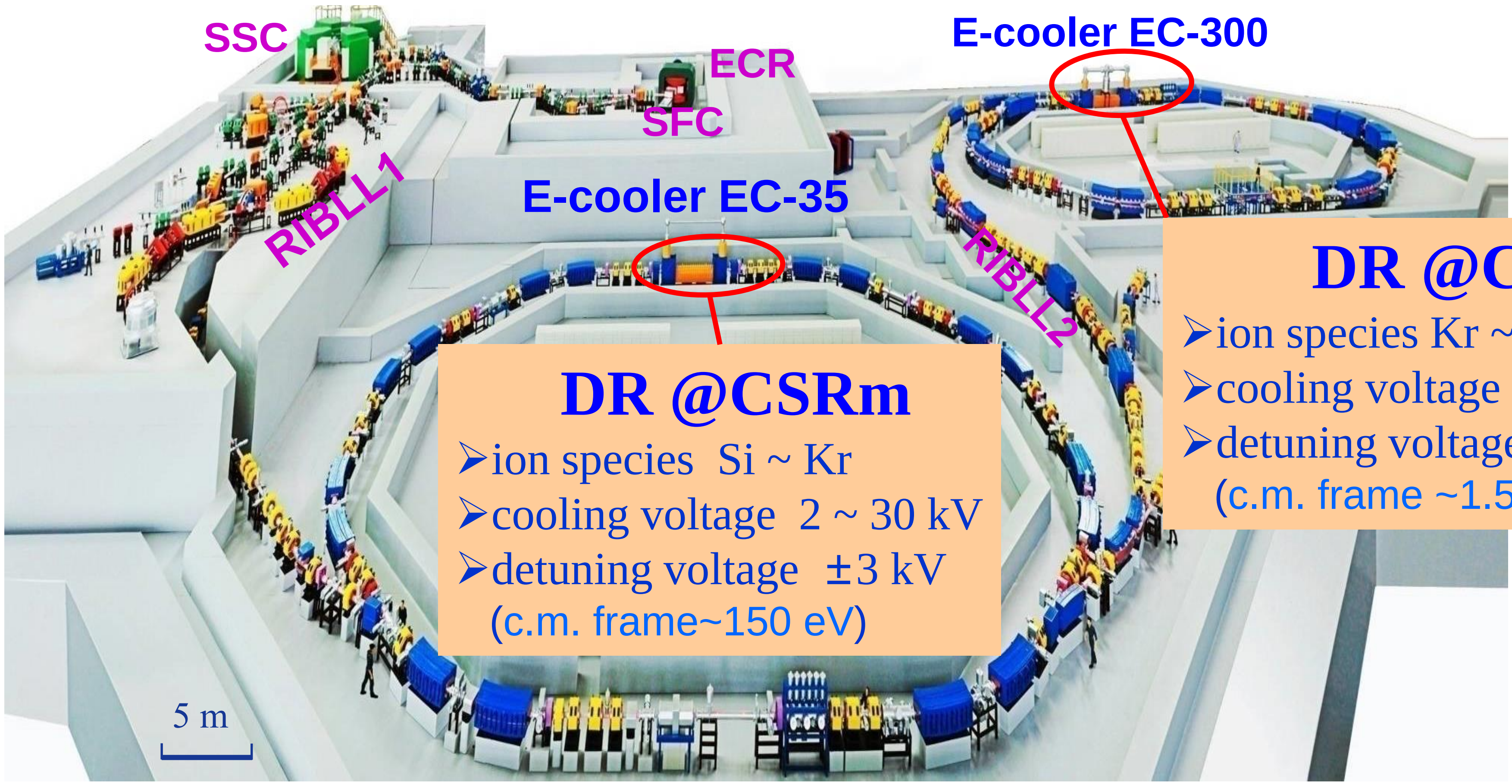
Kai Wang, Zhongwen Wu

MCDHF theory

Precision DR spectroscopy of HCI @CSR

- We will carry out more precision DR experiments with HCIs
- We need more precision calculations.

Heavy Ion Research Facility in Lanzhou

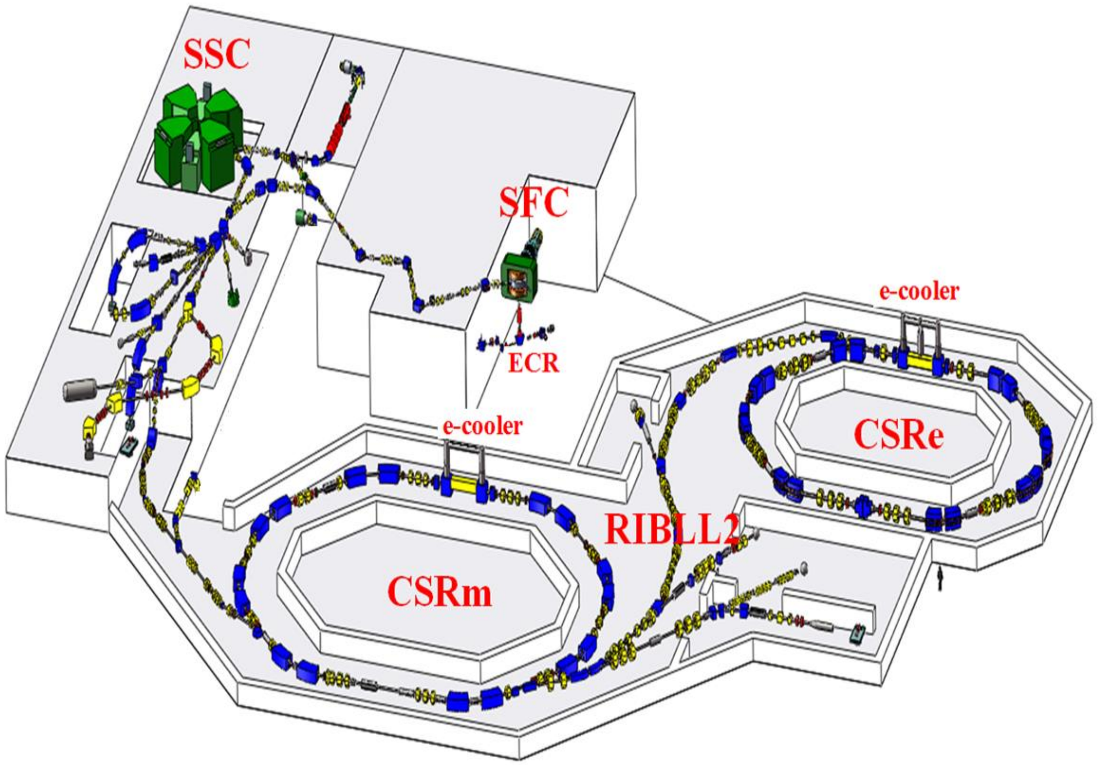


DR @CSRm
- ion species Si ~ Kr
- cooling voltage 2 ~ 30 kV
- detuning voltage ±3 kV
  (c.m. frame~150 eV)

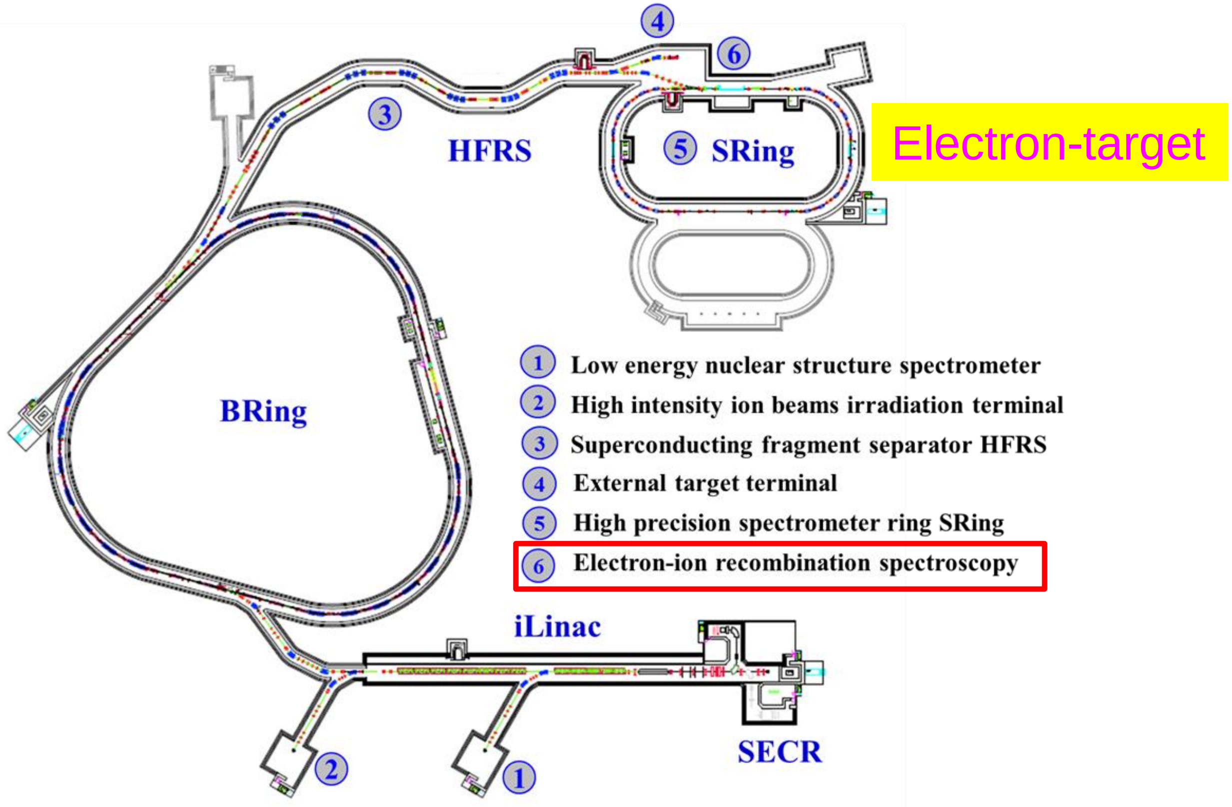
DR @CSRe
- ion species Kr ~ U
- cooling voltage 10~300 kV
- detuning voltage ±15 kV
  (c.m. frame ~1.5 keV)

Future DR experiments: from CSR to HIAF

HIRFL-CSR
Heavy Ion Research Facility in Lanzhou



HIAF
（High Intensity heavy ion Accelerator Facility）



Heavier ions, Higher charge state, higher precision →

X. Ma et al. *NIMB* 408 (2017) 169–173

Summary and outlook

- The absolute DR rate coefficients of 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 3*s* → 3*p* and 3*s* → 3*d* 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 Ni^{19+}: test high-order QED effect with HCI.
- We will perform more DR experiments to investigate on astrophysics & precision spectroscopy at storage rings: CSRm → CSRe → HIAF

DR Collaboration @CSR

IMPCAS, Lanzhou	X. Ma, W.Q. Wen, Z.K. Huang, H.B. Wang, H.K. Huang, L. Shao, X. Liu, D.Y. Chen, X.P. Zhou, D.M. Zhao, L.J. Mao, J. Li, T.M. Tang, Y.B. Zhou, K.M. Yan, D.Y. Yin, Y.J. Yuan, J.C. Yang;
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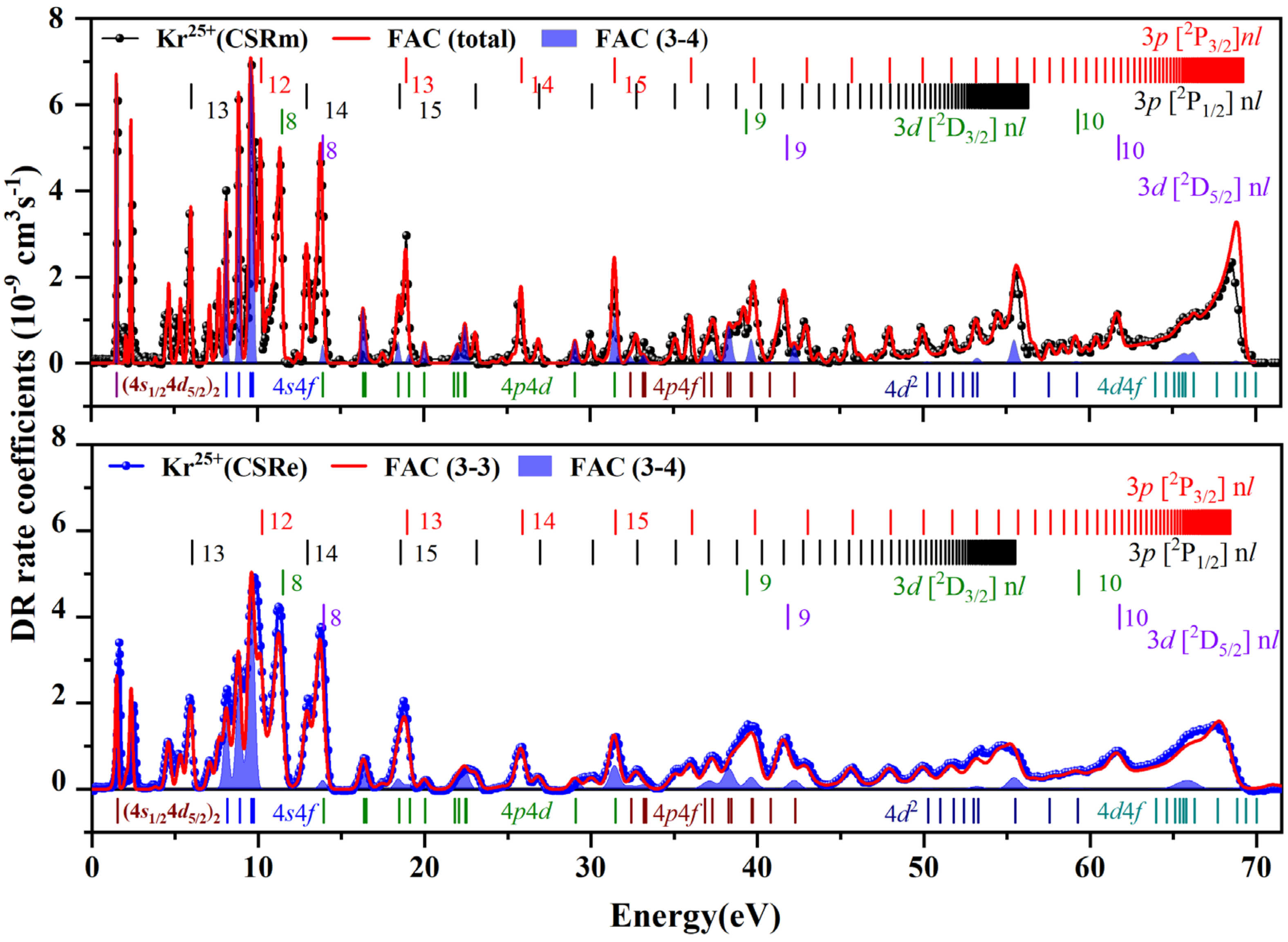
Thank you
for your attention!

Precision spectroscopy of HCI @CSRe



- **First DR rate experiment of Na-like Kr^{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