Precision measurements on dielectronic recombination rate coefficients and state-resolved cross sections relevant to fusion plasmas

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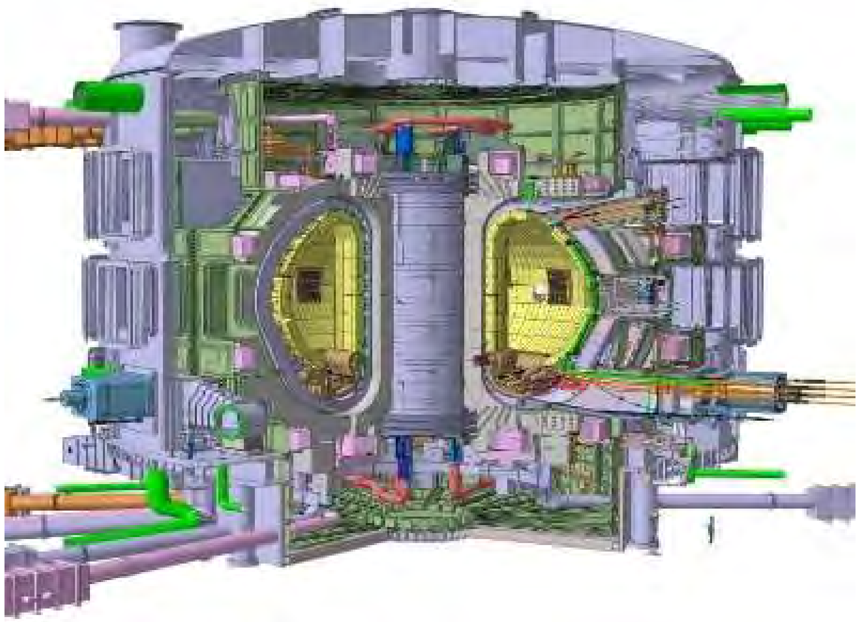
- Motivation and background
- Experimental setup
  1. DR spectroscopy and typical results
  2. Charge exchange and typical results
- Work plan
- Summary

Motivation and Background

Next generation fusion devices like ITER and DEMO aims to demonstrate their economic feasibility.

However, it is known that the plasma transient events, such as the plasma disruption or continuous burst from the edge plasma regions, may cause overload to plasma facing components (PFCs) and result in their deterioration such as unwanted sputtering, erosion and melting.

Thus, these events will finally lead to the unexpected interruption of the operation of a fusion reactor.



Motivation and Background

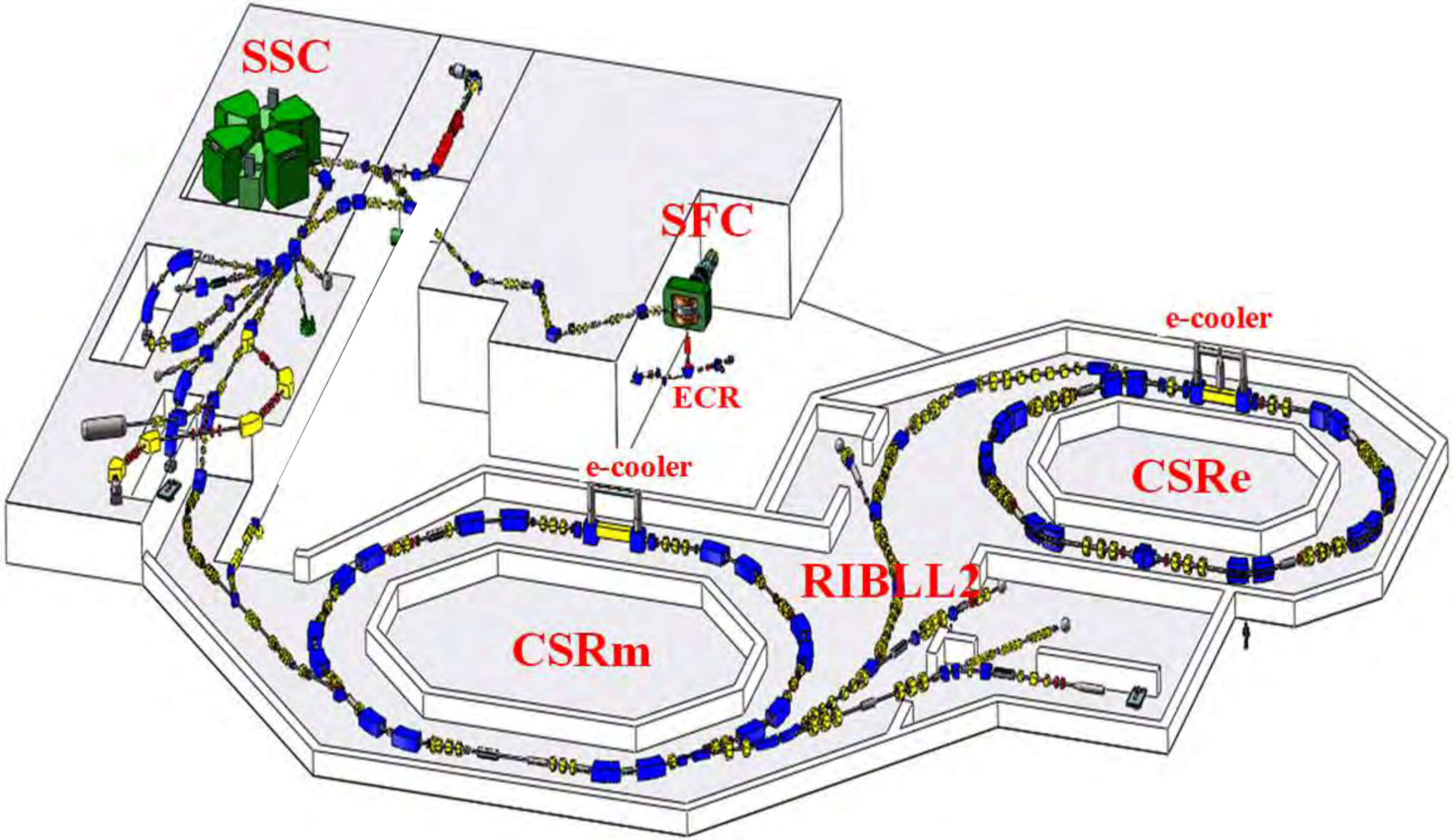
The proposed approaches to these challenging problems are radiative cooling by impurity seeding, namely, to inject low- or medium-Z impurities into the fusion plasma, converting part of the incoming plasma power into radiation, which is less destructive to the PFC materials.

Reliable data relevant to fusion plasmas are crucial for fusion plasma models to predict and asses the viability of different approaches to impurity injection to avoid the damage of PFC and to interpret empirical results obtained from existing experimental fusion devices.

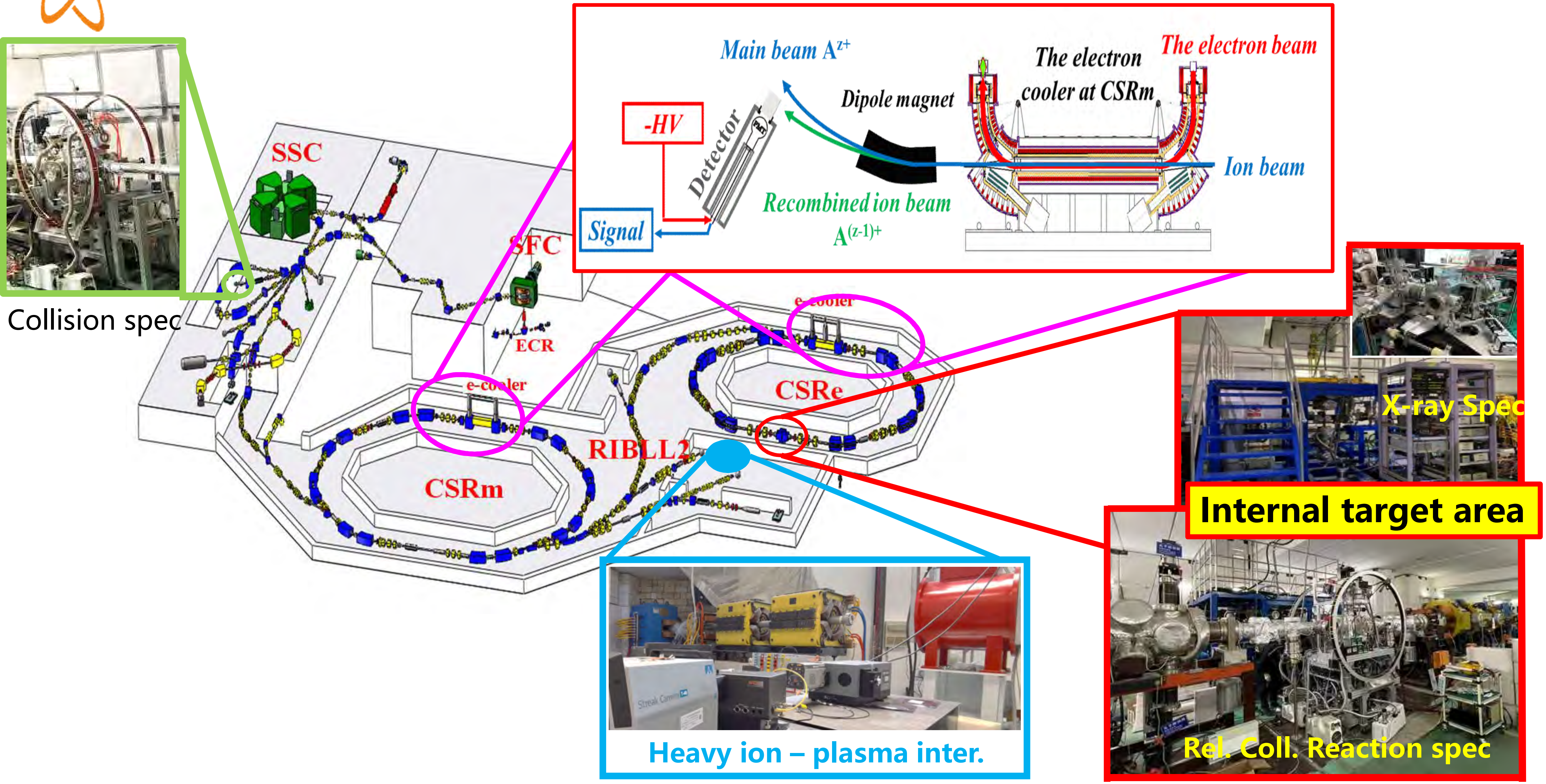
The currently recommended injected impurity species are Nitrogen (Neon) for use in ITER and Argon for DEMO as a better option, respectively. other impurities have potential benefits and better data on a variety of impurities is required to optimize plasma operation.

Within the current CRP, we will focus on experiments employing accelerator based setups and provide precise and reliable experimental data for related processes on the impurity species that are required to optimize plasma operation.

Heavy Ion Research Facility in Lanzhou (HIRFL)

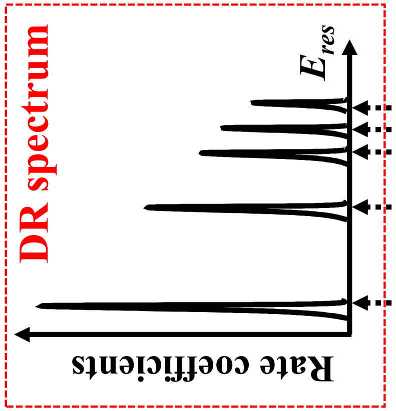


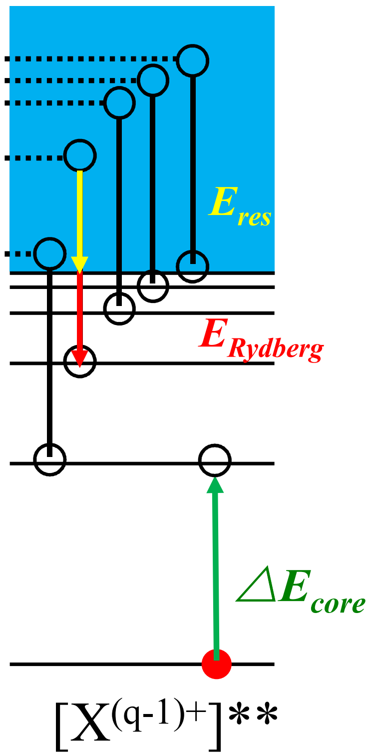
Experimental arrangements @HIRFL



(1) Electron – ion collision Spectroscopy

Dielectronic Recombination (DR) spectroscopy





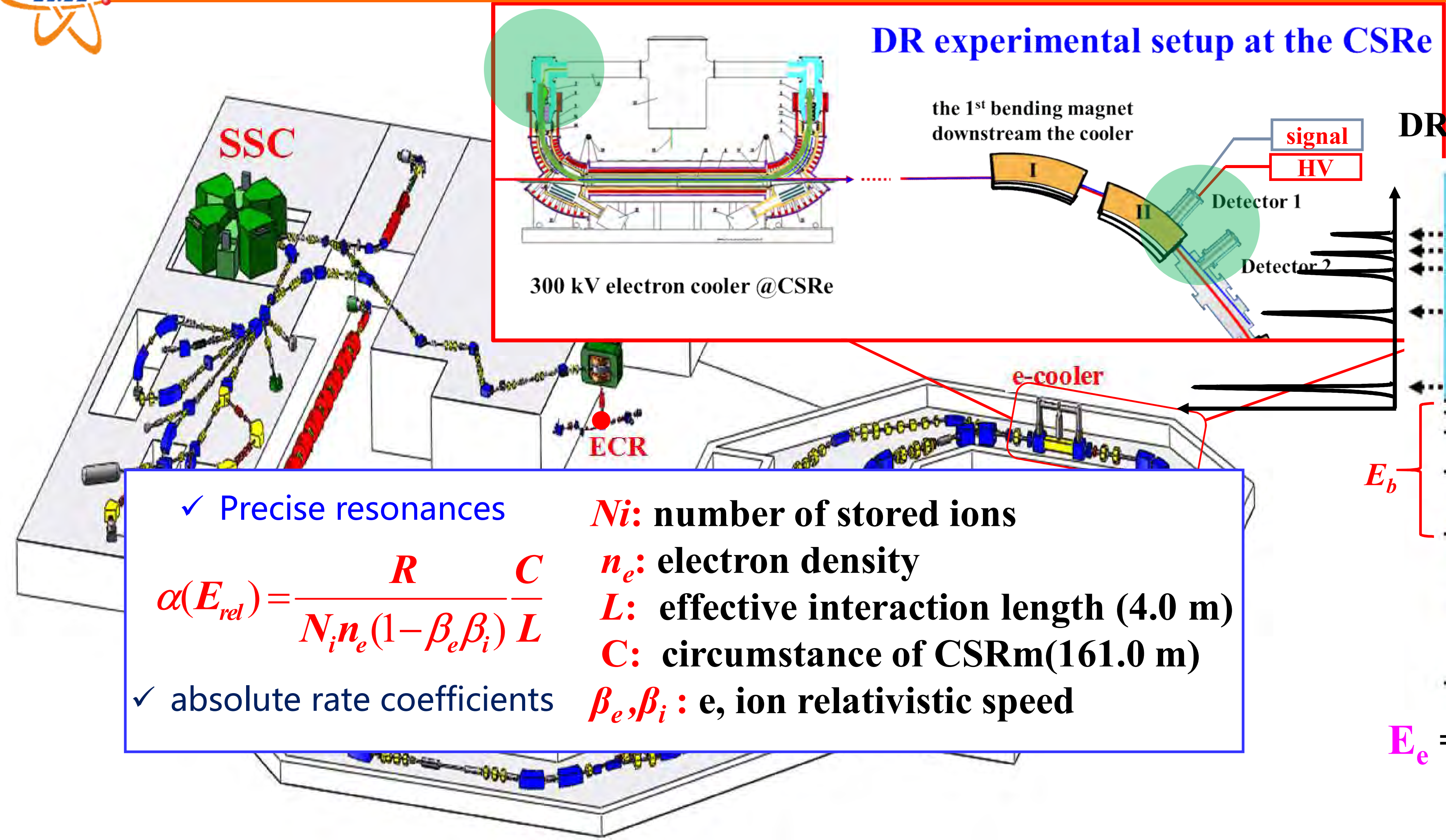
$$E_{res} = \Delta E_{core} + E_{Rydberg}$$

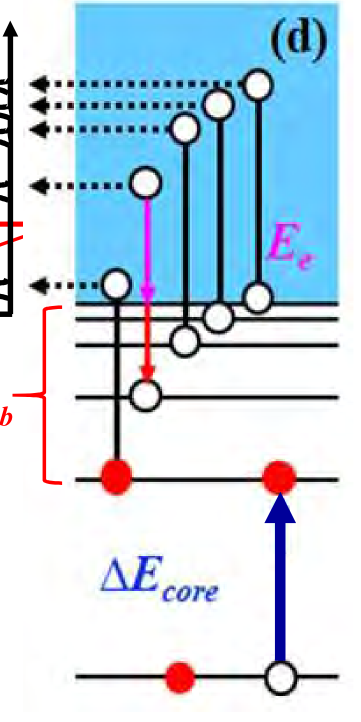
$$E_{n\_Rydberg} = -R\left(\frac{q}{n-\delta}\right)^2$$

δ quantum defect, R=13.6 eV

$$\Delta E_{core} + E_{Rydberg} > 0$$

(1) DR spectroscopy at cooling storage ring





$E_e = \Delta E_{core} - E_b$

- ✓ Precise resonances

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

- ✓ absolute rate coefficients

Ni: number of stored ions

n_e: electron density

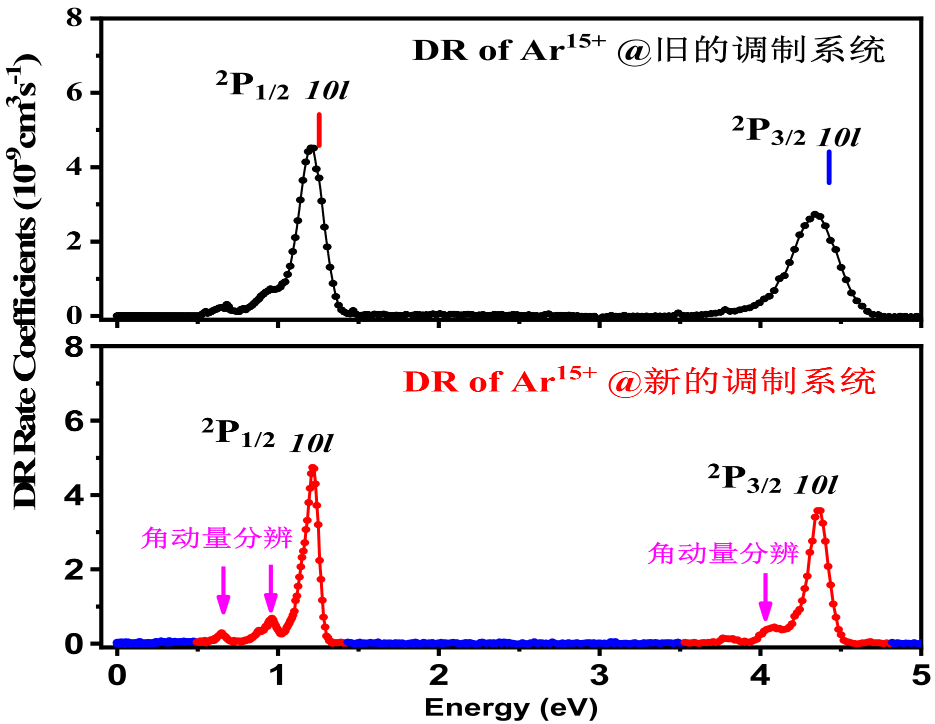
L: effective interaction length (4.0 m)

C: circumstance of CSRm(161.0 m)

β_e, β_i : e, ion relativistic speed

(1) Electron – ion collision Spectroscopy

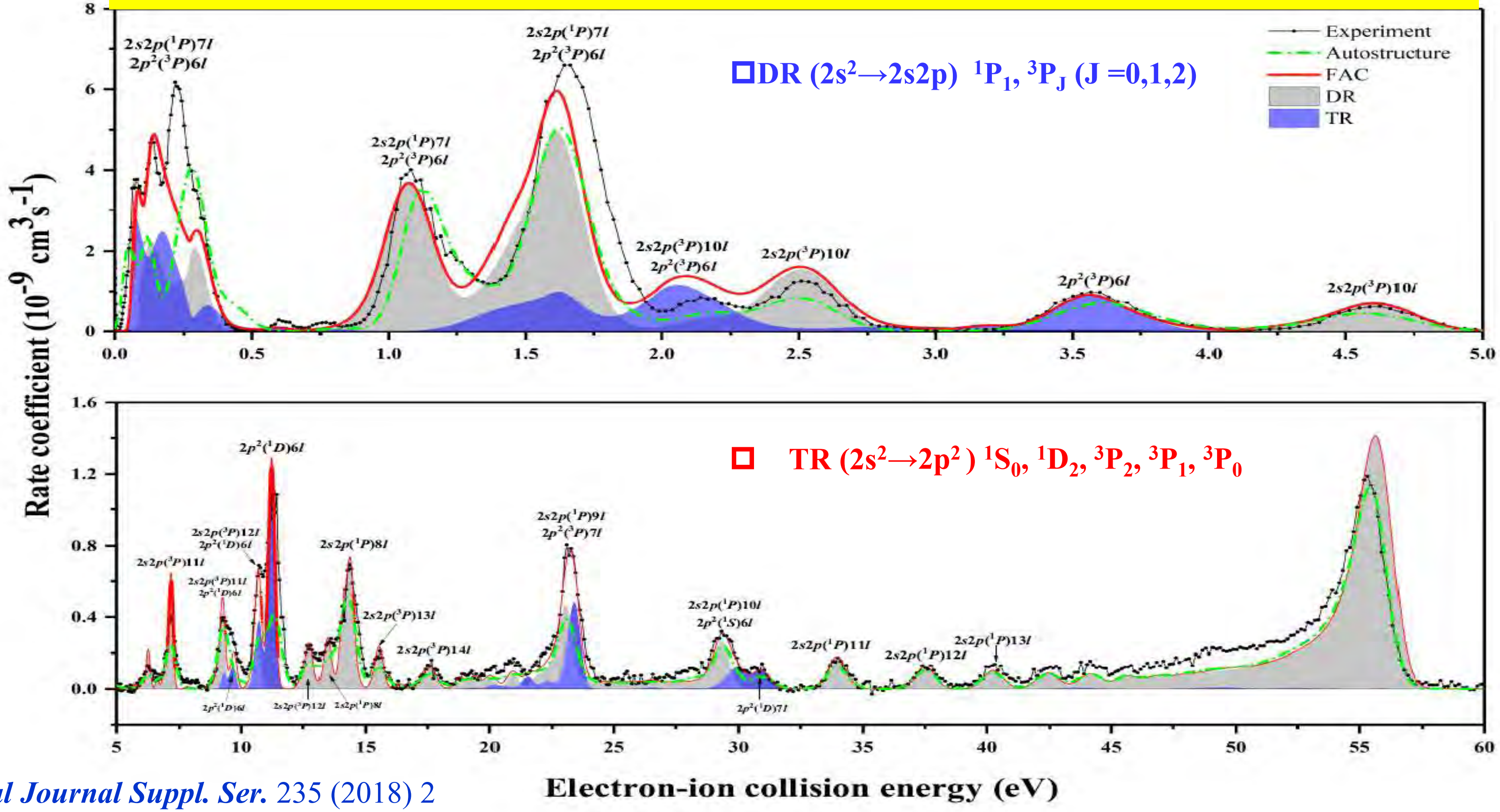
- The DR spectroscopy updated with a new energy detuning system, test run using Li-like argon ion (Ar^{15+});
- The energy precision is better than 10 meV in low energy range (below 10 eV);



DR spectroscopy of Be-like ions

DR spectrum of Be-like Ar^{14+} (Dielectronic & Trielectronic)

strong e-e correlation, strong CI interaction, mixing of configurations with different *n*, interference between DR and TR. Good Agreement!

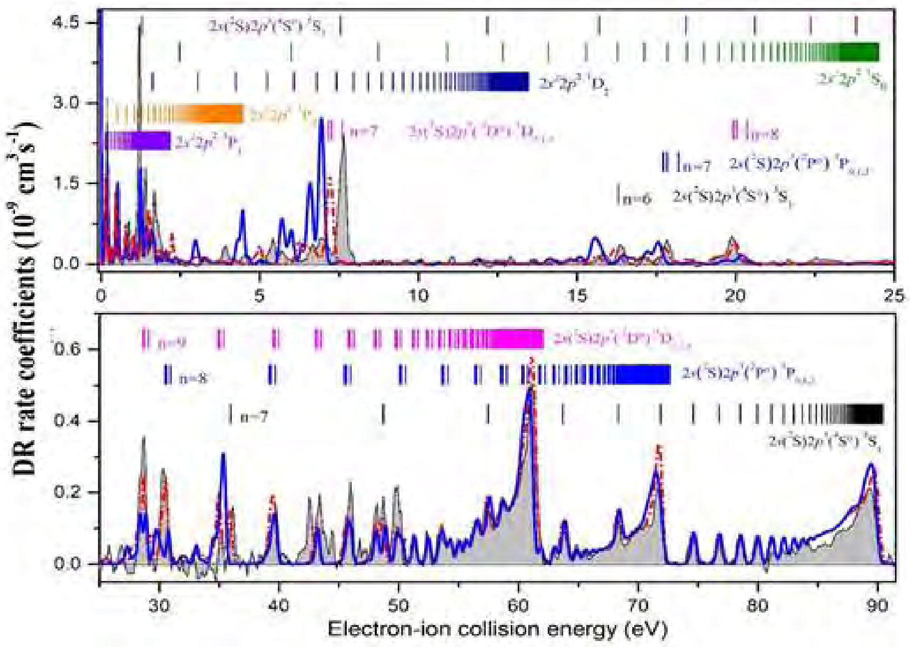


The Astrophysical Journal Suppl. Ser. 235 (2018) 2

(1) Electron – ion collision Spectroscopy

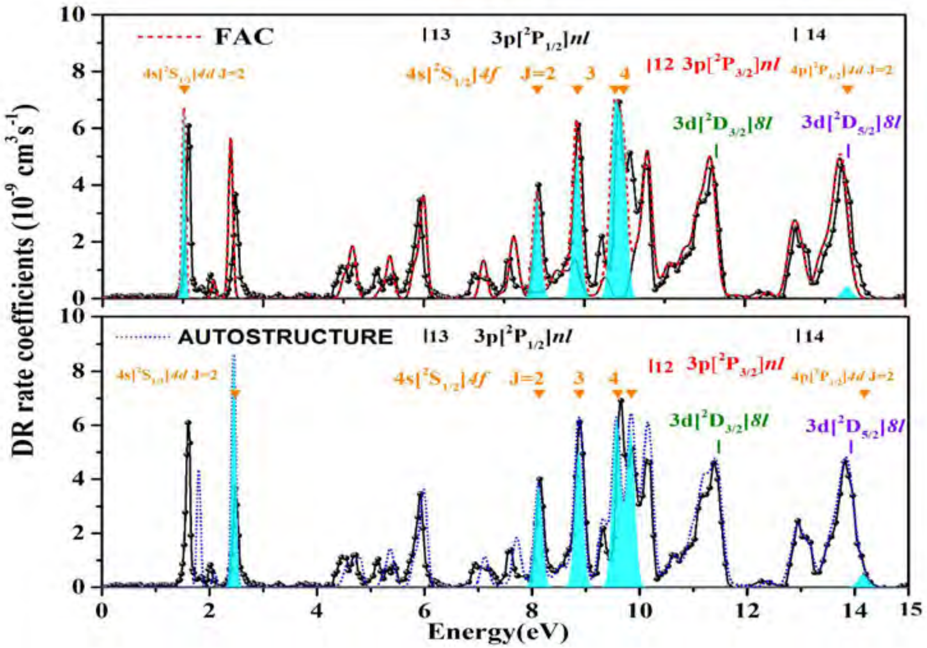
The absolute DR rate coefficients measurements of highly charged ions

DR rate coefficients of C-like Ca^{14+} ions



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

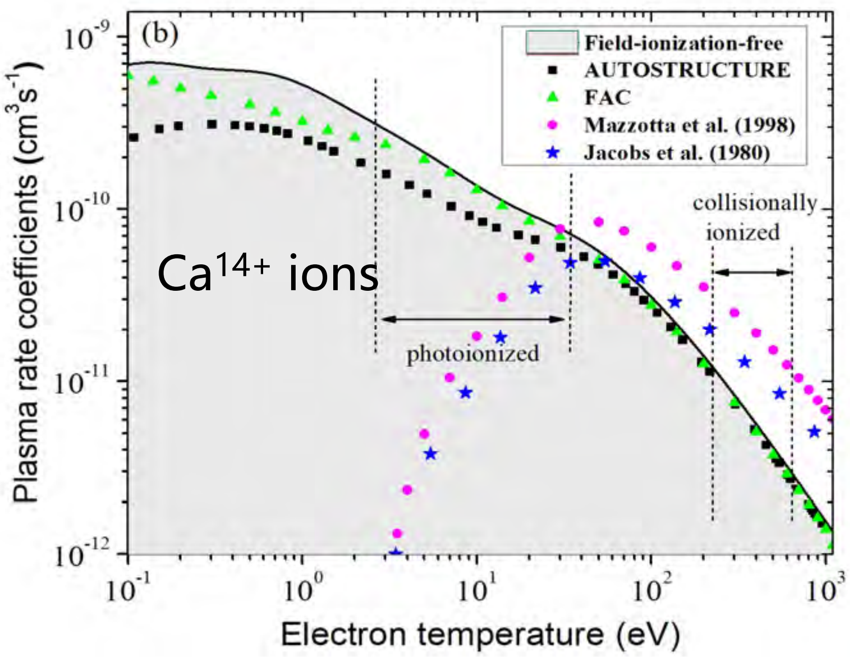
DR rate coefficients of Na-like Kr^{25+} ions

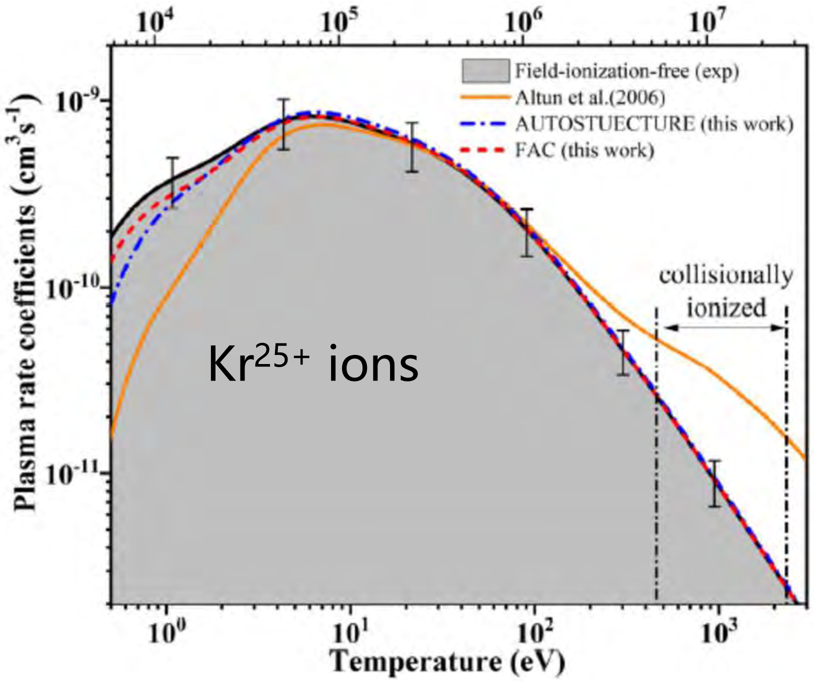


Z.K. Huang *et al., Physical Review A* 102, 062823 (2020)

(1) Electron – ion collision Spectroscopy

Plasma rate coefficients obtained from the measured absolute DR rate coefficients, comparison with theoretical values in the range of of photoionized and collisionally ionized plasmas, testing different theoretical mdels, benchmark data for astrophysics modeling.



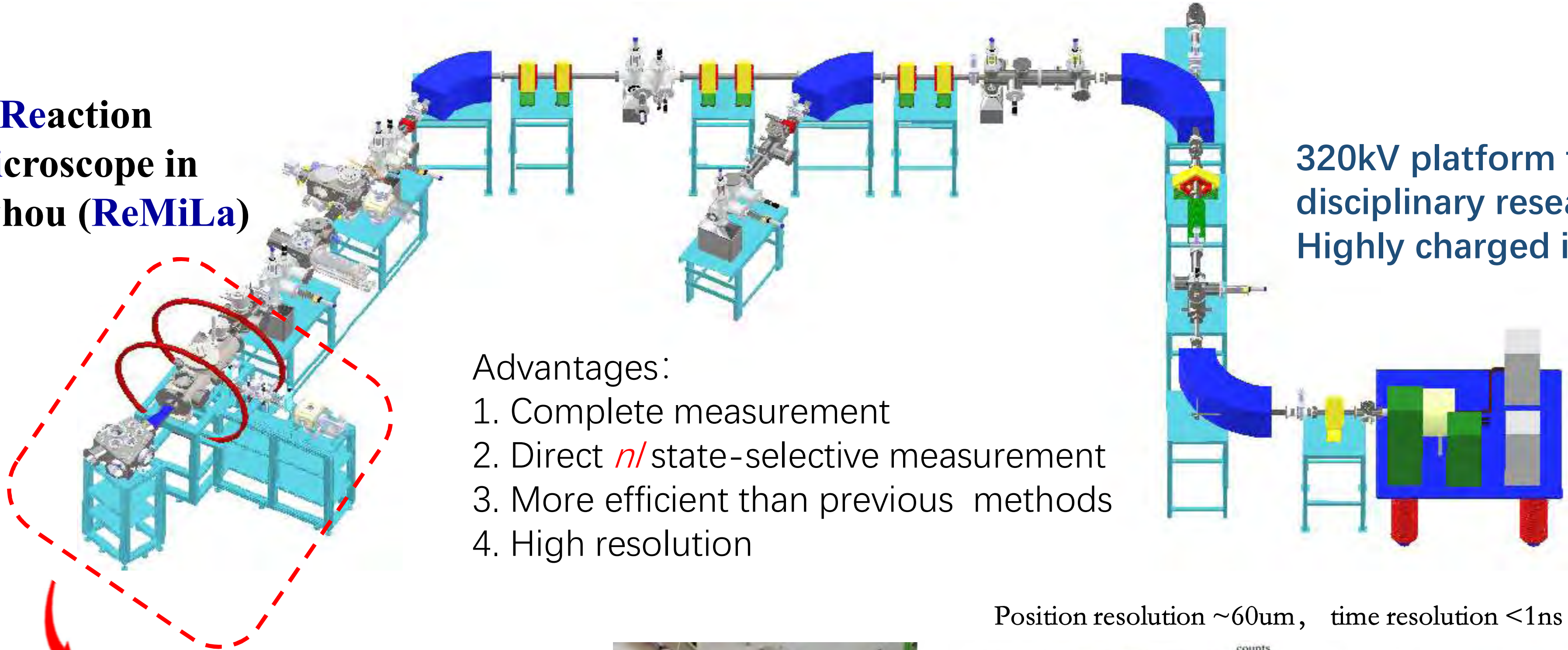


W.Q. Wen *et al., The Astrophysical Journal* 905(2020)36

Z.K. Huang *et al., Physical Review A* 102, 062823 (2020)

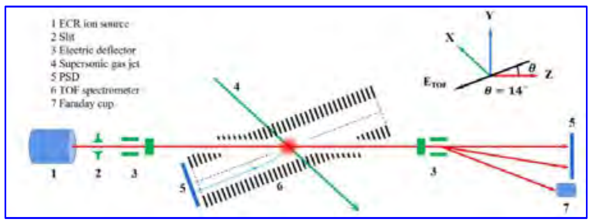
(2) Experimental setup for charge exchange process

Reaction Microscope in Lanzhou (ReMiLa)

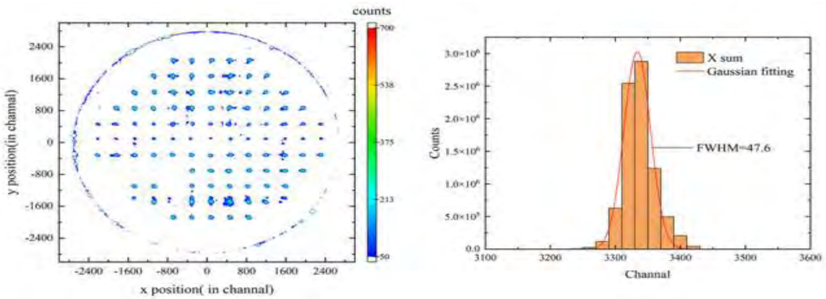


320kV platform for multi-disciplinary research with Highly charged ions

Advantages：
1. Complete measurement
2. Direct *nl* state-selective measurement
3. More efficient than previous methods
4. High resolution



Position resolution ~60um， time resolution <1ns



(2) Charge exchange and following radiative decays

4 keV/u Ne^{8+} + He, @ X-ray spectrum

When the resolution is low/poor, only principal quantum number can be resolved

Using angular momentum *l*-distribution model to produce cascade decay radiation

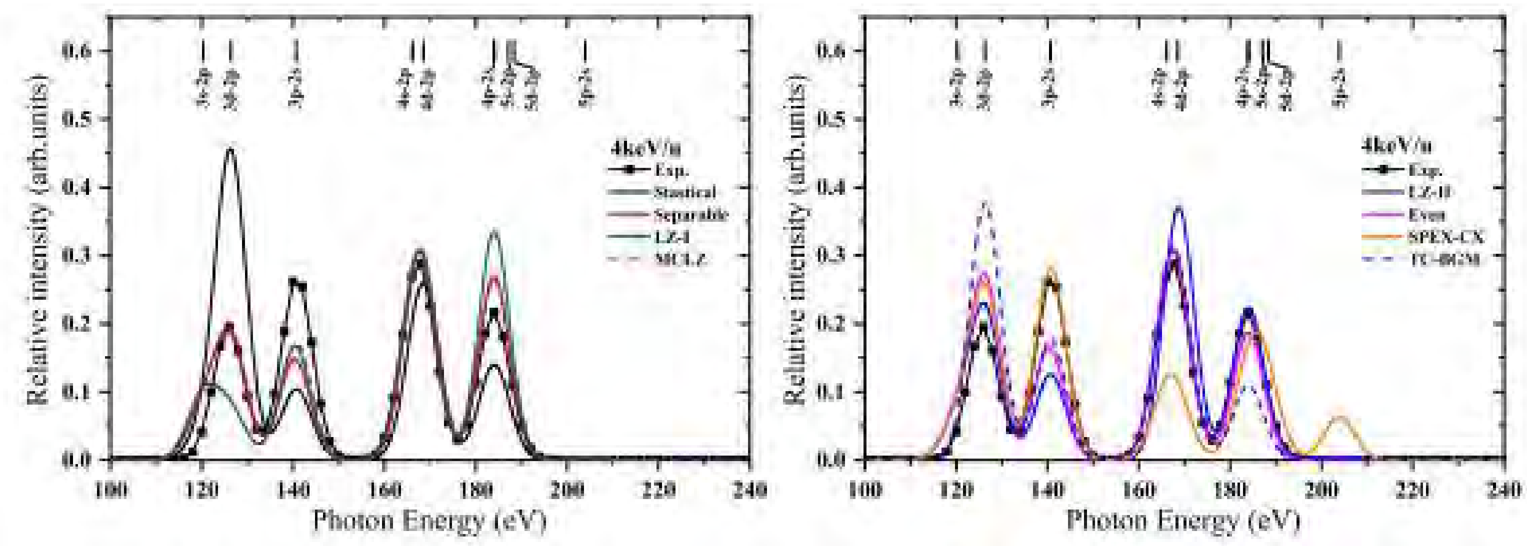
$$W_{nl}^{\mathrm{Stat}} = \frac{2l+1}{n^2}$$

$$W_{nl}^{\mathrm{Low}} = \frac{(2l+1)[(n-1)!]^2}{(n+l)!(n-1-l)!}$$

$$W_{nl}^{\mathrm{Sep}} = \frac{2l+1}{q}\exp[\frac{-l(l+1)}{q}]$$

$$W_{nl}^{\mathrm{LZ}} = \frac{l(l+1)(2l+1)(n-1)!(n-2)!}{(n+l)!(n-1-l)!}$$

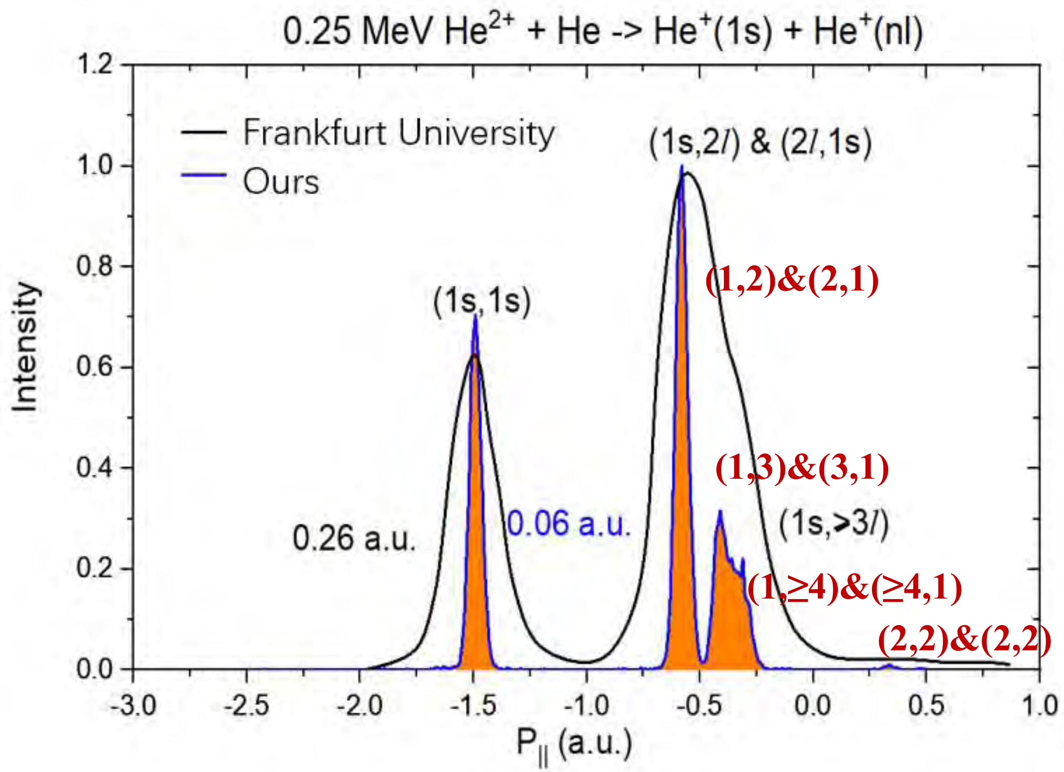
$$W_{nl}^{\mathrm{SL1}} = W_{l'}^{\mathrm{Low}}, \quad l' = l-1$$



J. W. Xu, C. X. Xu, R. T. Zhang# et al., ApJS 2021

(2) Experimental setup for charge exchange process

Improvement of recoil momentum resolution @ resolving power of *nl* state



Experiments perform using the upgrated setup: $C^{(4-5)+}$, $N^{(3-5)+}$, $O^{(5-6)+}$, $Ne^{(8-10)+}$

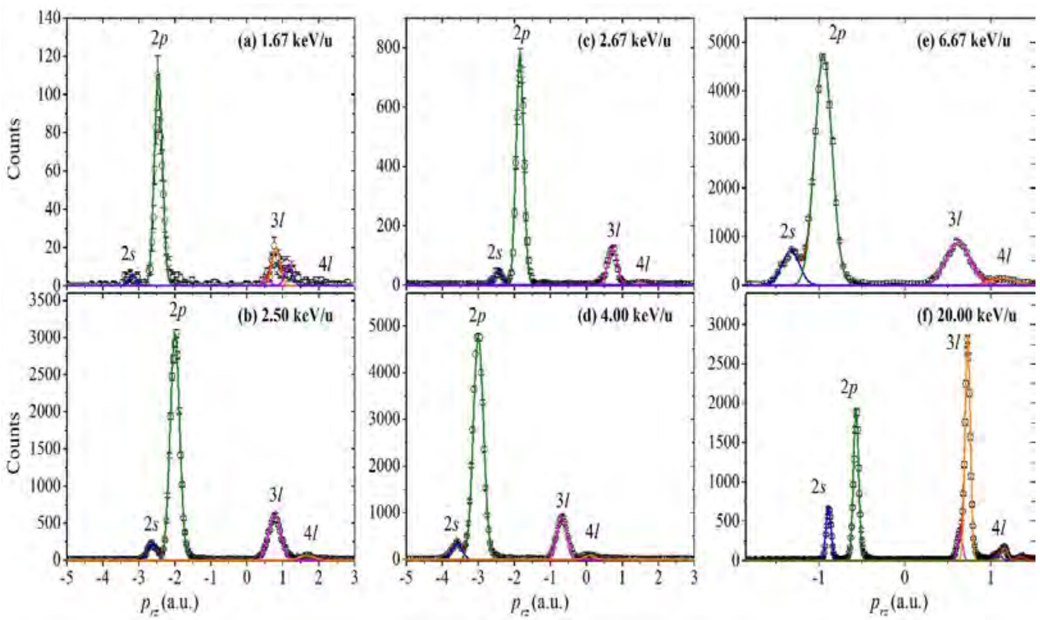
Collision energy range: (15 – 320)q keV. Gas target: H_2, He

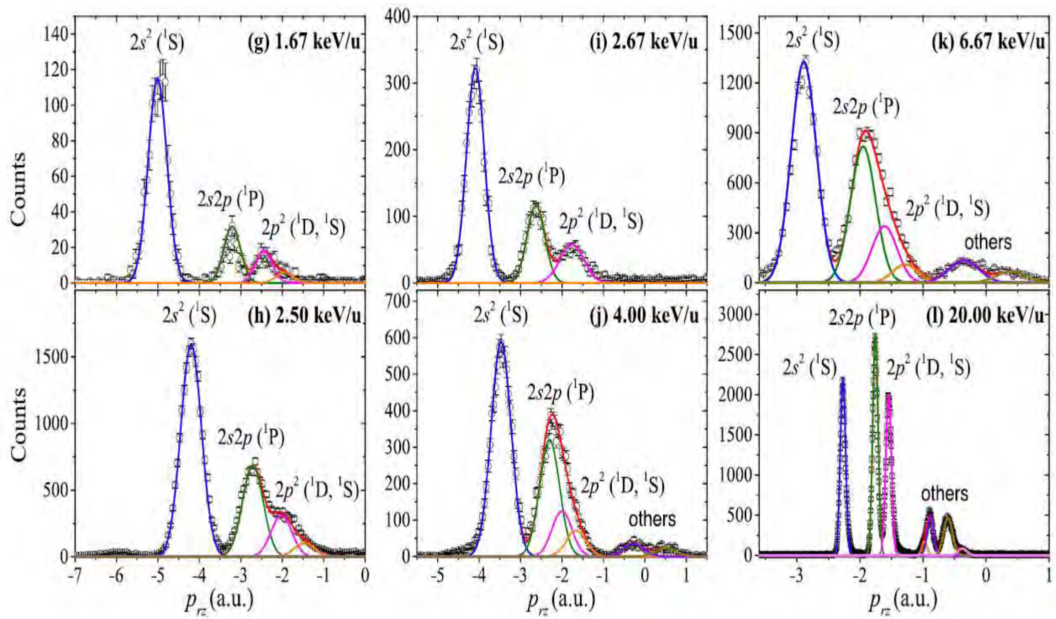
(2) Benchmark measurements of charge exchange cross sections

nℓ-resolved Cross Sections of Single and Double Charge Exchange Processes

SC $C^{4+}(1s^2) + He \rightarrow C^{3+}(1s^2 nl) + He^{+}(1s)$

DC $C^{4+}(1s^2) + He \rightarrow C^{2+}(1s^2 nln'l') + He^{2+}$





D. L. Guo *et al.*, ***The Astrophysical Journal,*** 941, 31 (2022)

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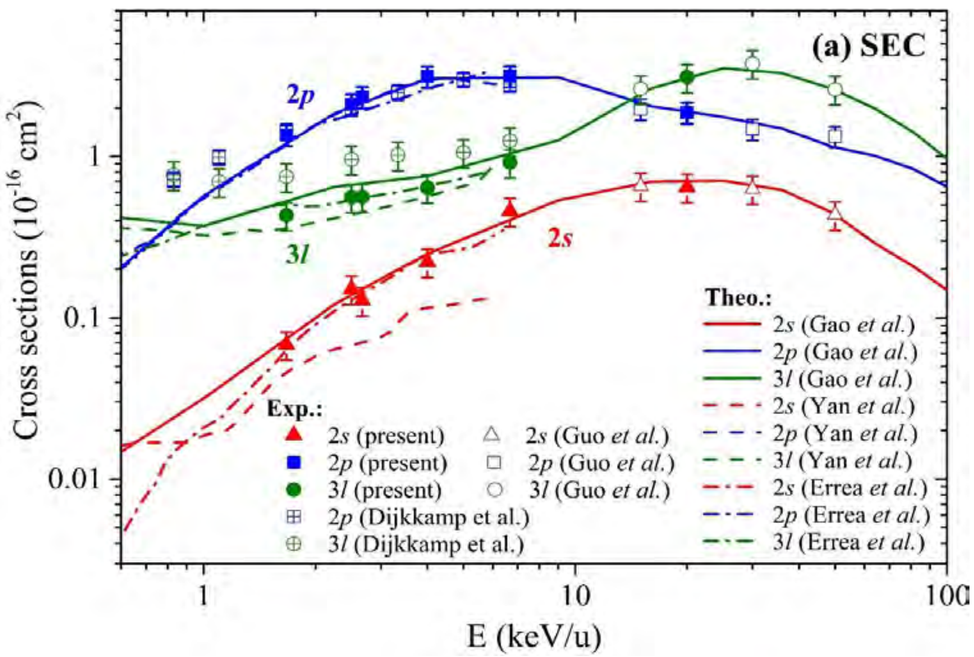
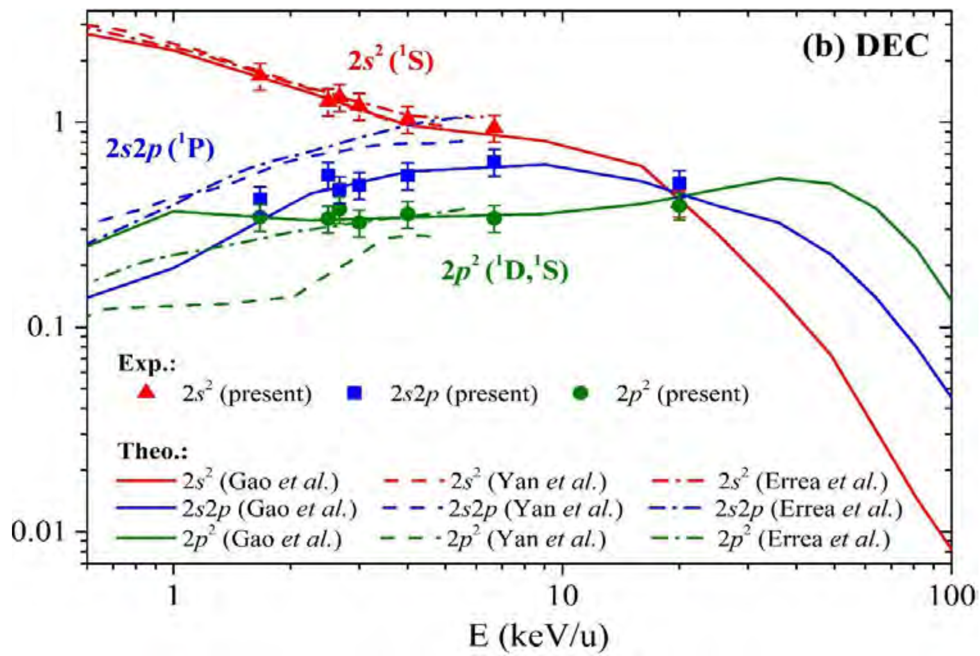




D. L. Guo *et al.*, ***The Astrophysical Journal,*** 941, 31 (2022)

(2) Benchmark measurements of charge exchange cross sections

nℓ-resolved Charge Exchange Cross Sections

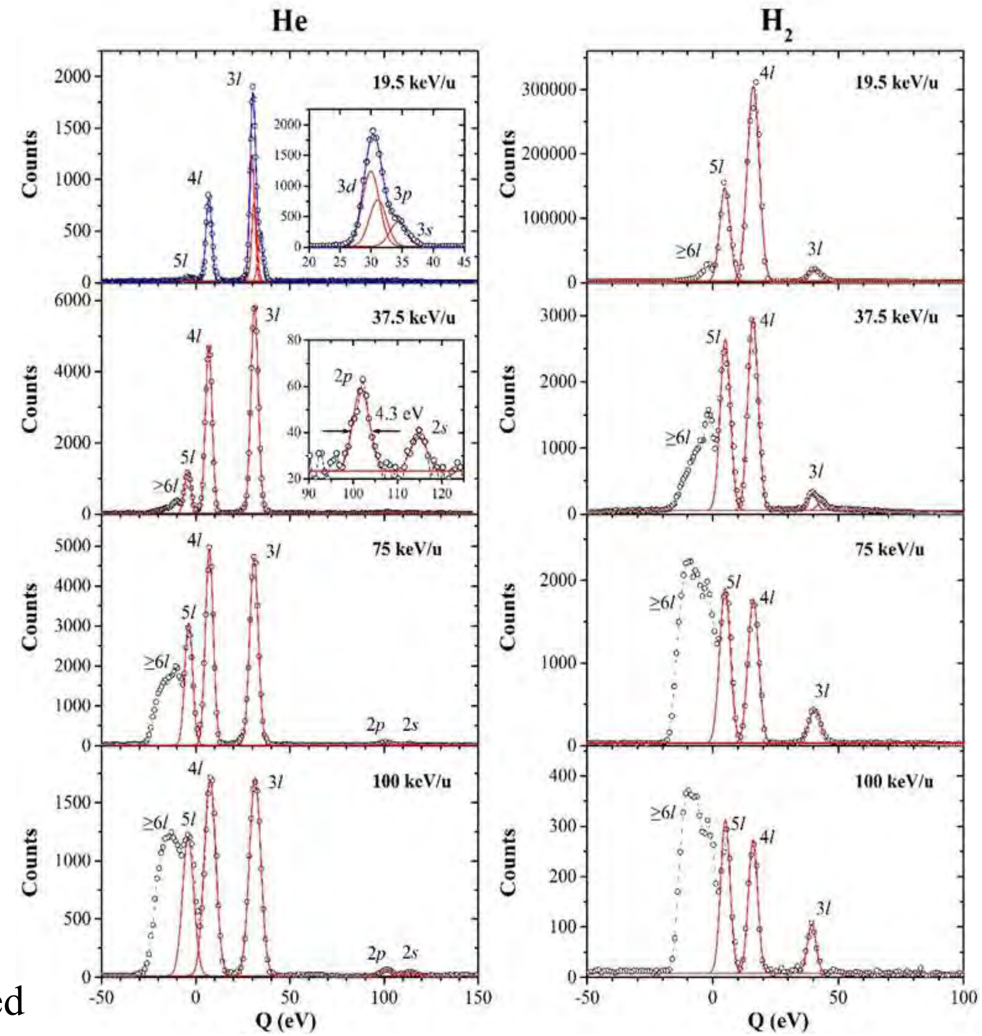
19.5, 37.5, 75, 100 keV/u

$$O^{6+} + He \rightarrow O^{5+}(1s^2 nl) + He^+$$

$$O^{6+} + H_2 \rightarrow O^{5+}(1s^2 nl) + H_2^+$$

- **He： mainly capture to n = 3**
- **H_2： mainly capture to n = 4**

- **with the collision energy increasing, the main capture shifts to channels with larger n and finally to n ≥ 6 for both targets.**



T. Cao *et al.*, ***The Astrophysical Journal Supplement Series***, submitted

Work Plan

The reliability and accuracy of atomic and molecular data are of crucial importance for use in modelling the effects of impurity injection on the mitigation of adverse energy loading on the plasma-facing materials of magnetic confinement fusion devices. The aim for the proposed project is to acquire high-precision and reliable atomic data through dedicated experimental measurements, including dielectronic recombination coefficients and quantum-state resolved cross section of the injected impurity ions with different charge states.

For charge exchange experiments:
320 kV platform for multidisciplinary research with highly charged ions, ion source, acceleration stage. Cold target recoil ion momentum spectroscopy (COLTRIMS), including time of flight spectrometer, supersonic gas jet, recoil ion and scattered ion detectors with position-time sensitivity, data acquisition system, pumping and vacuum system, analyzing magnet, etc.

For dielctronic recombination experiments:
Heavy Ion Research Facility at Lanzhou (HIRFL), Cooler storage ring (CSR). Dielectronic recombination experimental setup at CSR, including electron cooler, high voltage suppliers, electron beam energy fast detuning system, ion detectors, pumping and vacuum system, data acquisition system, remote control system, beam current monitors, beam profile monitors, etc.

Work Plan

1st year, First half: modification of the experimental apparatus, preparation of state-resolved the cross section measurements, upgrading the ion detector system, control system, preparing the dielectronic recombination experiments at storage ring CSRe
Second half: measure single electron capture (SEC) cross sections of the **N^{4+} + He** and **Ar^{8+} + He** collision systems at incident energies of 10 - 100 keV/u, compile the data, and analyze the energy dependence. Analysis of the dielectronic recombination data of **Ar^{14+}** ions.

2nd year, First half: measure state-resolved SEC cross sections of the **$N^{4+,5+}$ + H_2** collision system at incident energies of 10 - 100 keV/u, compile the data, and analyze the energy dependence.
Second half: measure dielectronic recombination rates of the **$Ar^{9+,13+}$** ions, analyze and compile the data.

3rd year, First half: measure state-resolved SEC cross sections of the **Ne^{8+} + He/H_2** collision system at incident energies of 10 - 70 keV/u, compile the data, and analyze the energy dependence.
Second half: measure dielectronic recombination rates of the **$Ar^{10+,11+}$** ions, analyze and compile the data. Prepare progress report.

Summary

- Improve the resolution of the experimental setups.
- Obtain experimental data on the absolute dielectronic recombination rate coefficients and plasma rate coefficients for Ar^{9+}(F-like), Ar^{10+}(O-like), Ar^{11+}(N-like), and Ar^{13+}(B-like);
- Obtain experimental data on the state-resolved SEC cross sections for N^{4+}, N^{5+}, Ne^{8+}, Ar^{8+} on He/H_2 collisions.
- All measured data will be compiled and published in the peer-reviewed journals

Thank you for your attention!