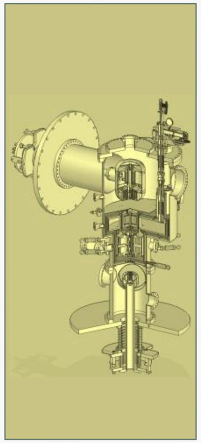
Technical Meeting on
Uncertainty Assessment and Benchmark Experiments for Atomic and Molecular Data for Fusion Applications

19 - 21 December 2016, IAEA, Vienna

KLL DIELECTRONIC RECOMBINATION RESONANT STRENGTHS OF TUNGSTEN IONS IN SH-EBIT



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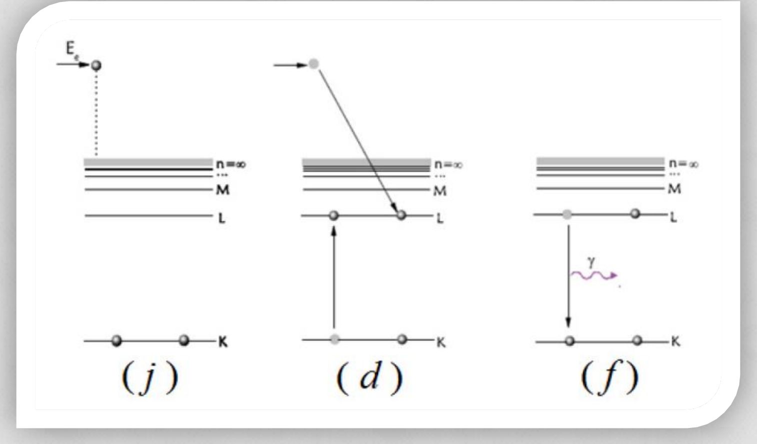
SHORT PREFACE

- Dielectronic Recombination of highly charged ions contributes significantly to radiation energy loss in fusion plasmas.
- While Tungsten, which will be the strongest candidate of divertor material in ITER, is an high Z elements and will become highly charged ion in the core plasma.

DR resonance strengths of all charge state Tungsten ions are crucial data for the modeling and diagnostic of fusion plasma.



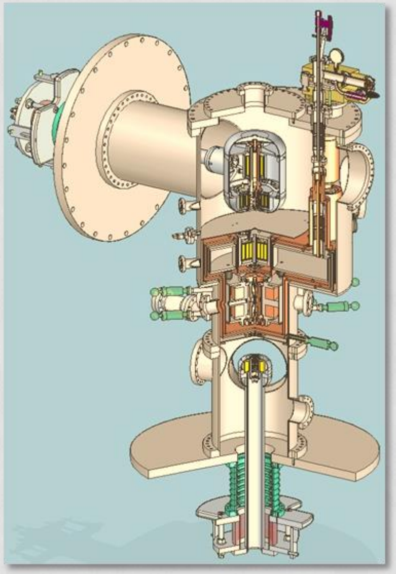
EXPERIMENTAL METHODS

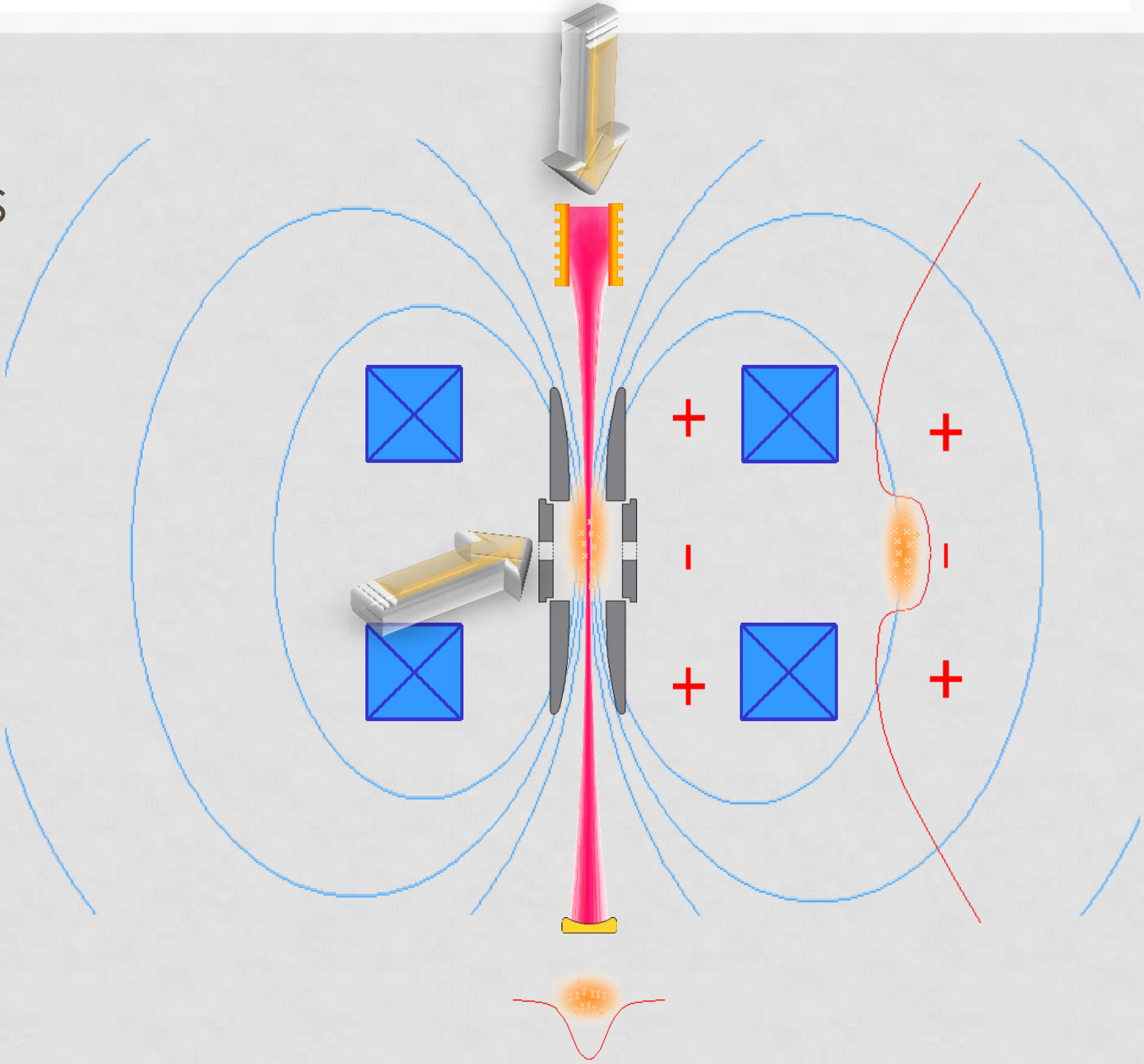
- DR process is one kind of inelastic collision and there are generally two common methods to collide electron and ion beam to measure the strength.
  - Crossed-beam
  - Merged beam

- There is another unique way that could be applied to the measurements of DR resonance strength.
  - To trap the ions and guide an electron beam passing through – an Electron Beam Ion Trap

PRINCIPLE OF EBIT

- Operation of EBIT
- Atomic processes in the trap of an EBIT

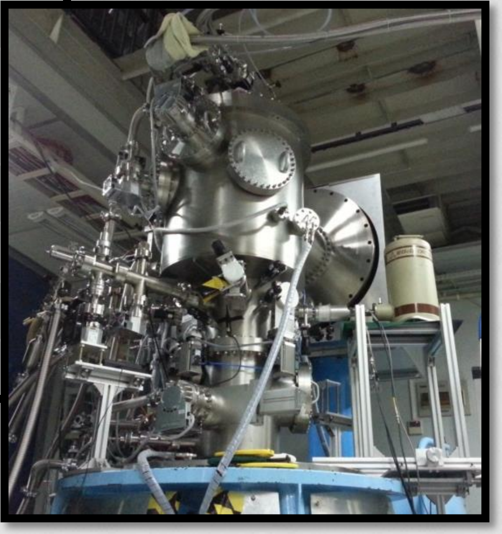




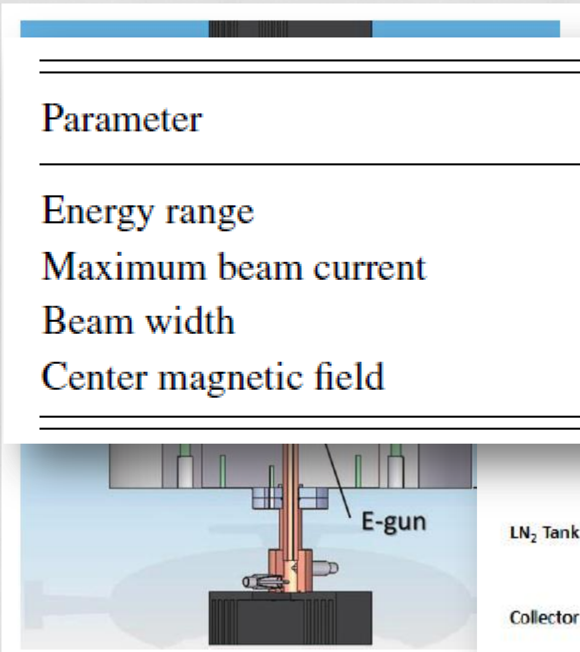
SOME ADVANTAGE OF EBIT MEASUREMENT

- EBIT has an advantage on relatively high energy investigation

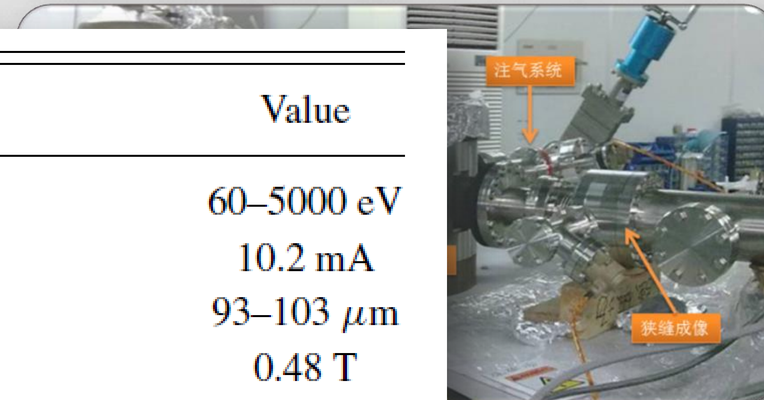
Para.	Value
Electron energy	1~180 keV
Electron current	20~210 mA
Electron Density	$10^{9\sim13}$ cm^{-3}
e- Beam density	>2500 A/cm^2
e- Beam radius	~35 μm
Maximum Magnetic field, B	4.8 T
Uniformity of B	2.77 ‱
Vacuum	$\sim 7.5 \times 10^{-11}$ Torr
collimation	<0.05 mm

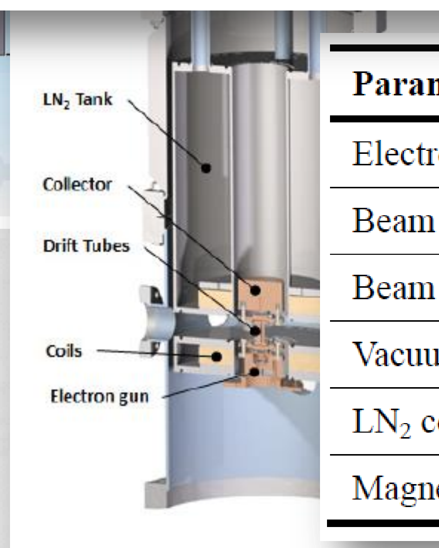


LOW-ENERGY EBIT



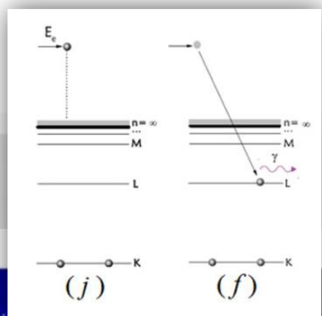
Parameter	Value
Energy range	60–5000 eV
Maximum beam current	10.2 mA
Beam width	93–103 μm
Center magnetic field	0.48 T

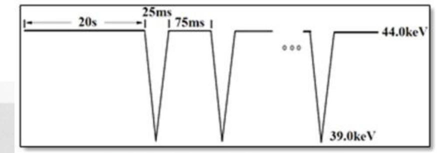


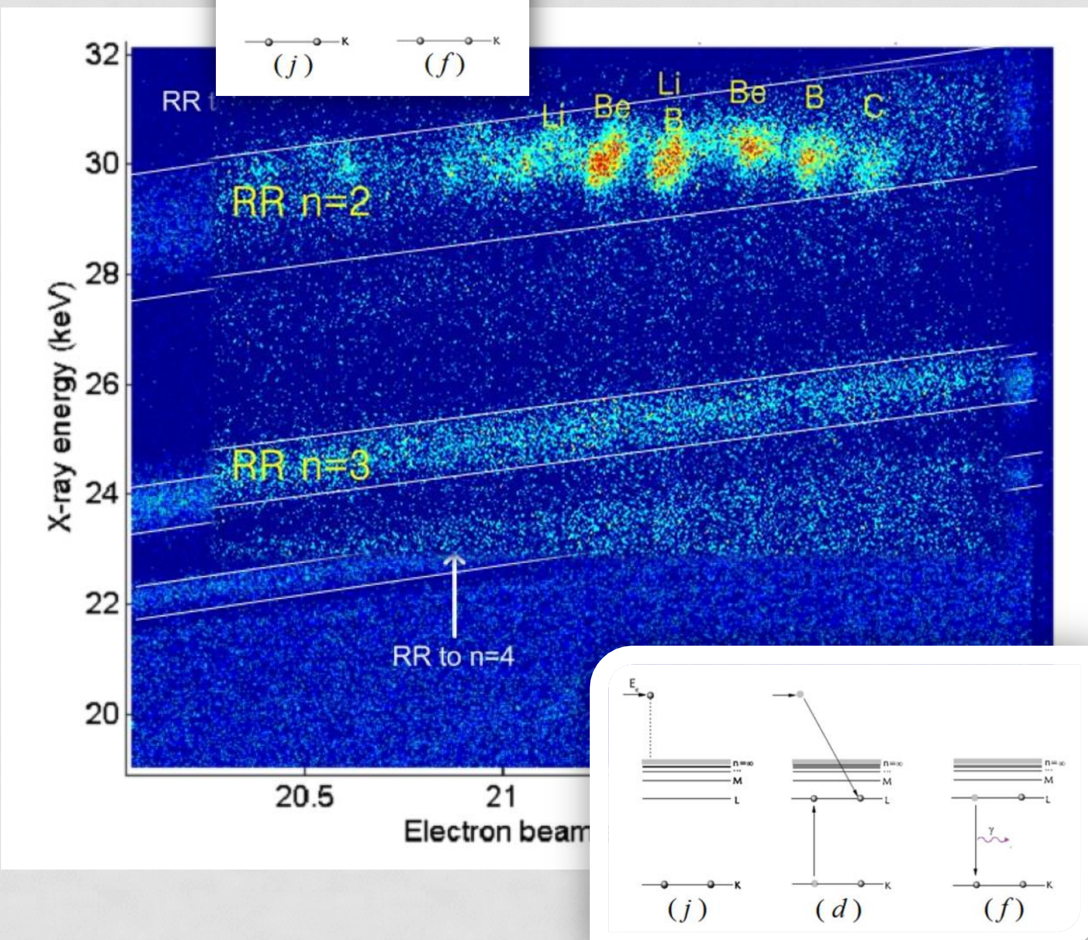


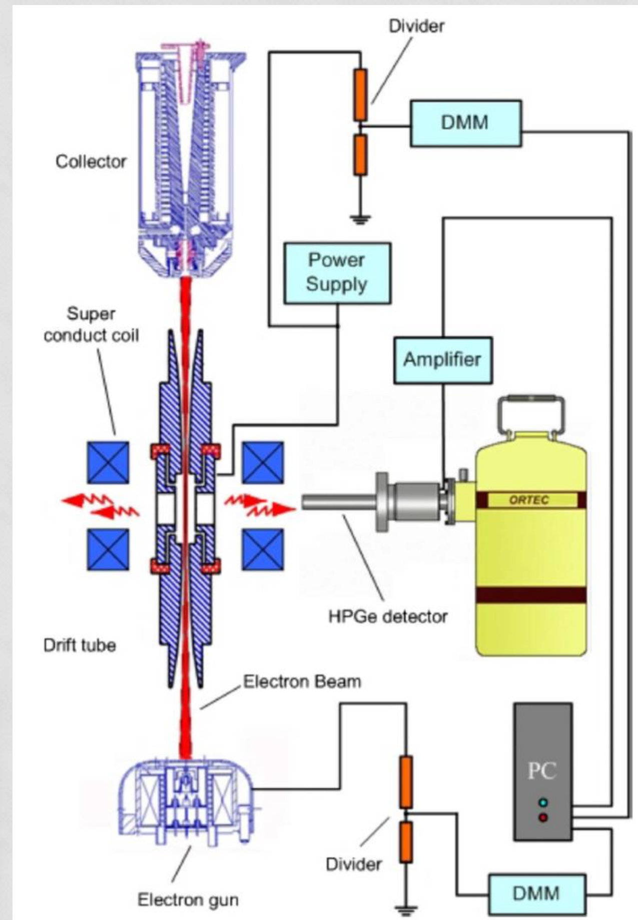
Parameters	Achieved
Electron energy	30-4000 eV
Beam current	10 mA
Beam radius	~65 μm
Vacuum	~1.0×10^{-9} torr
LN_2 consumption	0.6 ~1.5 L/h
Magnetic field	0~0.25 T

HOW EBIT WORKS FOR DR MEASUREMENT

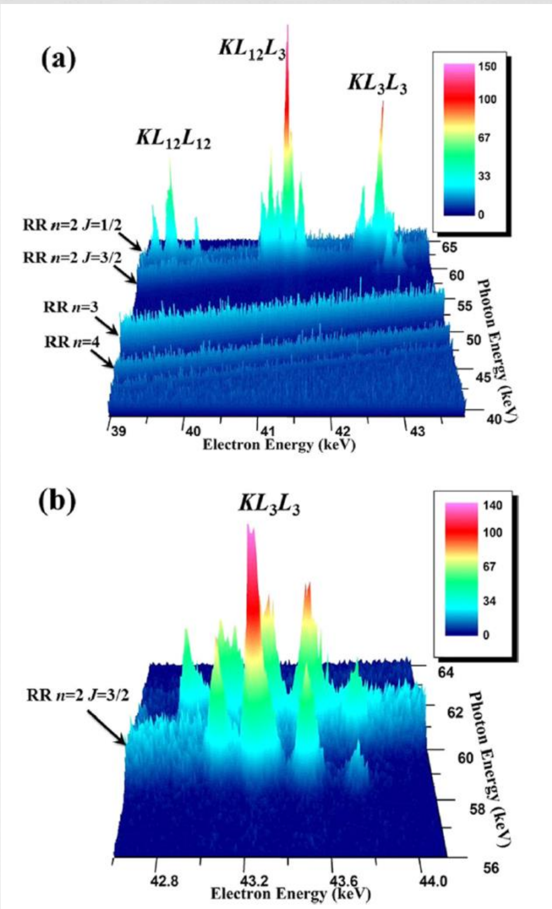


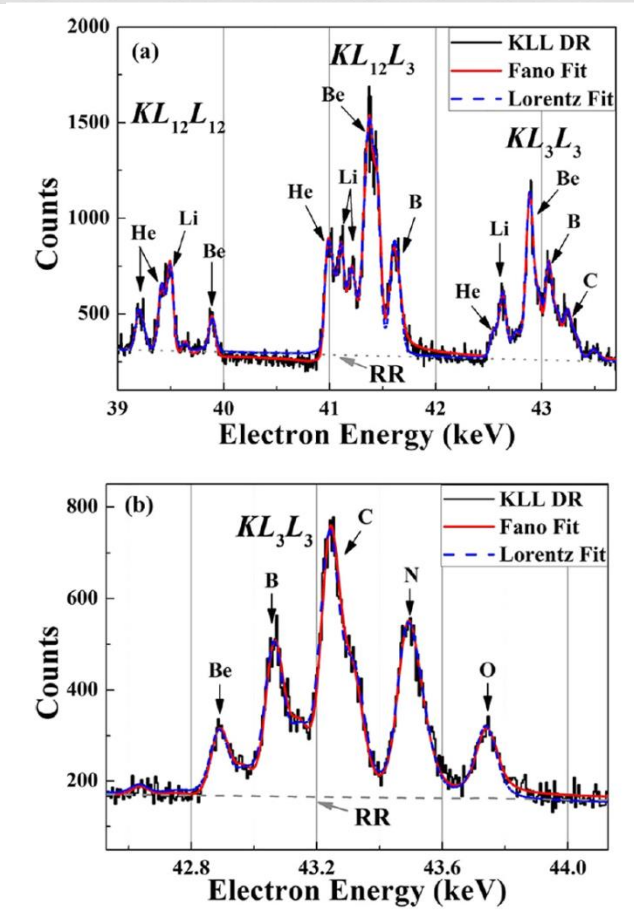




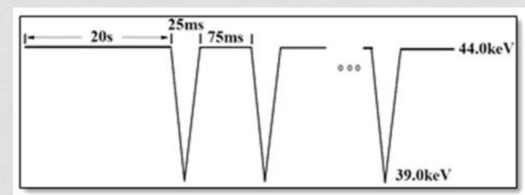


DATA ANALYSIS FOR TUNGSTEN MEASUREMENTS





	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

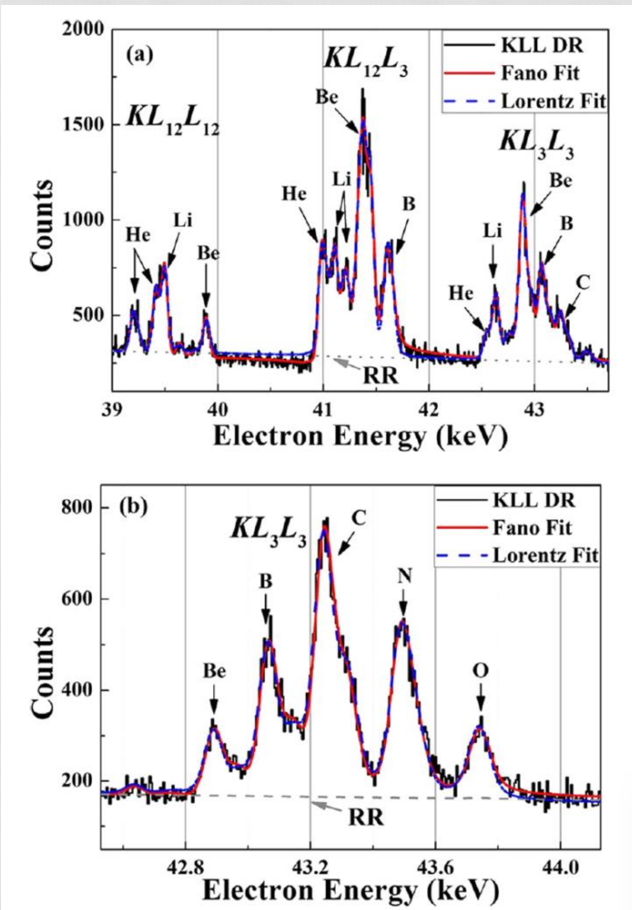


	Expt. B
Electron energy scanned	42.5 – 44.1 keV
Electron beam current	140 mA
Gas injection pressure	2×10^{-7} Torr
Trapping potential	130 V
Electron energy spread	61 eV
Charge state obtained	Be- up to O-like

W(CO)6

*B. Tu, et. Al,. Phys. Plasmas **23**, 053301 (2016)*

DATA ANALYSIS FOR TUNGSTEN MEASUREMENTS *CON'T*

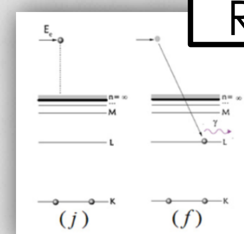


$$C(q,E) = D(E)\sum_q f_q \left[\frac{d\sigma_{RR}(q,E)}{d\Omega} + \frac{\sum_{jdf} S_{jdf} \times DR(q,E) \times W_{df}(90°)}{4\pi} \right]$$

$$\begin{aligned} DR_{Lorentz} &= \int_{-\infty}^{+\infty} L(E')G(E'-E)dE' \\ &= \frac{2ln2\Gamma_d}{w^2\pi\sqrt{\pi}} \int_{-\infty}^{+\infty} \frac{e^{-t^2}}{(t-x)^2+y^2} dt, \end{aligned}$$

$$t = \frac{2\sqrt{ln2}(E'-E)}{w}; \quad x = \frac{2\sqrt{ln2}(E_d-E)}{w}; \quad y = \frac{\sqrt{ln2}\Gamma_d}{w},$$

RR



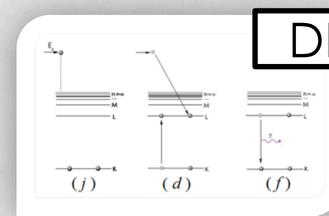
$$\begin{aligned} DR_{Fano} &= \int_{-\infty}^{+\infty} \boxed{F(E')} G(E'-E)dE' \\ &= \frac{2}{Q^2\Gamma_d\pi\sqrt{\pi}} \\ &\times \int_{-\infty}^{+\infty} \left[\frac{(Qy+t-x)^2+(B_a-1)^2y^2}{(t-x)^2+y^2} - 1 \right] e^{-t^2} dt, \end{aligned}$$

$$F(E) = \frac{2}{Q^2\Gamma_d\pi} \left[\frac{(Q+\epsilon)^2+(B_a-1)^2}{1+\epsilon^2} - 1 \right],$$

$$\epsilon = \frac{2(E_e-E_d)}{\Gamma_d}; Q = \frac{2\langle i|V|d\rangle\langle d|R|f\rangle}{\Gamma_d\langle i|R|f\rangle},$$

$B_a = \Gamma_a / \Gamma_d$

DR



DATA SHEETS

S_{idf}, $D(E)_{(etector)}$, f_q, and the beam energy width w are the free parameters

All others, including r… idth of middle state Γd, Fano factor Q, autoi… fferential cross sections of n=2 RR, and angu… 90, are calculated by RCI method in FAC.

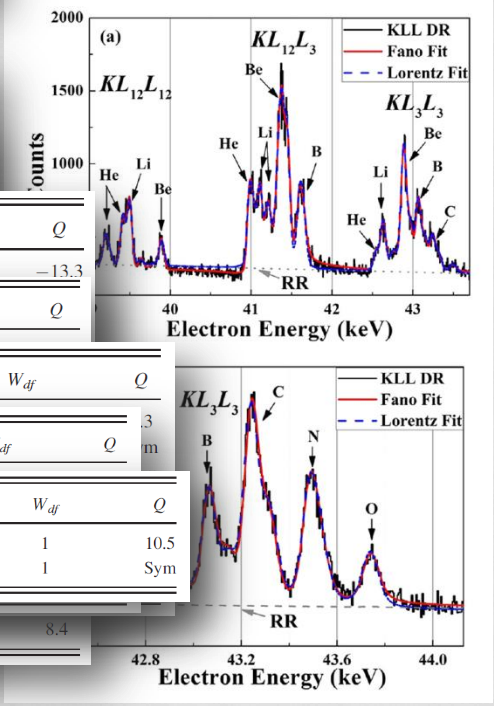
TABLE IX. Two sets of fitted charge state distribution f_q in Expt. A and Expt. B.

	He	Li	Be	B	C	N	O	F
Expt. A	6.5%	21.0%	30.2%	24.8%	13.0%	4.5%		
Expt. B		<1%	3.5%	9.7%	17.2%	23.0%	26.7%	19%

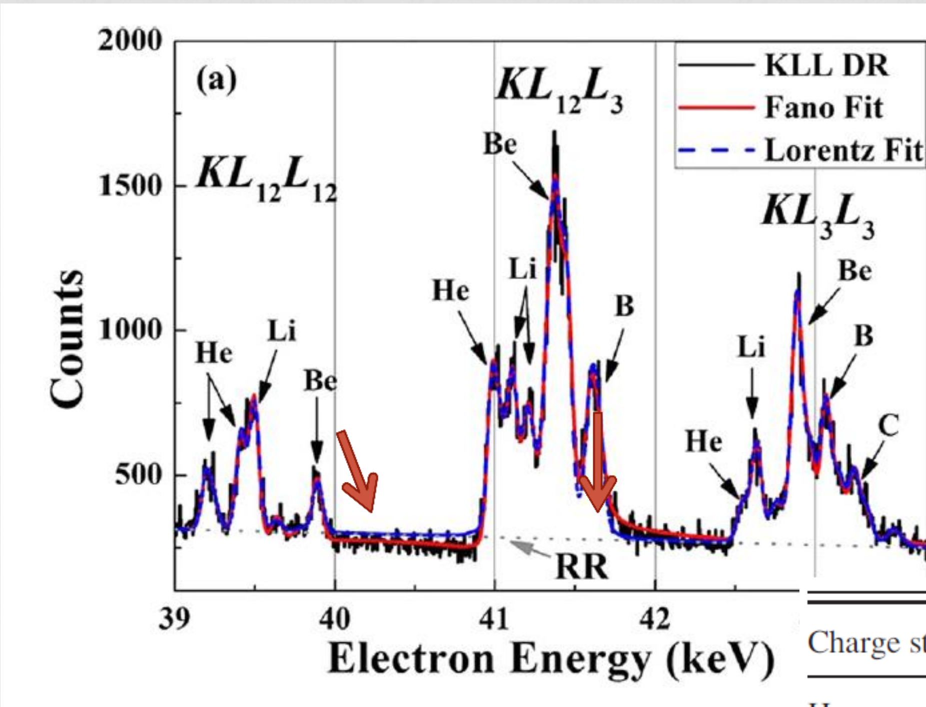
S (10^{20} cm^2 eV)

Label	Middle state	Final state	E_{res}	Γ(eV)	S	W_{df}	Q
O_1	$[1s2s^22p^2_{1/2}2p^4_{3/2}]_{1/2}$	$[1s^22s^22p^2_{1/2}2p^3_{3/2}]_{3/2}$	43739	34.263	0.289	1	10.5
		$[1s^22s^22p_{1/2}2p^4_{3/2}]_{1/2}$			0.138	1	Sym

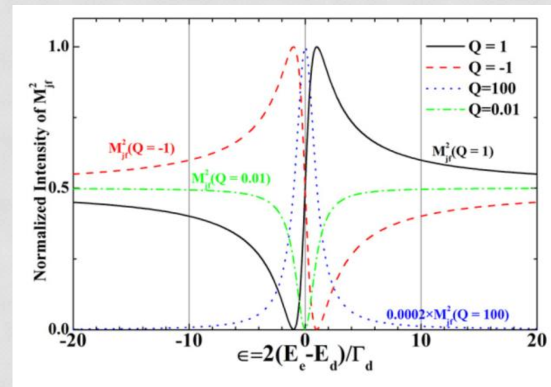
Label	Middle state	Final state	E_{res}	Γ(eV)	S	W_{df}	Q
B_6	$[(1s2s^22p_{1/2})_0(2p^2_{3/2})_2]_2$	$[1s^22s^22p_{1/2}2p_{3/2}]_2$	43143	19.687	0.236	0.77	8.4



IMPROVEMENTS BY USING FANO PROFILES

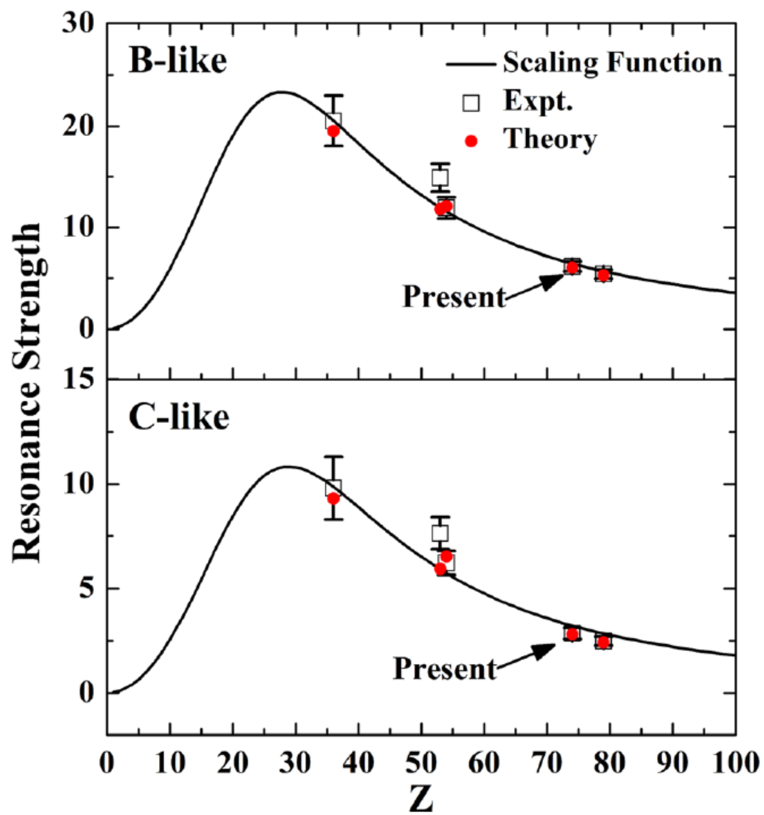


Label	Middle state	Final state	E_{res}	S	Q
Be_3	$[(1s2s^22p_{1/2})_12p_{3/2}]_{5/2}$	$[1s^22s^22p_{3/2}]_{3/2}$	41373	3.354	14.9
Be_4	$[(1s2s^22p_{1/2})_02p_{3/2}]_{3/2}$	$[1s^22s^22p_{1/2}]_{1/2}$	41444	2.041	6.6



Charge state	$S_{expt}(Fano)$	$S_{expt}(Lorentz)$	S_{theory}
He	22.99(2.13)	23.26(2.35)	22.35
Li	14.31(1.20)	12.58(1.08)	13.70
Be	10.17(0.77)	10.16(0.88)	9.95
B	6.18(0.50)	6.62(0.54)	6.05
C	2.85(0.27)	3.18(0.28)	2.81
N	1.37(0.09)	1.44(0.10)	1.35
O	0.41(0.03)	0.46(0.04)	0.43

KLL RESONANCE SCALING AS THE ATOMIC NUMBER Z



$$S = \frac{1}{m_1 Z^2 + m_2 Z^{-2}},$$

Ions	m_1	m_2
B-like	2.77(0.07)	16.6(1.6)
C-like	5.53(0.4)	38.5(9.2)

UNCERTAINTIES

- Uncertainties of the resonance strengths are less than 11%.
  - the statistic uncertainties and peaks mixing from weak resonances of each charge state 3–8%
  - RR cross-section calculation, which is considered to have an uncertainty of about 3%
  - the change of charge state distribution in a single sweep cycle
  - …

$$\frac{\Delta N_q}{N_q} = -\langle j_e \rangle S \frac{dt}{dE}, \tag{6}$$

where $\langle j_e \rangle$ is the effective electron beam flux density, and dE/dt is the scanning rate. Using the total resonance strength, $\Delta N_q/N_q$ is estimated to be less than 1% for each charge state, except for Be-like of 1.3% in Expt. B.

THANK YOU FOR YOUR ATTENTION

AND MERRY CHRISTMAS!!