INTERNATIONAL CONFERENCE ON PHOTONIC ELECTRONIC AND ATOMIC COLLISIONS

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Photorecombination studies at Shanghai EBIT

B. Tu, J. Xiao, K. Yao, D. Lu and Y. Zou

Institute of Modern Physics, Fudan University, Shanghai ,China

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Outline

§ Introduction and Motivation

§ Experiment Setup at Shanghai-EBIT

§ Photorecombination studies for highly charged ions

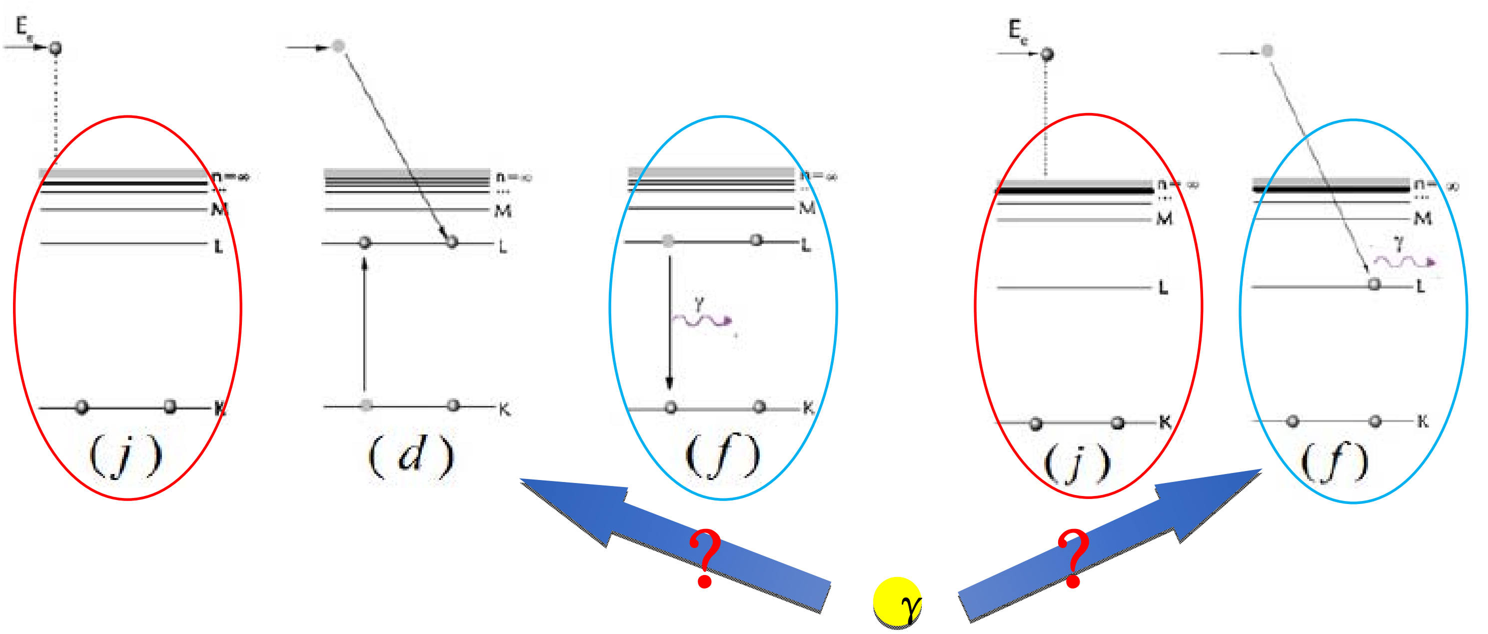
- *KLL* DR measurements for W ions
- *L*-shell DR measurements for W ions
- DR measurements for Ar and Xe ions

§ Summary

Introduction

Photorecombination (PR)

Dielectronic Recombination (DR) Radiative Recombination (RR)

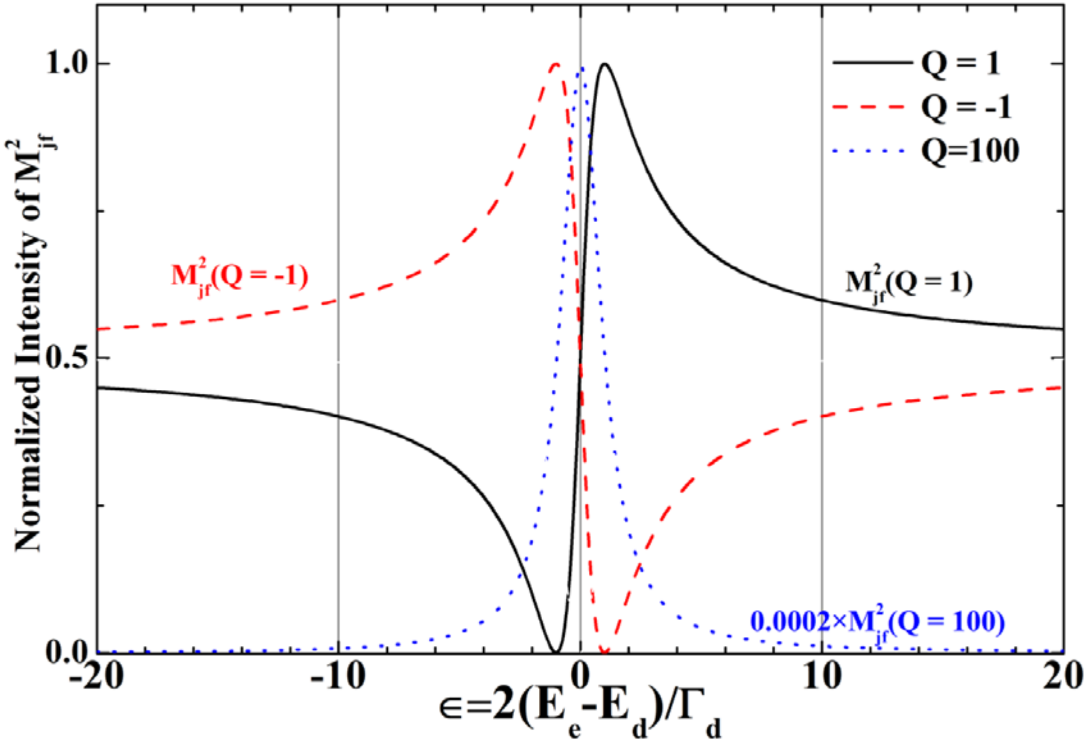


Interefering !

Introduction

Fano line profile

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



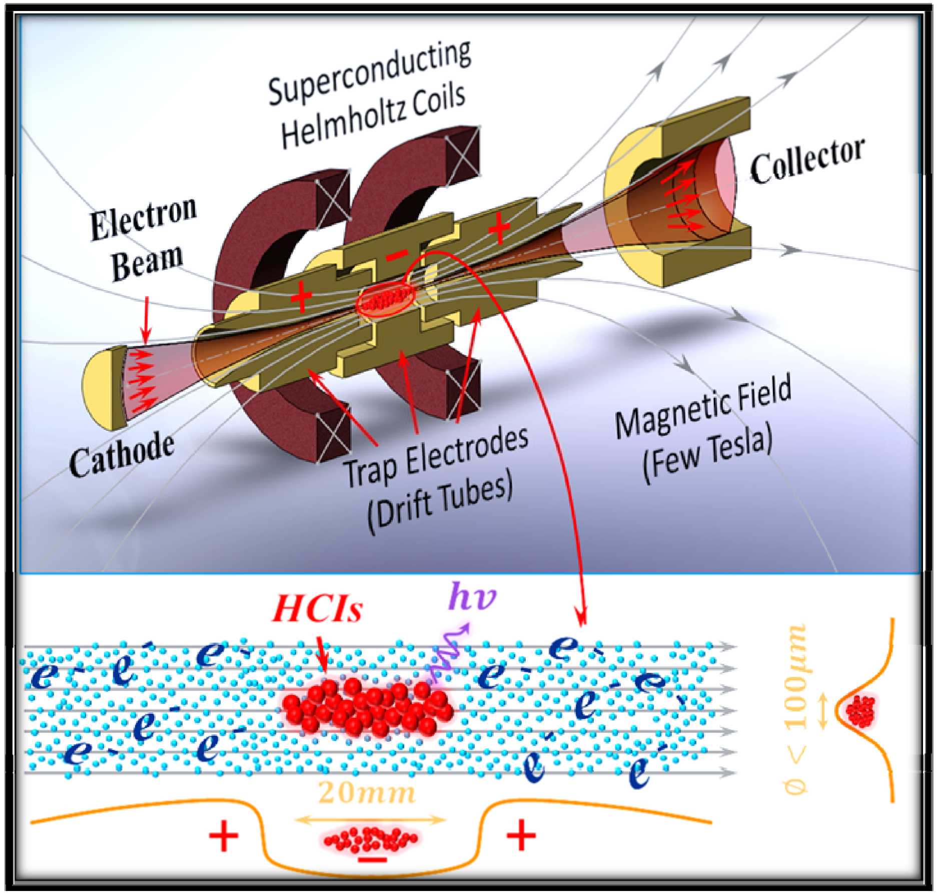
Motivation

- 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

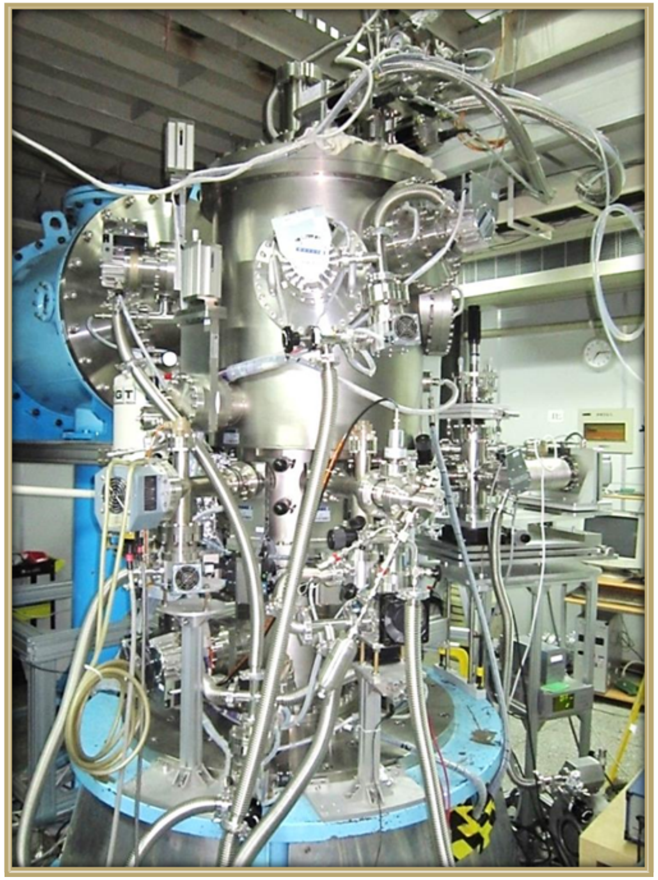
Introduction

Electron Beam Ion trap (EBIT)

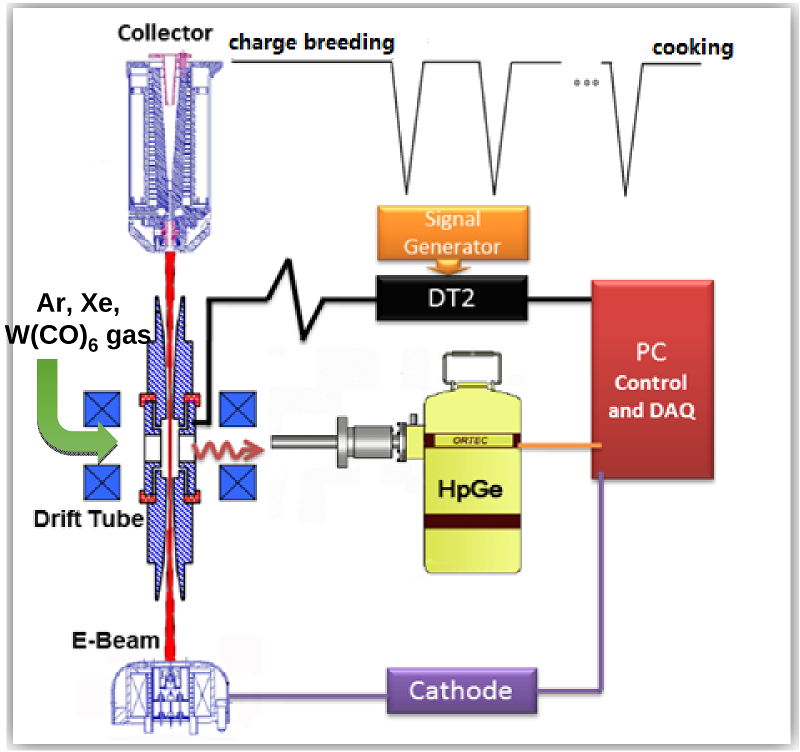


- Highly charged ions
- Monoenergetic electron beam
- Energy adjustable
- Atomic spectroscopy
  Structure
  Collision process

Experiment Setup on Shanghai-EBIT



Data acquisition system



Recent experiments at Shanghai-EBIT

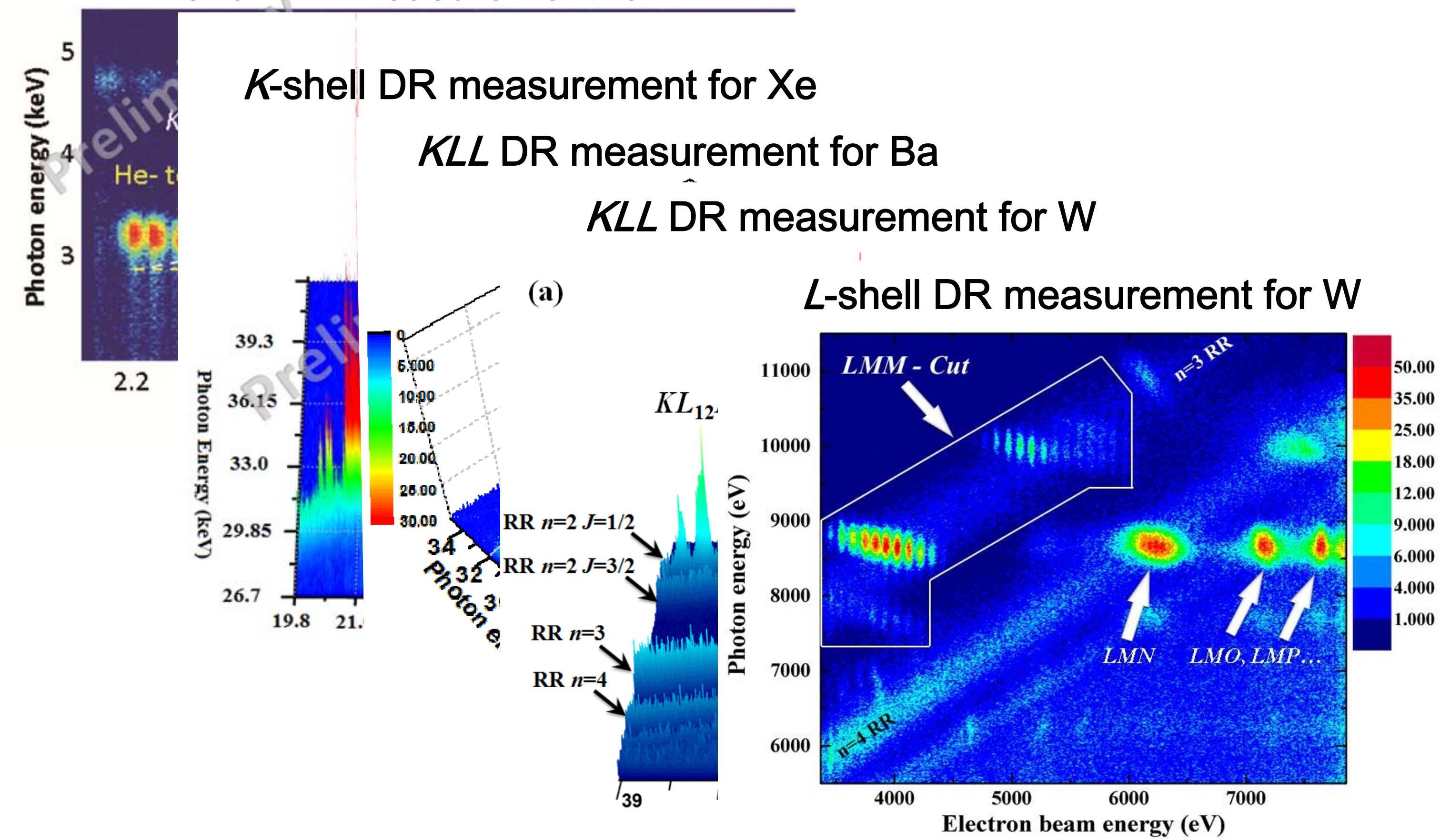
K-shell DR measurement for Ar

K-shell DR measurement for Xe

KLL DR measurement for Ba

KLL DR measurement for W

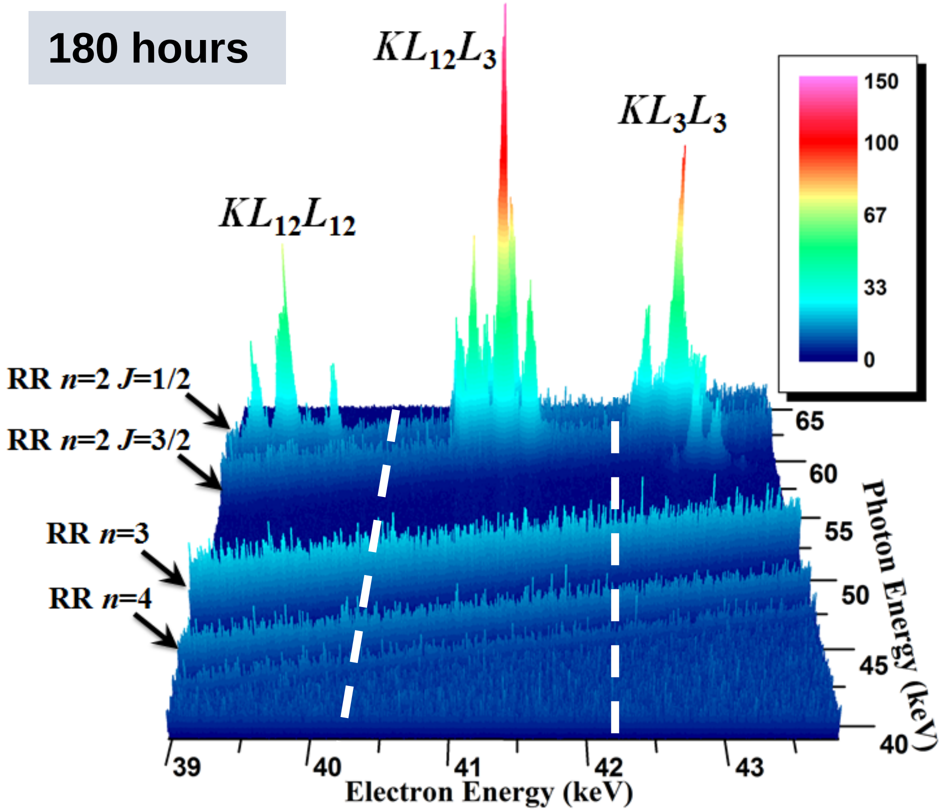
L-shell DR measurement for W



Result

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

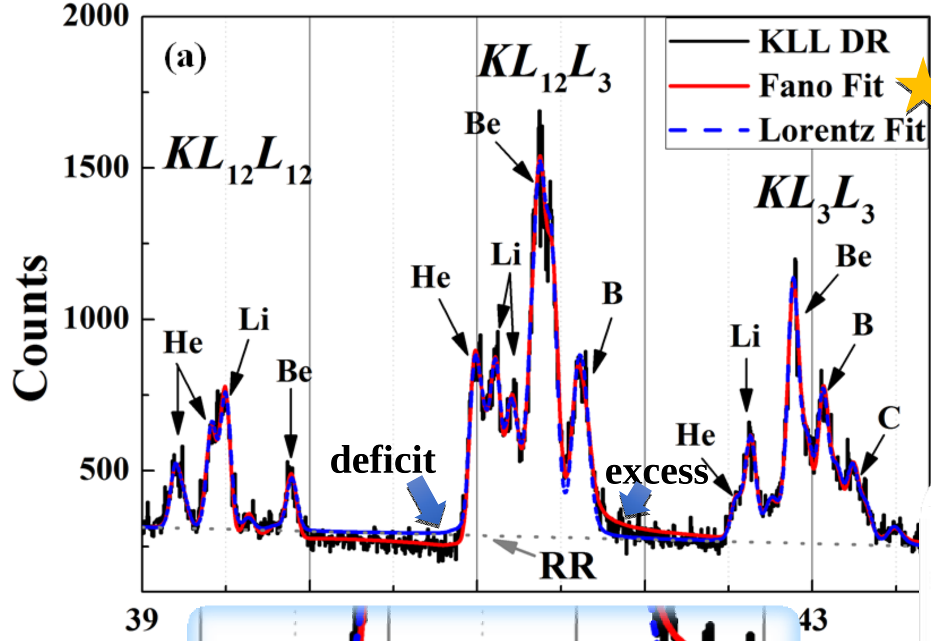
3D x-ray intensity spectrum

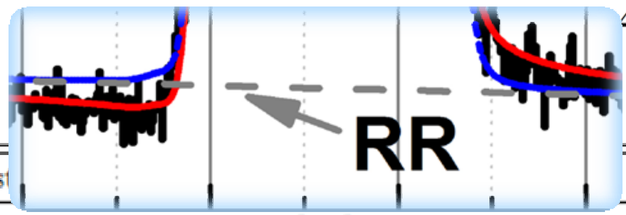


	Expt. A
Electron energy scanned	39 – 43.8 keV
Electron beam current	170 mA
Gas injection pressure	5×10^{-8} Torr
Trapping potential	60 V
Electron energy spread	67 eV
Charge state obtained	He- up to C-like

Excitation function

$$C(q,E)=D(E)\sum_q f_q\left[\frac{d\sigma_{RR}(q,E)}{d\Omega}+\frac{\sum_{jdf}S_{jdf}\times DR(q,E)\times W_{df}(90°)}{4\pi}\right]$$



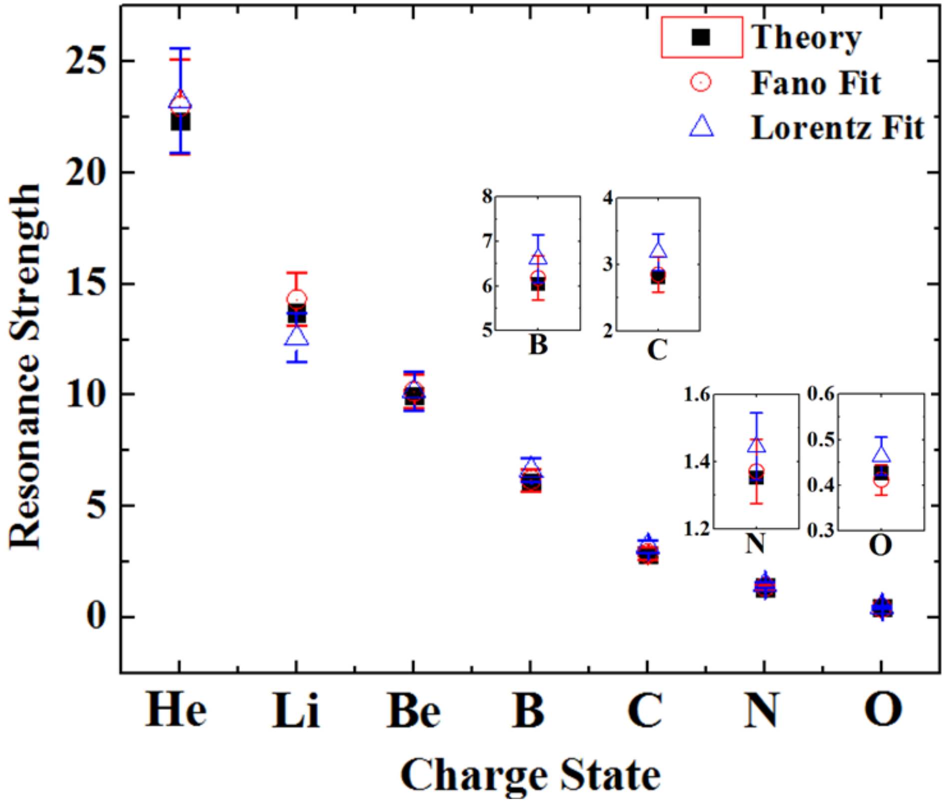


More tailored

Label	Q
Be_3	14.9
Be_4	6.6

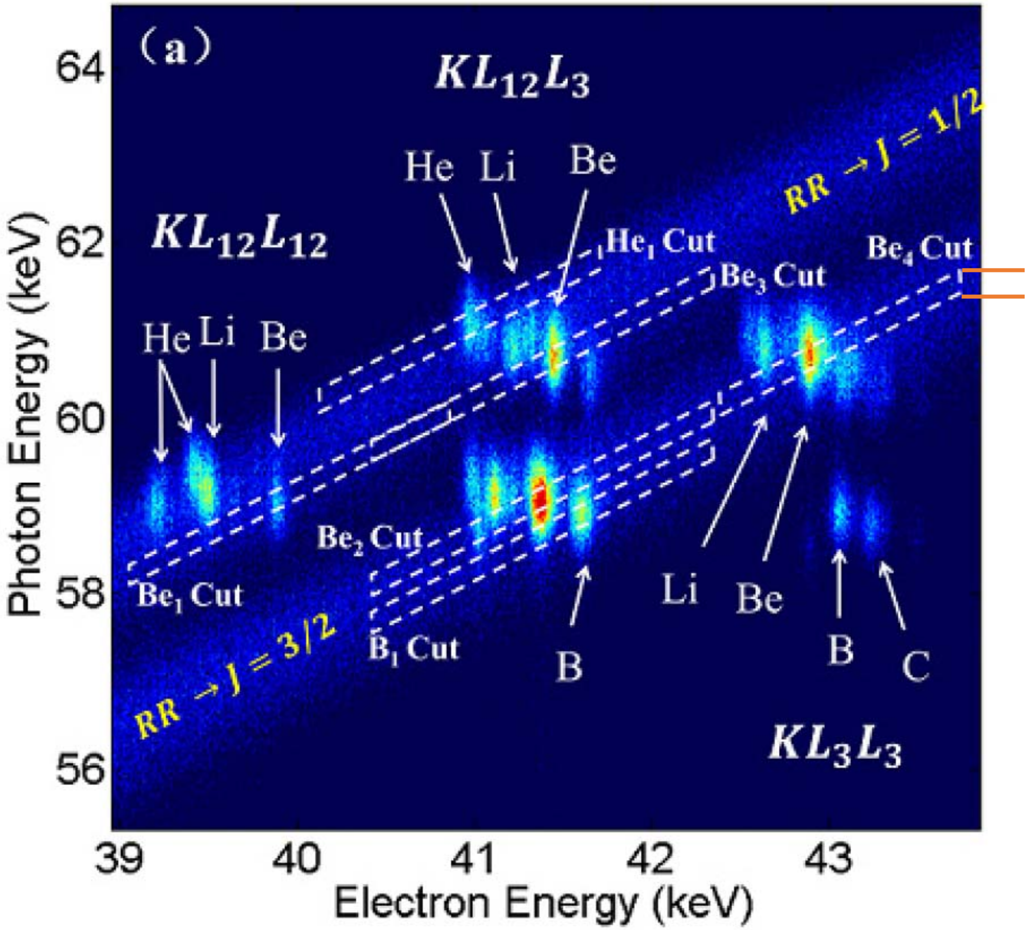
Label	Middle st			S	Q
Be_3	$[(1s2s^22p_{1/2})_12p_{3/2}]_{5/2}$	$[1s^22s^22p_{3/2}]_{3/2}$	41373	3.354	14.9
Be_4	$[(1s2s^22p_{1/2})_02p_{3/2}]_{3/2}$	$[1s^22s^22p_{1/2}]_{1/2}$	41444	2.041	6.6

KLL DR resonance strengths



B. Tu *et al*. Physics of Plasmas 23, 053301 (2016)

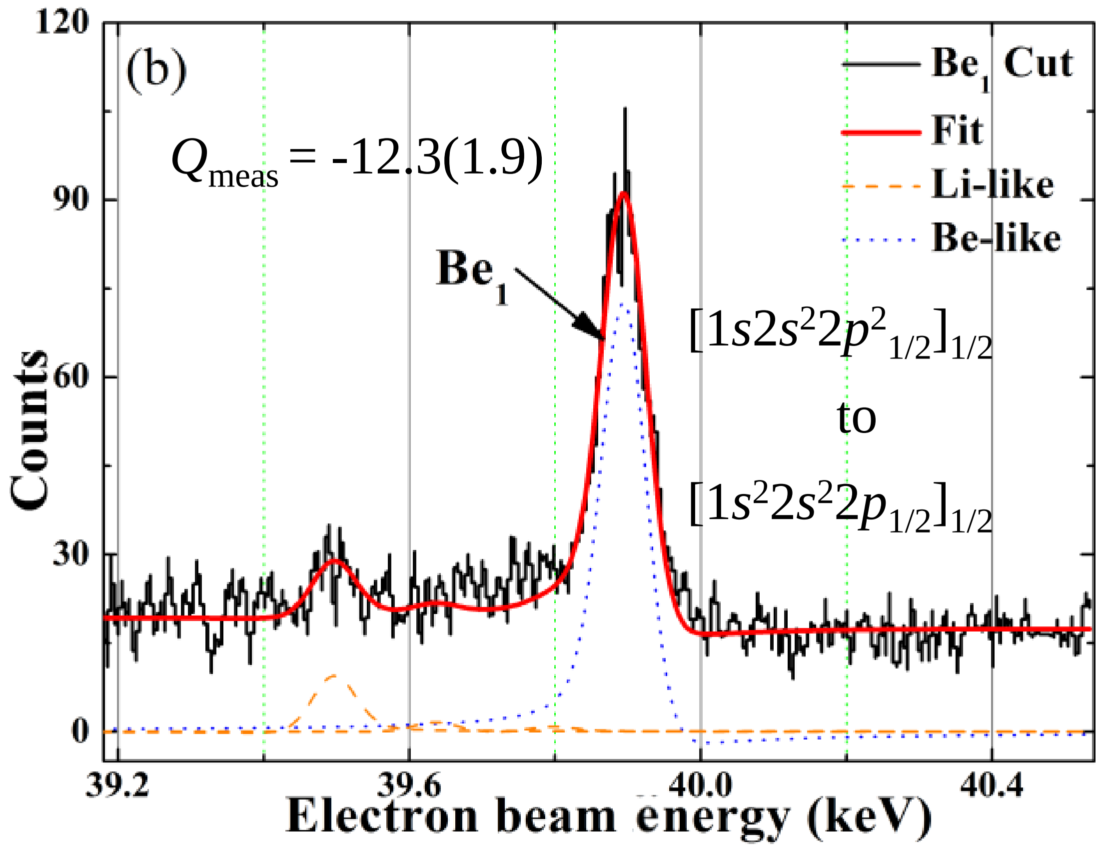
2D x-ray intensity spectrum



~ 500 eV

Interference effect

Fano Line Shape



Interference effect

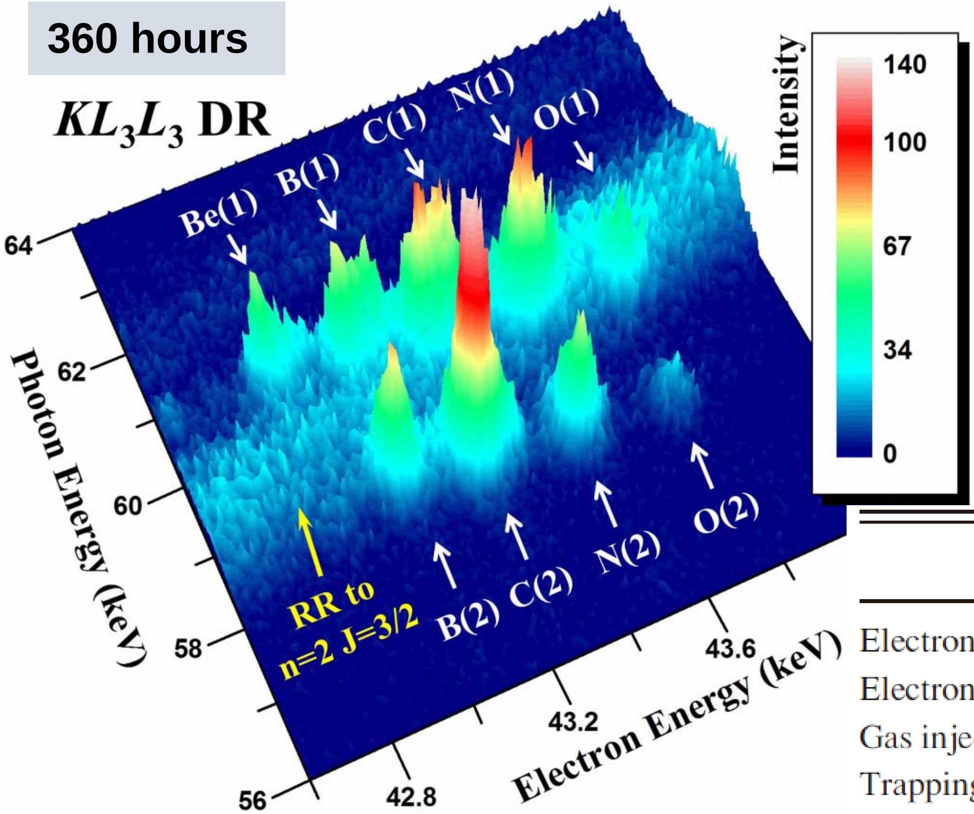
Q Factors

Label	Initial state	Intermediate state	Final state	Q_{meas}	Q_{cal}	Q_{aver}
He_1	$[1s^2]_0$	$[(1s2s)_0 2p_{3/2}]_{3/2}$	$[1s^2 2s_{1/2}]_{1/2}$	− 12.3(1.8)	− 13.2	
Be_1	$[1s^2 2s^2]_0$	$[1s2s^2 2p^2_{1/2}]_{1/2}$	$[1s^2 2s^2 2p_{1/2}]_{1/2}$	− 12.3(1.9)	− 13.3	
Be_2	$[1s^2 2s^2]_0$	$[(1s2s^2 2p_{1/2})_1 2p_{3/2}]_{5/2}$	$[1s^2 2s^2 2p_{3/2}]_{3/2}$	12.7(1.7)	14.9	
Be_3	$[1s^2 2s^2]_0$	$[(1s2s^2 2p_{1/2})_0 2p_{3/2}]_{3/2}$	$[1s^2 2s^2 2p_{1/2}]_{1/2}$	6.4(0.5)	6.6	
Be_4	$[1s^2 2s^2]_0$	$[1s2s^2 (2p^2_{3/2})_2]_{5/2}$	$[1s^2 2s^2 2p_{3/2}]_{3/2}$	17.4(2.4)	15.2	
B_1	$[1s^2 2s^2 2p_{1/2}]_{1/2}$	$[1s2s^2 2p^2_{1/2} 2p_{3/2}]_2$	$[1s^2 2s^2 2p_{1/2} 2p_{3/2}]_1$	26.5(6.8)	9.3	27.4[a]
			$[1s^2 2s^2 2p_{1/2} 2p_{3/2}]_2$		− 27.6	
C_1	$[1s^2 2s^2 2p^2_{1/2}]_0$	$[1s2s^2 2p^2_{1/2} (2p^2_{3/2})_2]_{5/2}$	$[1s^2 2s^2 2p^2_{1/2} 2p_{3/2}]_{3/2}$	4.4(0.4)	4.3	
N_1	$[1s^2 2s^2 2p^2_{1/2} 2p_{3/2}]_{3/2}$	$[1s2s^2 2p^2_{1/2} (2p^3_{3/2})_{3/2}]_2$	$[1s^2 2s^2 2p^2_{1/2} (2p^2_{3/2})_2]_2$	13.4(2.1)	13.7	
O_1	$[1s^2 2s^2 2p^2_{1/2} 2p^2_{3/2}]_2$	$[1s2s^2 2p^2_{1/2} 2p^4_{3/2}]_{1/2}$	$[1s^2 2s^2 2p^2_{1/2} 2p^3_{3/2}]_{3/2}$	11.8(1.6)	10.5	

[a]Obtained by averaging the Q values weighted with the branching ratios of the two transition channels.

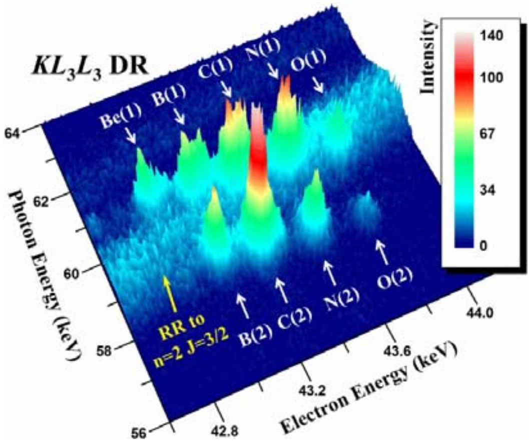
B. Tu *et al*. Phy Rev. A 93, 032707(2016)

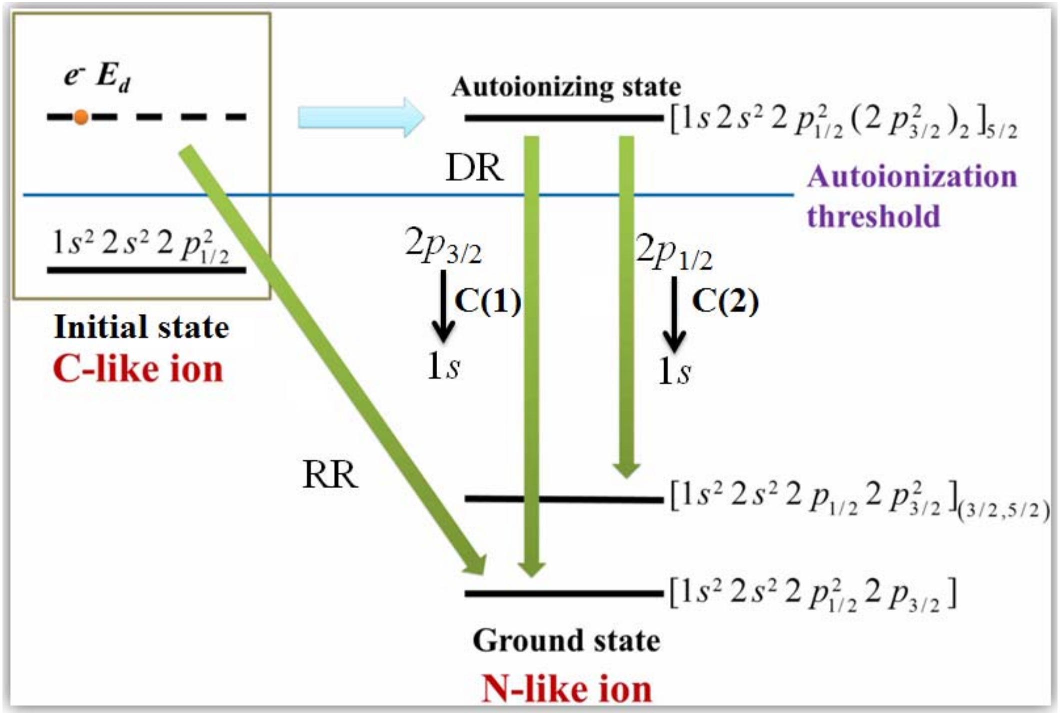
Dual Fano and Lorentzian line profile properties of autoionizing states



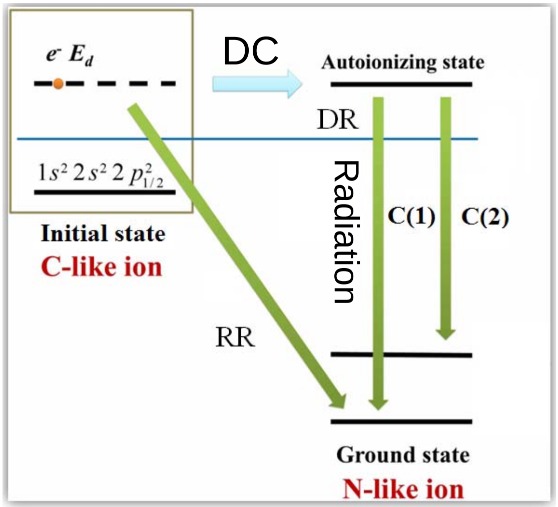
	Expt. B
Electron energy scanned	42.5 – 44.1 keV
Electron beam current	140 mA
Gas injection pressure	2×10^{-7} Torr
Trapping potential	130 V
Electron energy spread	61 eV
Charge state obtained	Be- up to O-like

Dual Fano and Lorentzian line profile properties of autoionizing states

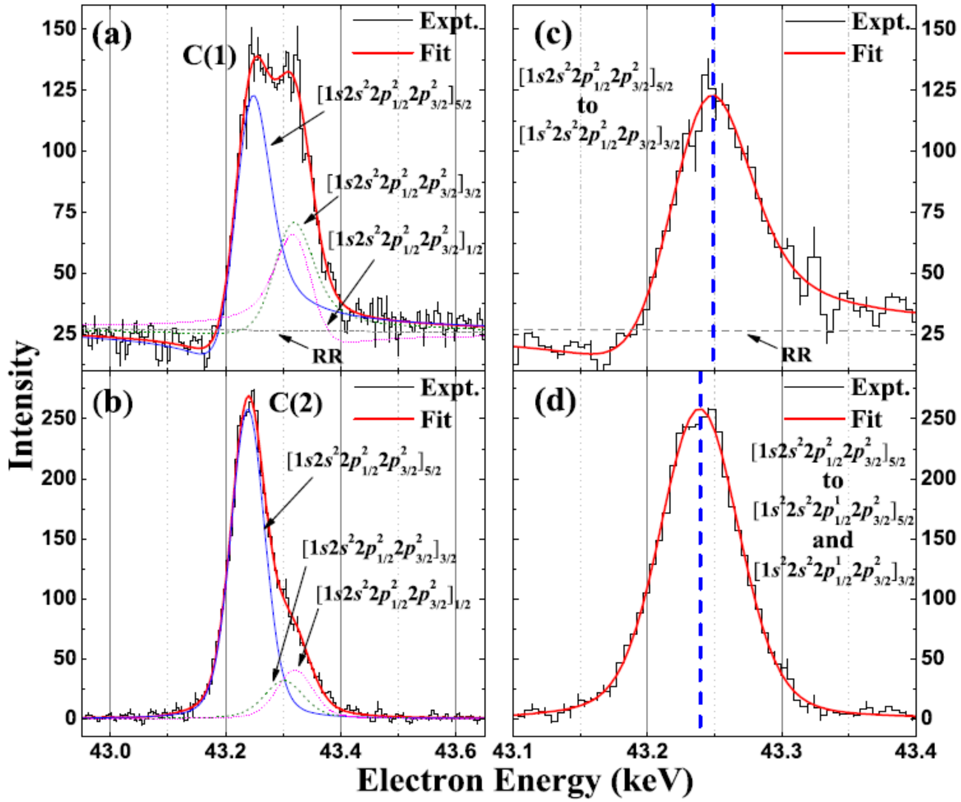




Dual Fano and Lorentzian line profile properties of autoionizing states



Different paths of radiation (or excitation) different line shapes



An autoionizing state can have both Fano and Lorentzian behavior.

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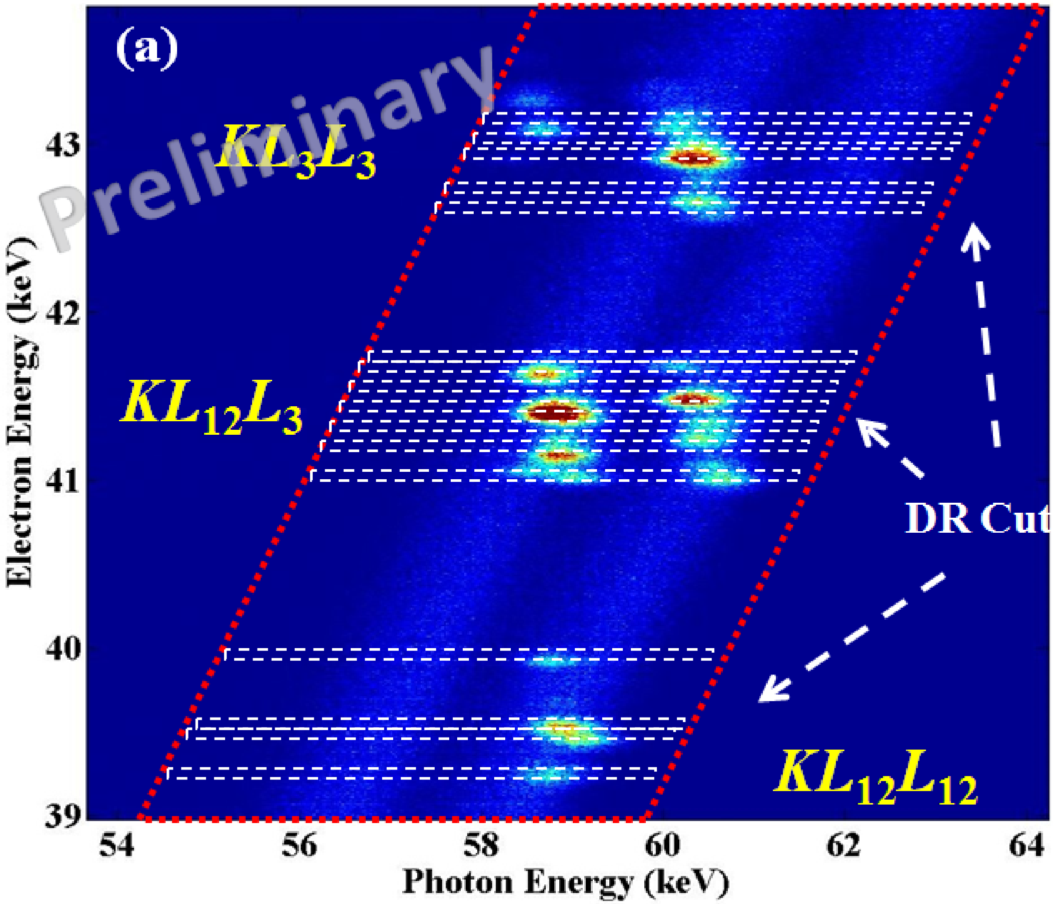
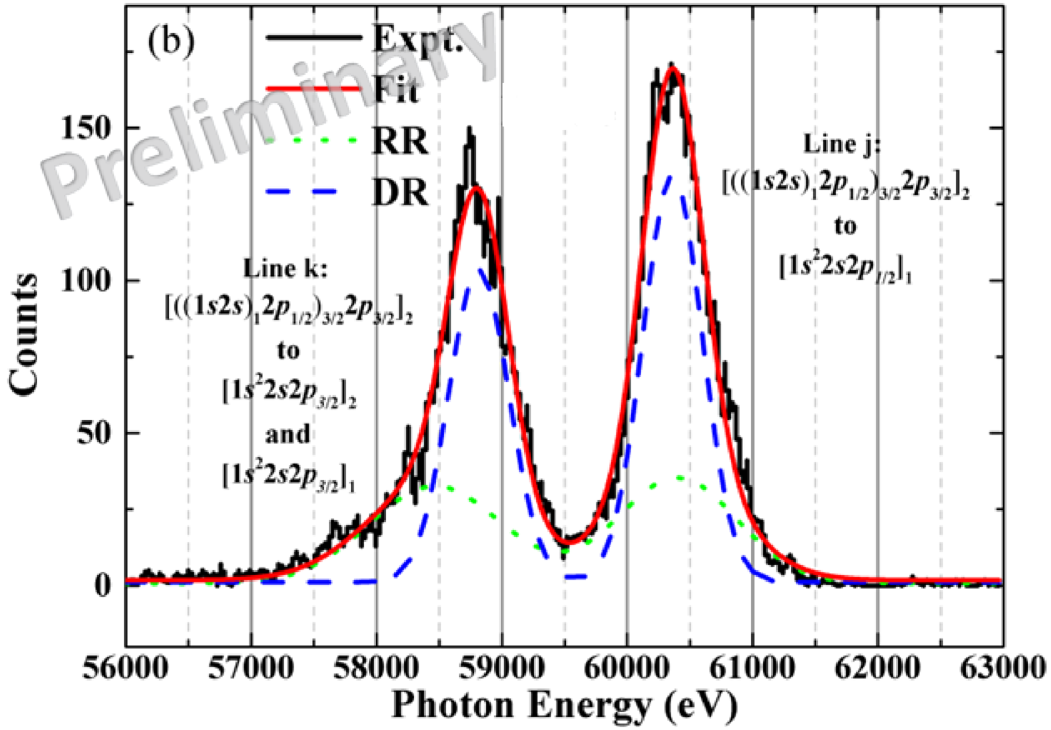
Dielectronic satellite x-ray spectra of the 2-1 transitions



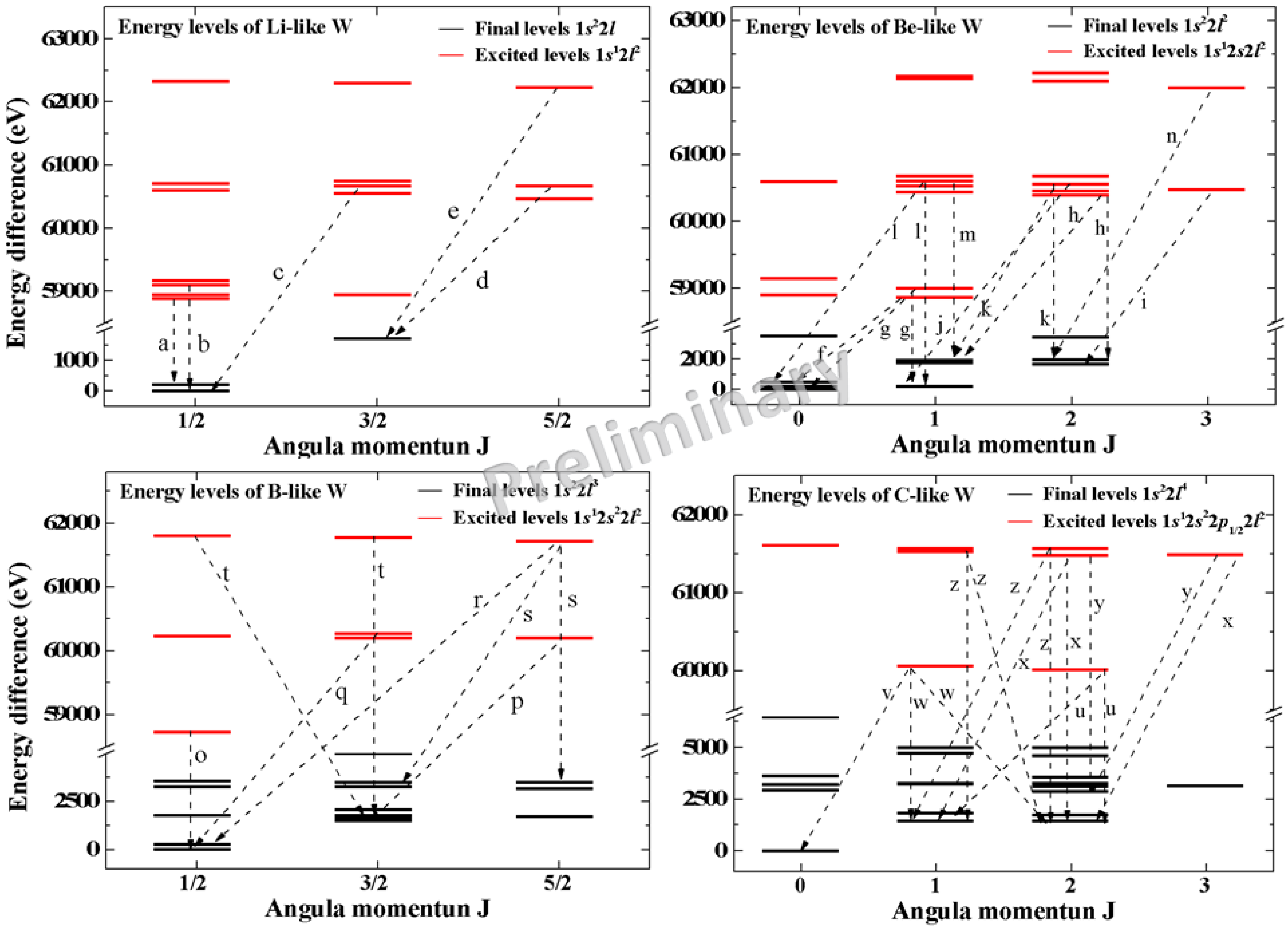
Dielectronic satellite x-ray spectra of the 2-1 transitions

Be-like: $[((1s2s)_1 2p_{1/2})_{3/2} 2p_{3/2}]_2 \rightarrow 1s^2 2s 2p_{3/2} + \gamma(2p_{1/2} \rightarrow 1s)$

$\rightarrow 1s^2 2s 2p_{1/2} + \gamma(2p_{3/2} \rightarrow 1s)$



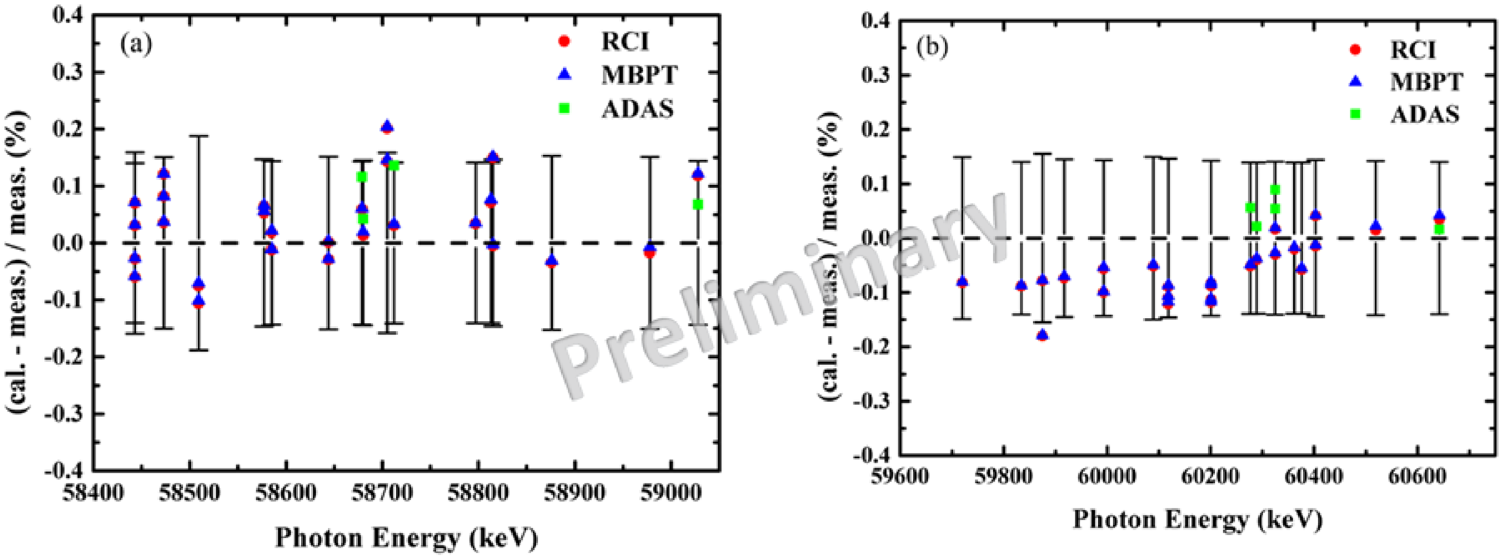
~ 500 eV @60 keV



Energy levels of Li-like W
Final levels 1s²2l
Excited levels 1s¹2l²
Energy levels of Be-like W
Final levels 1s²2l²
Excited levels 1s¹2s2l²
Energy levels of B-like W
Final levels 1s²2l³
Excited levels 1s¹2s²2l²
Energy levels of C-like W
Final levels 1s²2l⁴
Excited levels 1s¹2s²2p1/22l²
Energy difference (eV)
Angula momentun J
Preliminary

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

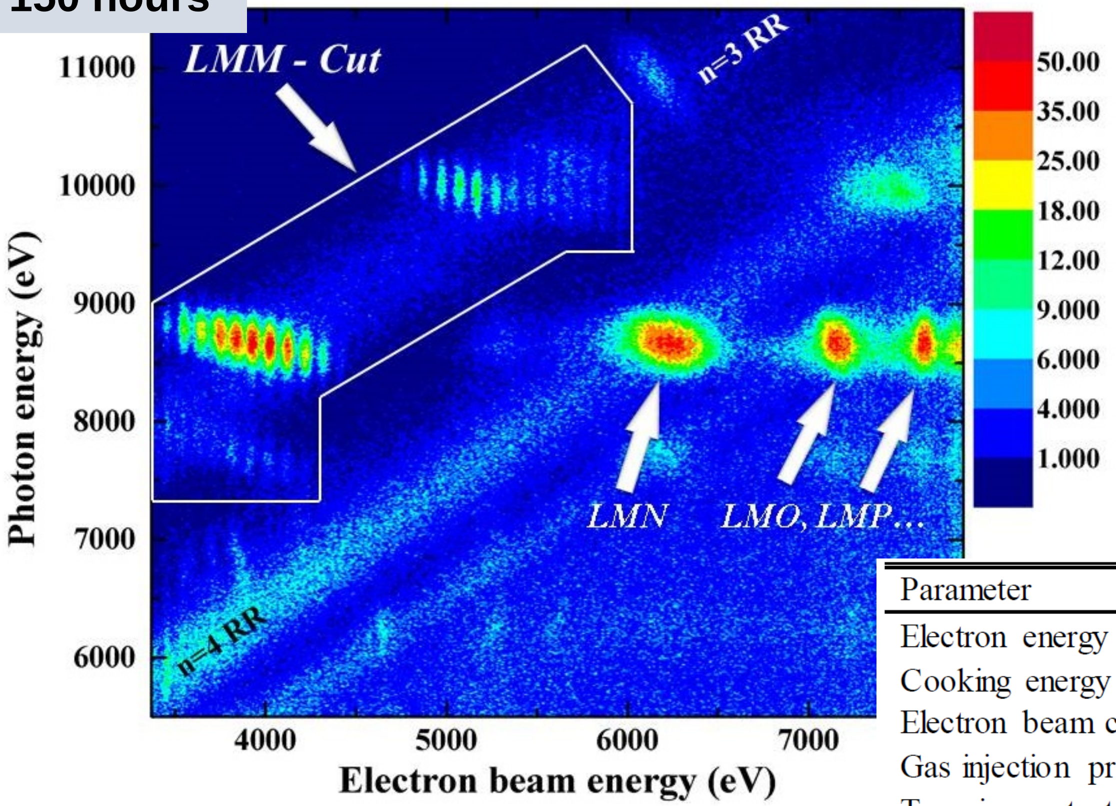
Middle States	Final States	A_{rci}	A_{rmbpt}	$^{adas}A_{ic}$
$1s2s^2$	$1s^2\ 2p_{1/2}$	8.38E+14	9.02E+14	**3.07E+10**

Result

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

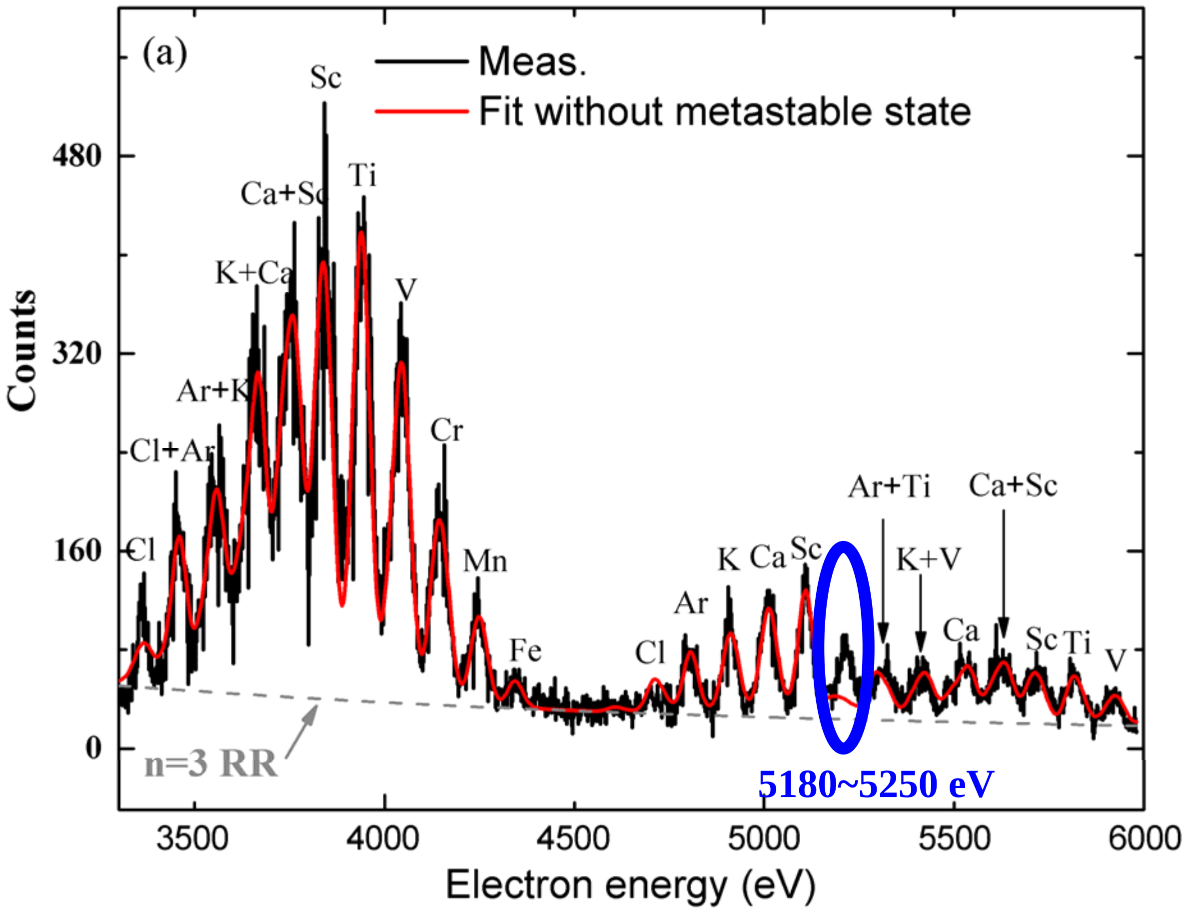
L-shell DR measurements for W ions

150 hours

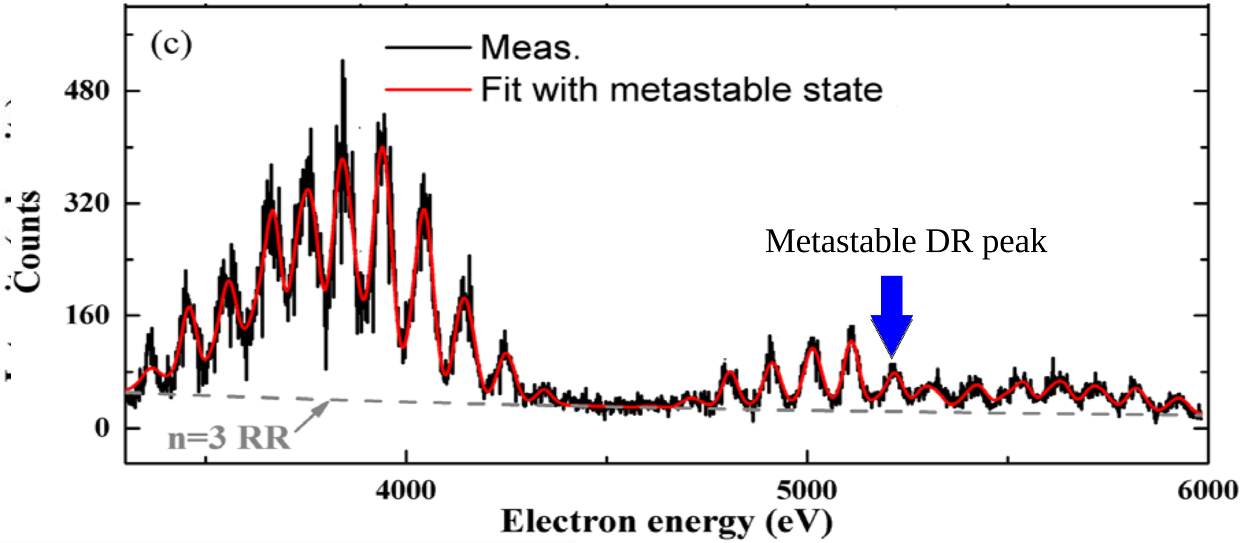


Parameter	Value
Electron energy scanned	7.84~3.26 keV
Cooking energy	7.84 keV
Electron beam current	20 mA
Gas injection pressure	1.7×10^{-7} torr
Trapping potential	80 V
Electron energy spread	43 eV

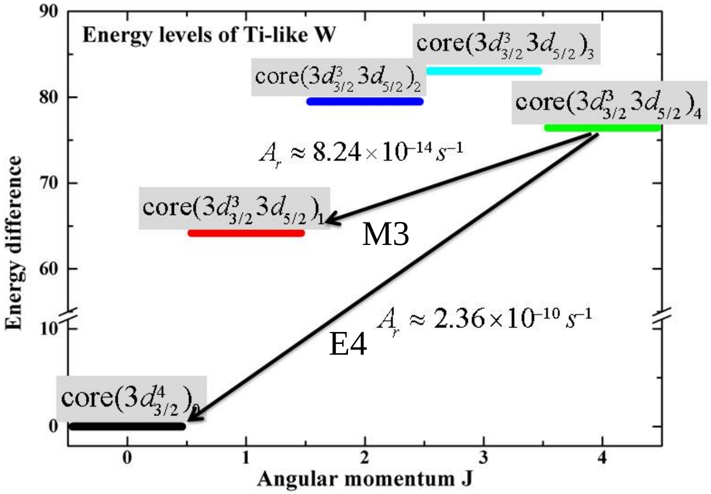
LMM DR excitation function



LMM DR excitation function



$2s + e \rightarrow 3d_{5/2}^2$



Metastable state

$core(3d_{3/2}^3 3d_{5/2})_4$

Lifetime ~143 years (cal.)

Ground state $core(3d_{3/2}^4)_0$

LMM DR resonance strengths

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

$core'$ represents $1s^2 2s^2 2p^6 3s^2 3p^6$

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

Ti* Extremely long-lived metastable state

Population ~45%

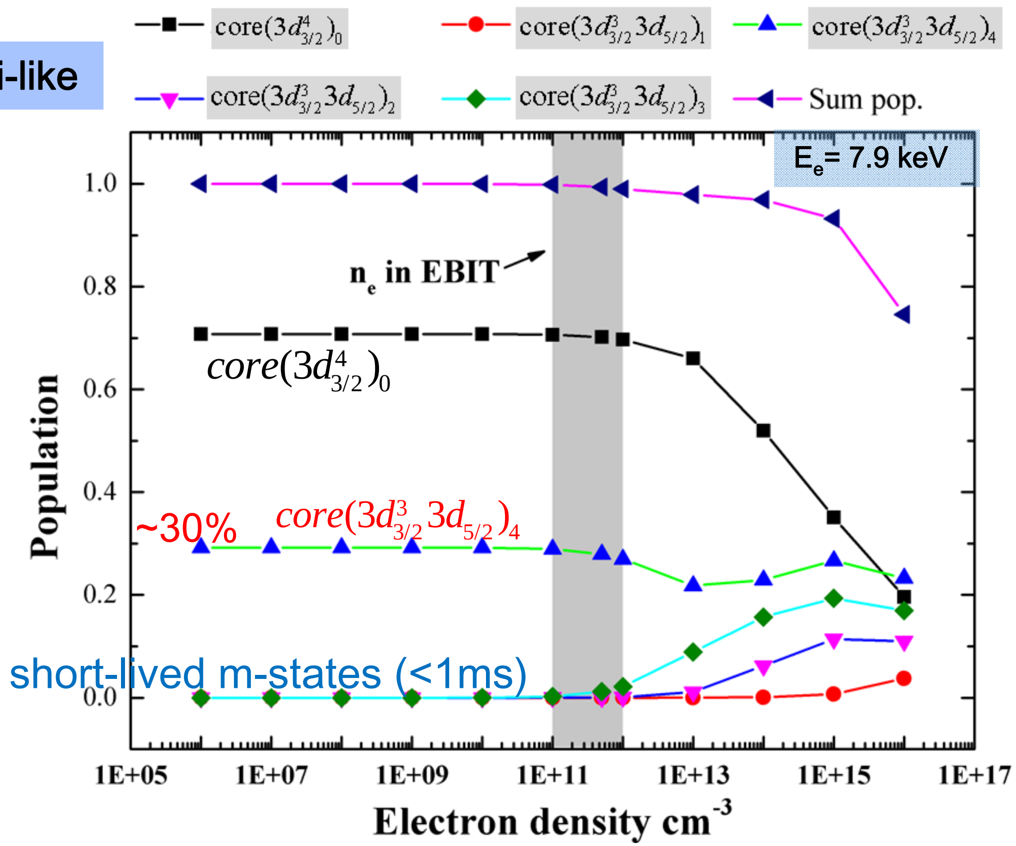
Electron energy 7.9 keV

Electron density 5×10^{11} cm^{-3}

Collisional Radiative(CR)-model calculation

Ti-like

pop. ~45% predicted in DR meas.



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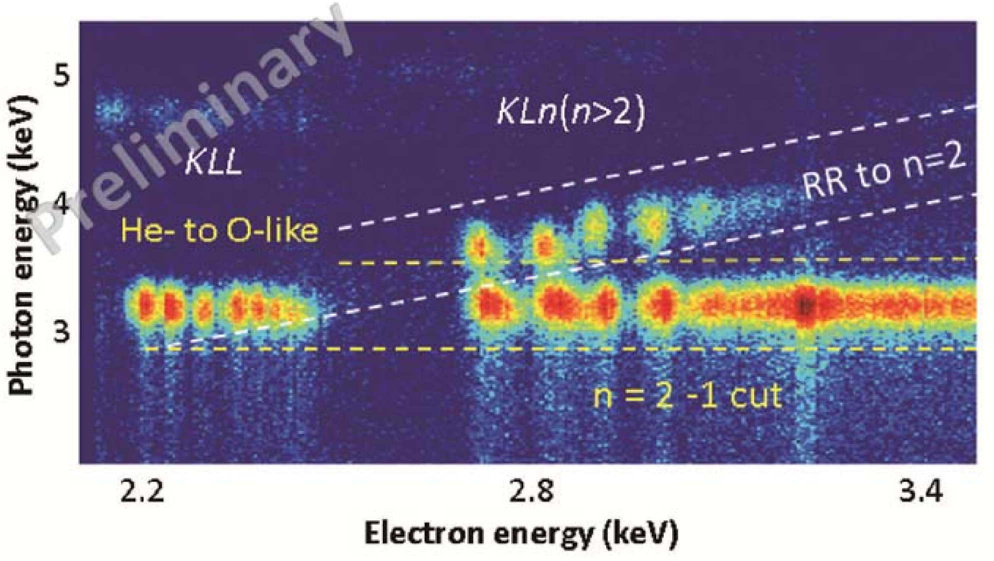
Long-lived metastable state be considered as a second ground
collision excitation and de-excitation, ionization, recombination
new transitions, resonances, indirect ionization processes

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

Energy scanned	2.2~3.6 keV
Electron beam current	20 mA
Gas injection pressure	1×10^{-7} torr
Energy spread	20 eV

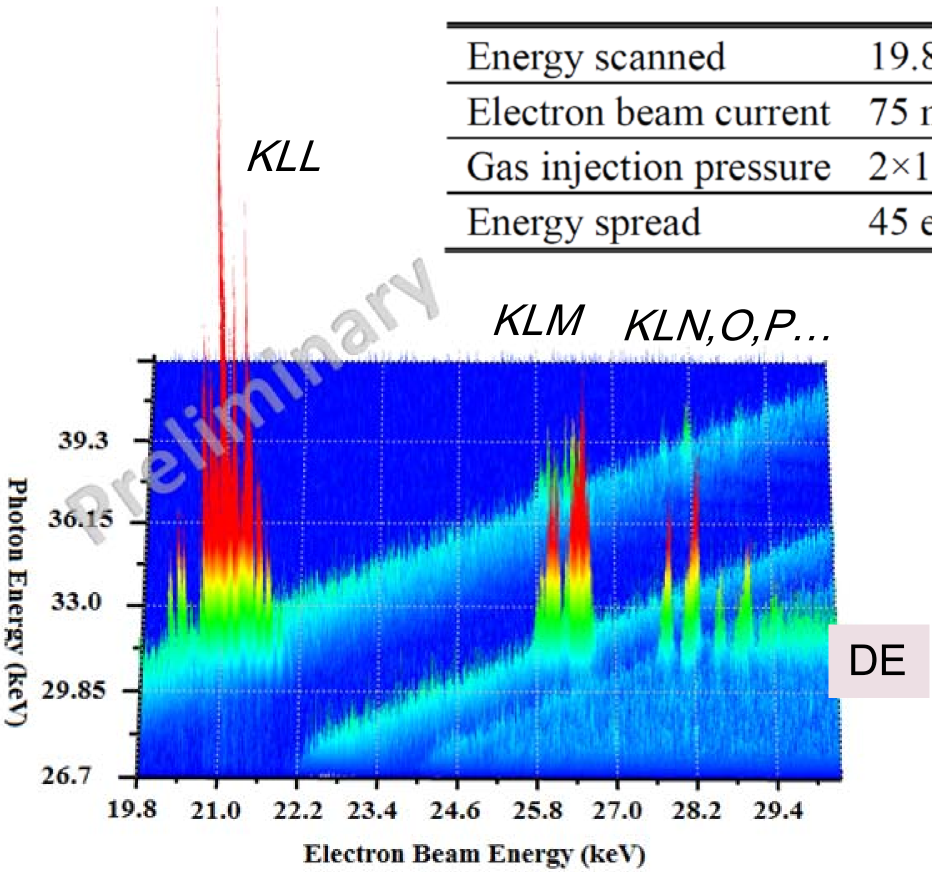


Data analysis
Ongoing…

By G. Xiong

K-shell DR measurements for Xe ions

Energy scanned	19.8~30 keV
Electron beam current	75 mA
Gas injection pressure	2×10^{-7} torr
Energy spread	45 eV



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

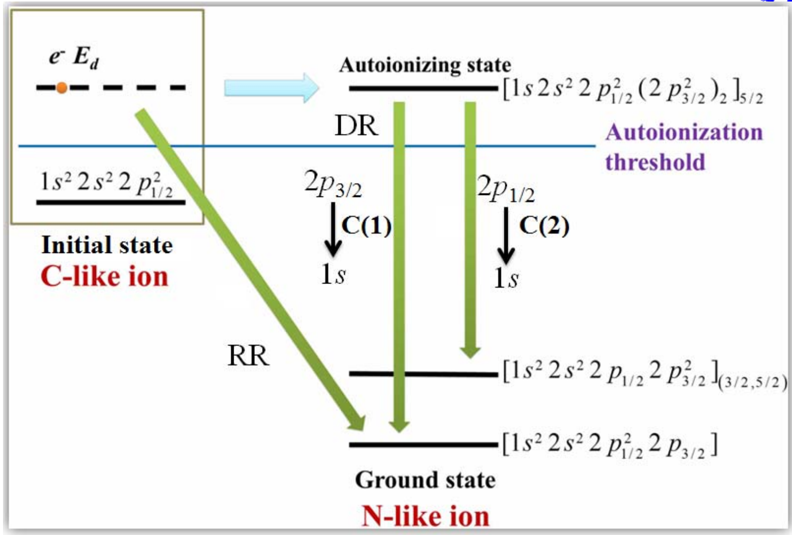
for

Your Attention !

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

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

$$B_a = \Gamma_a/\Gamma_d$$



$$\begin{aligned} DR_{Fano} &= \int_{-\infty}^{+\infty} F(E')G(E'-E)dE' \\ &= \frac{2}{Q^2\Gamma_d\pi\sqrt{\pi}} \\ &\times \int_{-\infty}^{+\infty}\left[\frac{(Qy+t-x)^2 + (B_a-1)^2y^2}{(t-x)^2+y^2} - 1\right]e^{-t^2}dt, \end{aligned}$$