Technical Meeting on Uncertainly Assessment and Benchmark Experiments
for Atomic and Molecular Data for Fusion Applications
Vienna, Austria, 19-21 December, 2016

Atomic and Molecular Data provided by Multiply Charged Ion Beam Collision Experiments at Low Energies

Hajime Tanuma
Department of Physics
Tokyo Metropolitan University

Charge eXchange Spectroscopy (CXS)

$$P^{q+} + T \rightarrow P^{(q-t)+*} + T^{t+}$$

$\downarrow$ **photon : energy, intensity**

$$P^{(q-t)+}$$

P : projectile, T : target

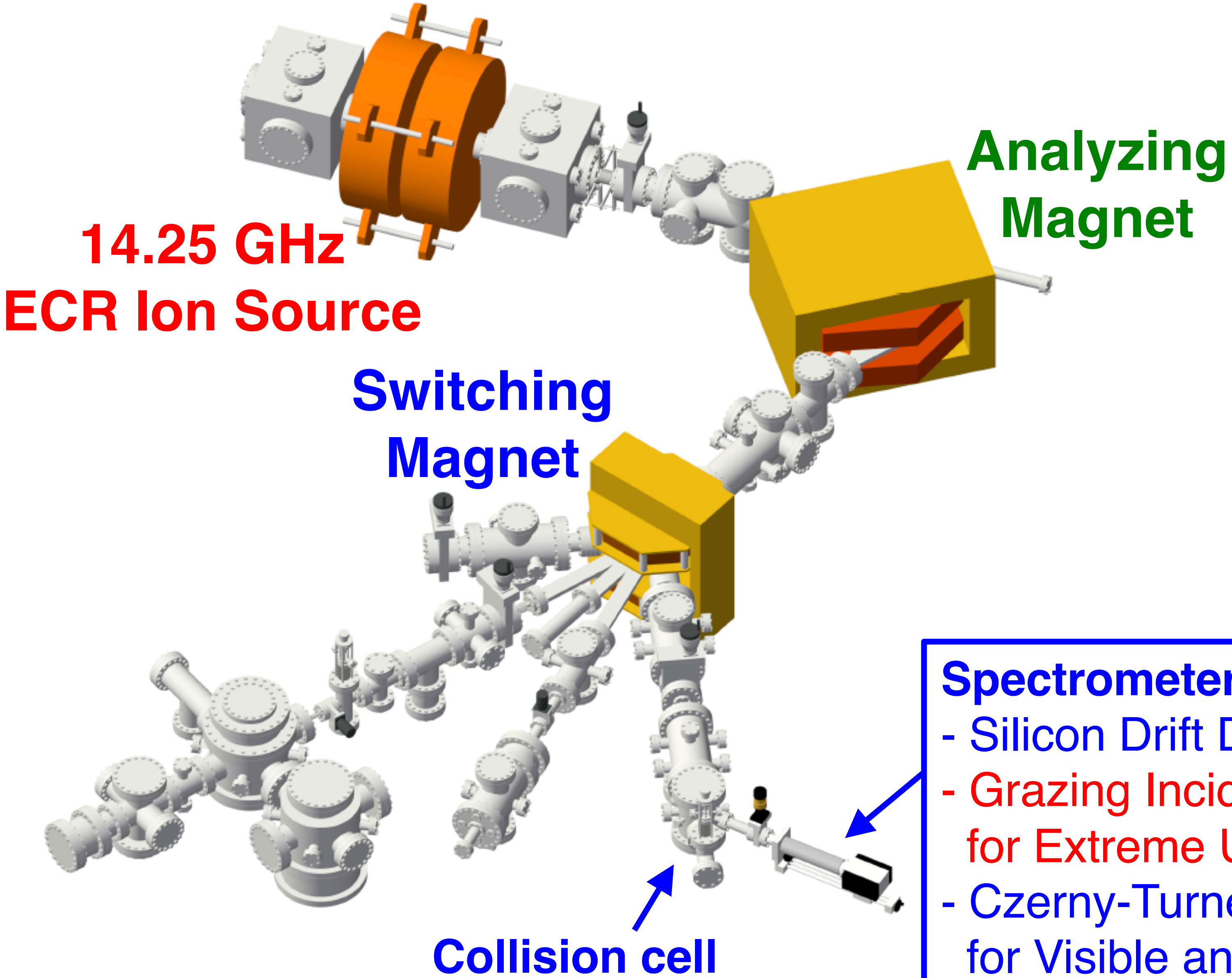
Experimental method for measurements of

1. **Charge transfer cross sections**
2. **Transition wavelengths**

Today's three messages from CXS

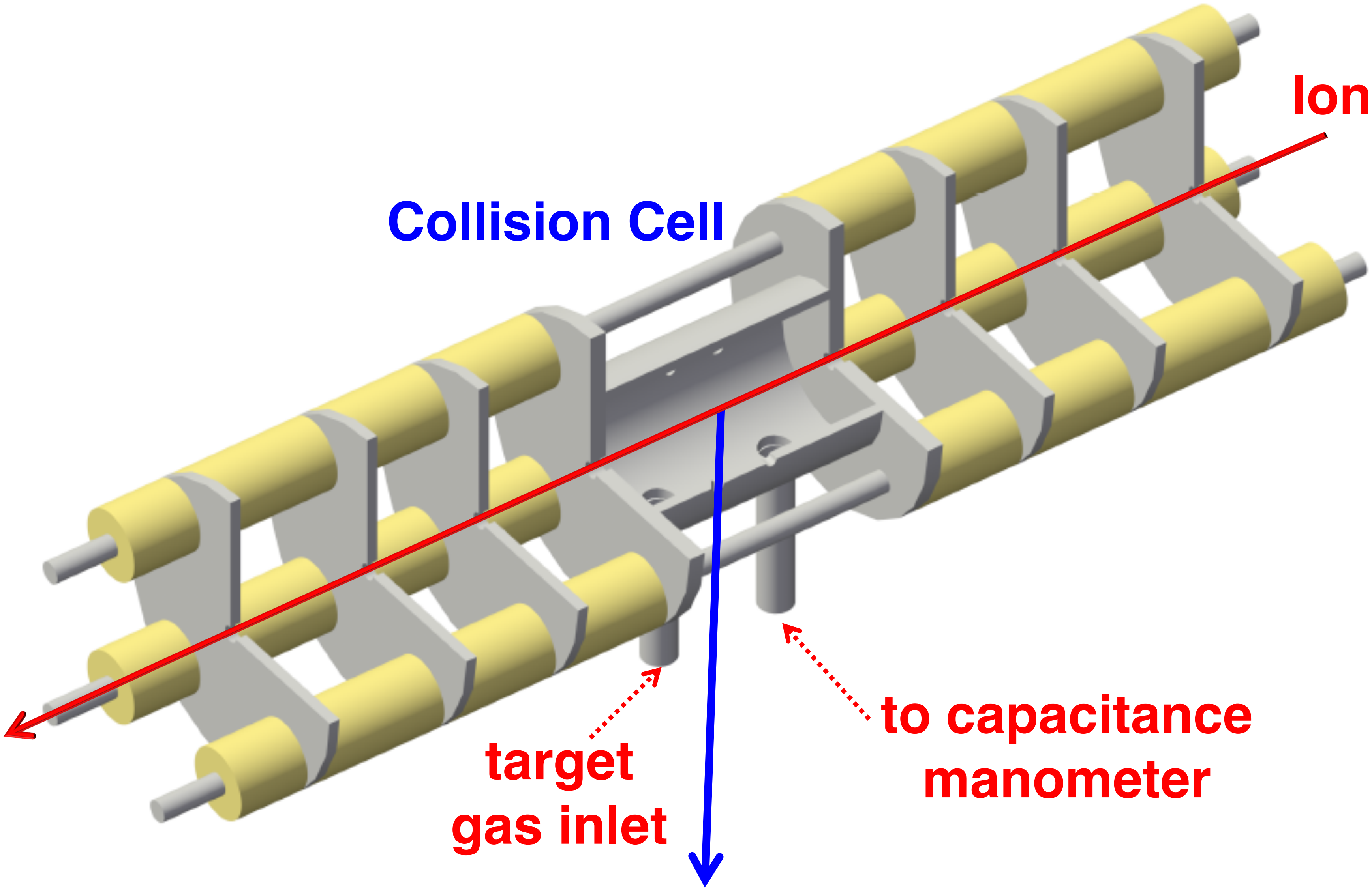
1. **CX spectra of lower charged W ions might be not suitable for plasma diagnosis.**
2. **Meta-stable He-like ions are interesting, but make cross section measurements complicated.**
3. **Triplet-Singlet ratios are very important in collisions of H-like ions with neutrals.**

Multiply Charged Ion Beam Lines in TMU



Spectrometers
- Silicon Drift Detector for X-ray
- Grazing Incident Spectrometer for Extreme Ultra-Violet
- Czerny-Turner Spectrometer for Visible and UV

Setup for X-ray measurements



Magic Angle = 54.736°

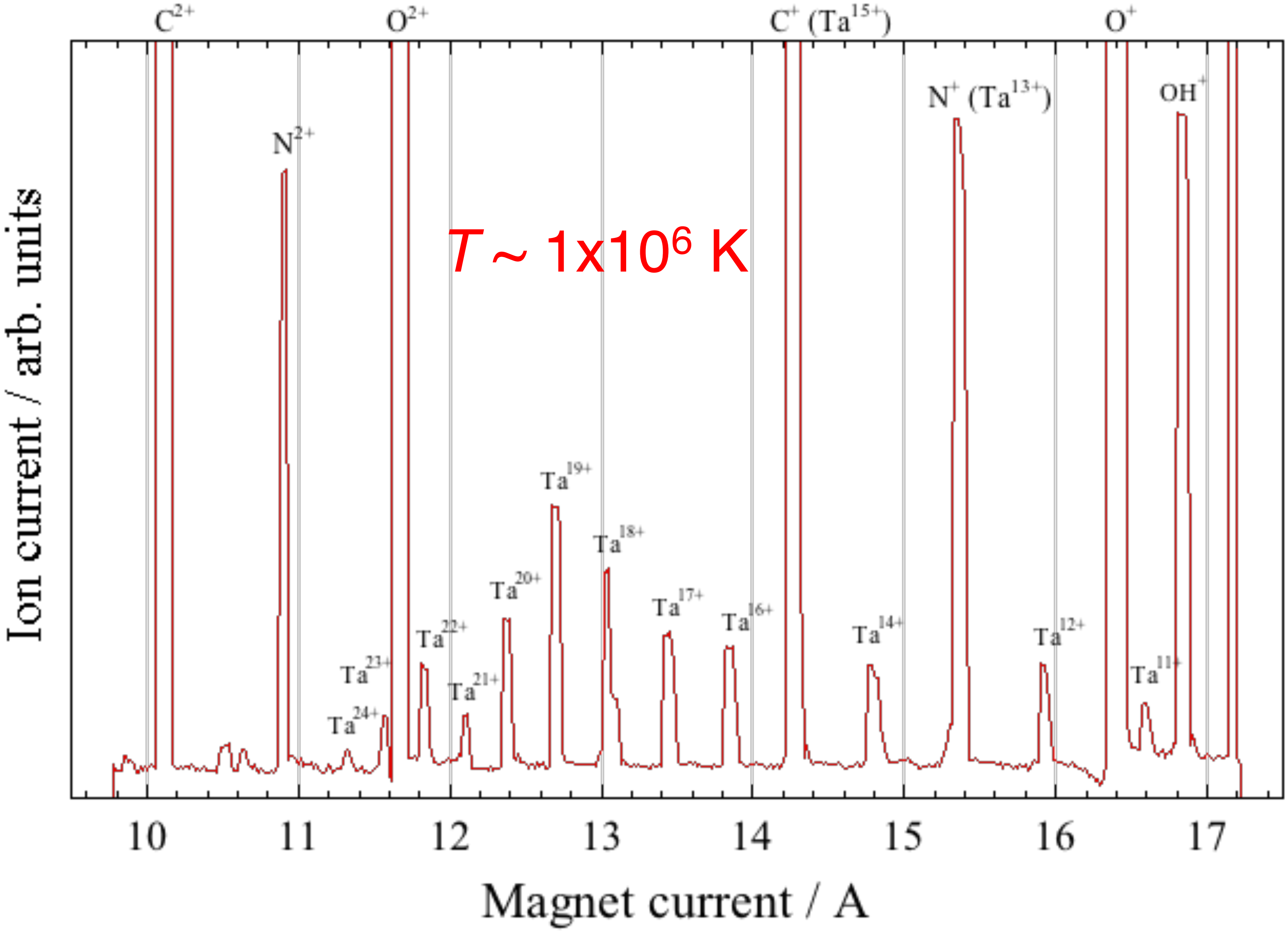
Ta instead of W

Isotopes of Ta & W

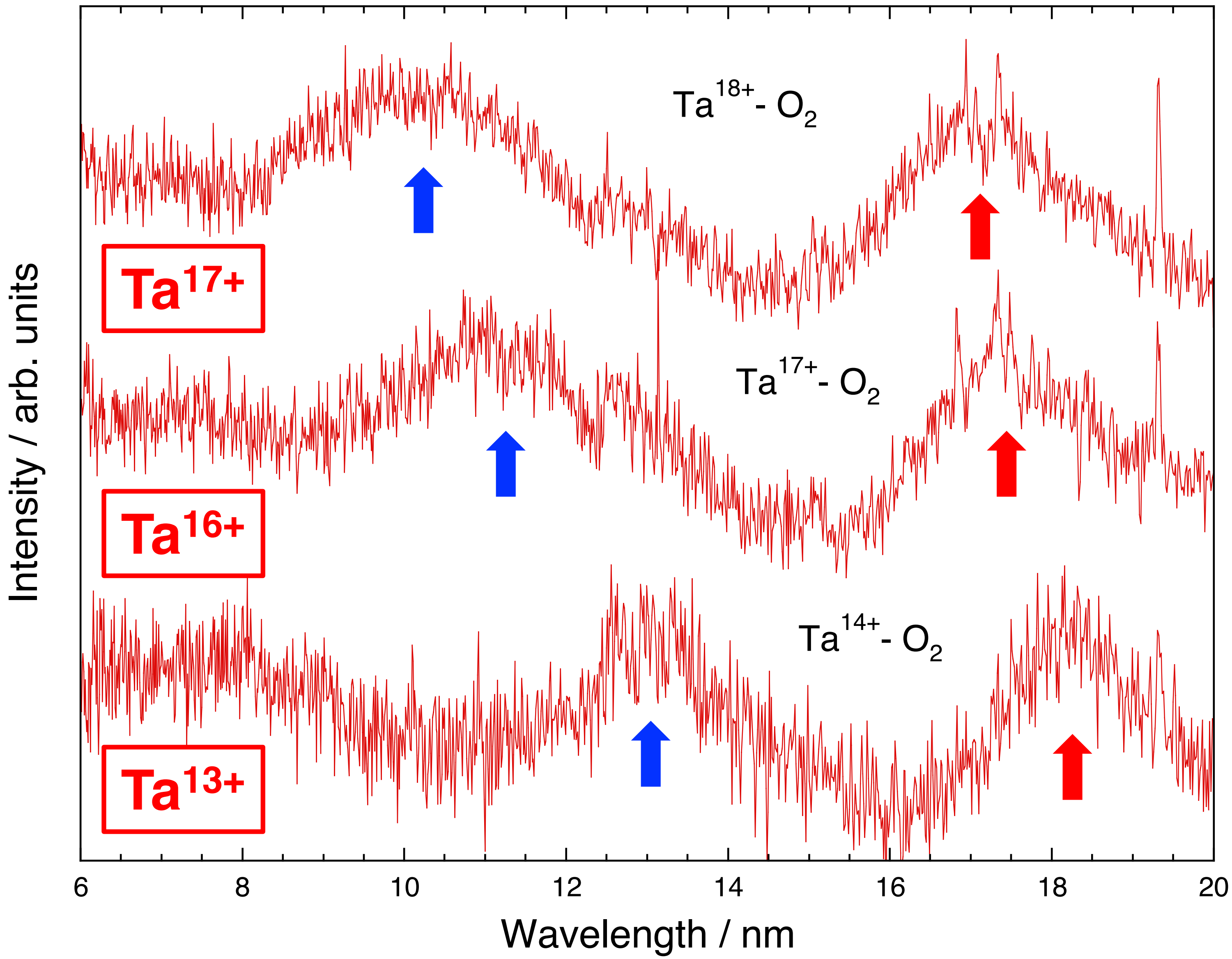
$Z = 73$		$Z = 74$		
Ta		**W**		
A	*NA*	*A*	*NA*	*A* : mass number
180	0.012%	180	0.12%	*NA* : natural abundance
181	**99.988%**	182	26.50%	
		183	14.31%	
		184	**30.64%**	
		186	28.43%	

For ion beam experiments with charge state separation, Ta is much suitable.

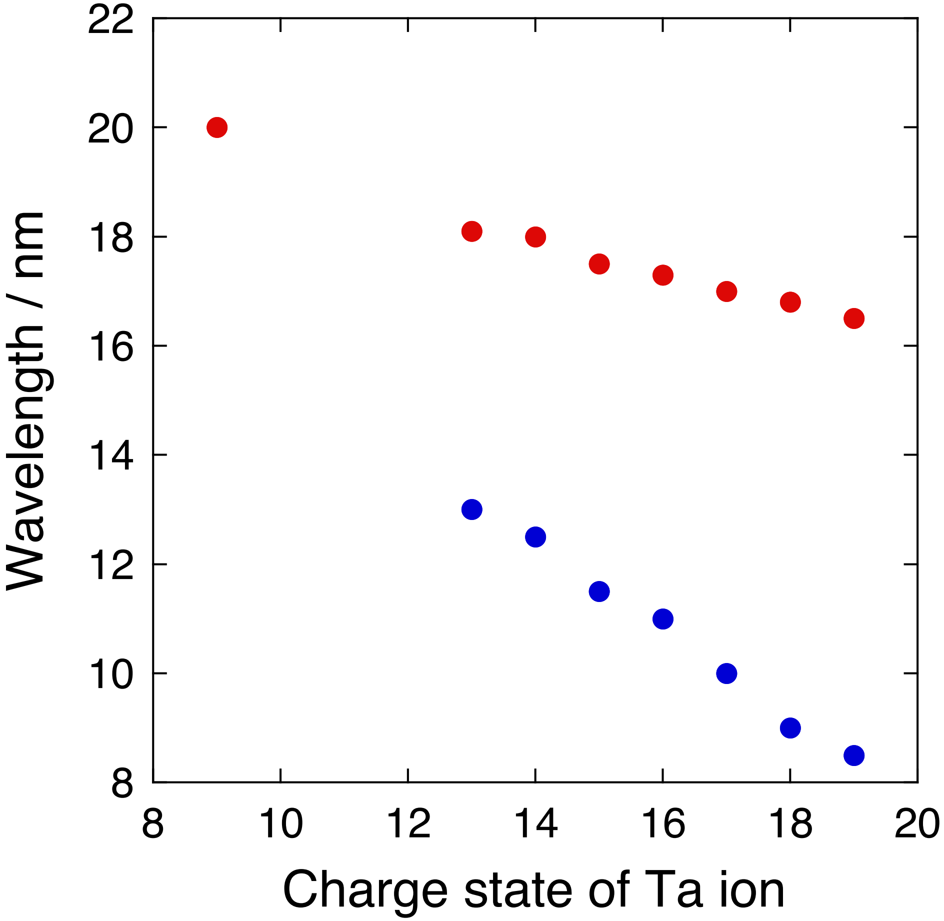
Mass Spectrum of Ta Ions



EUV Spectra in collisions with O_2



Charge dependence of UTA Peaks



Two series of UTAs with wide spreads

Identification of transitions is now in progress.
But, it seems to be difficult by the Cowan code.

Without charge separation, it might be difficult to distinguish charge states in EUV spectra of Ta.

The production mechanism of the excited states

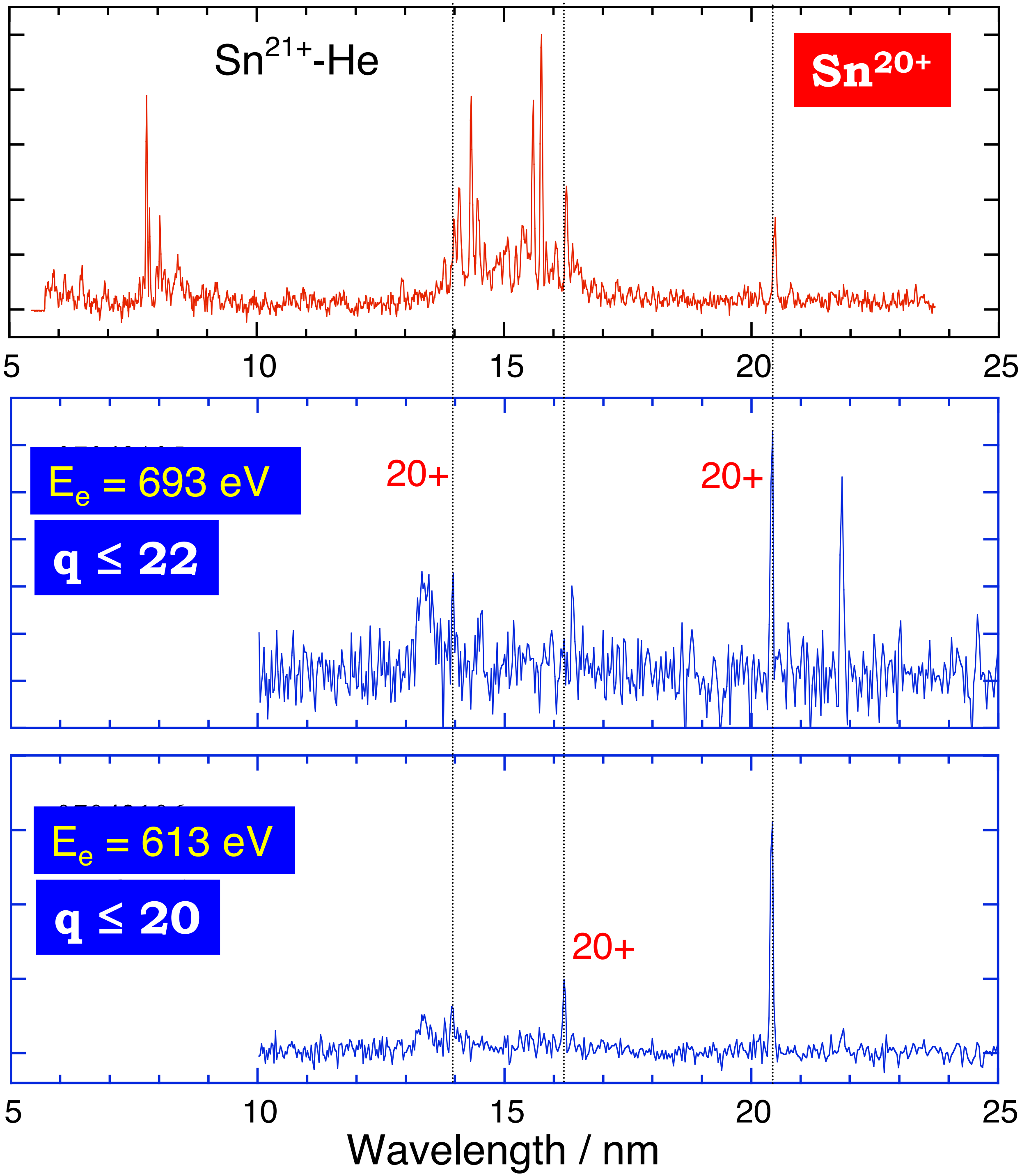
Plasmas (LPP, LHD, EBIT, etc.) :

excitation from the ground state
by electron impact
→ Almost **Resonance Lines (RL)**

CXS :

electron transfer to the excited orbital from
the neutral targets
→ **Transitions between excited states (TBES)**

Different mechanism = Complementary data
→ *"Complementary Spectroscopy"*



CXS@TMU

3 RL of Sn^{20+}
& many TBES

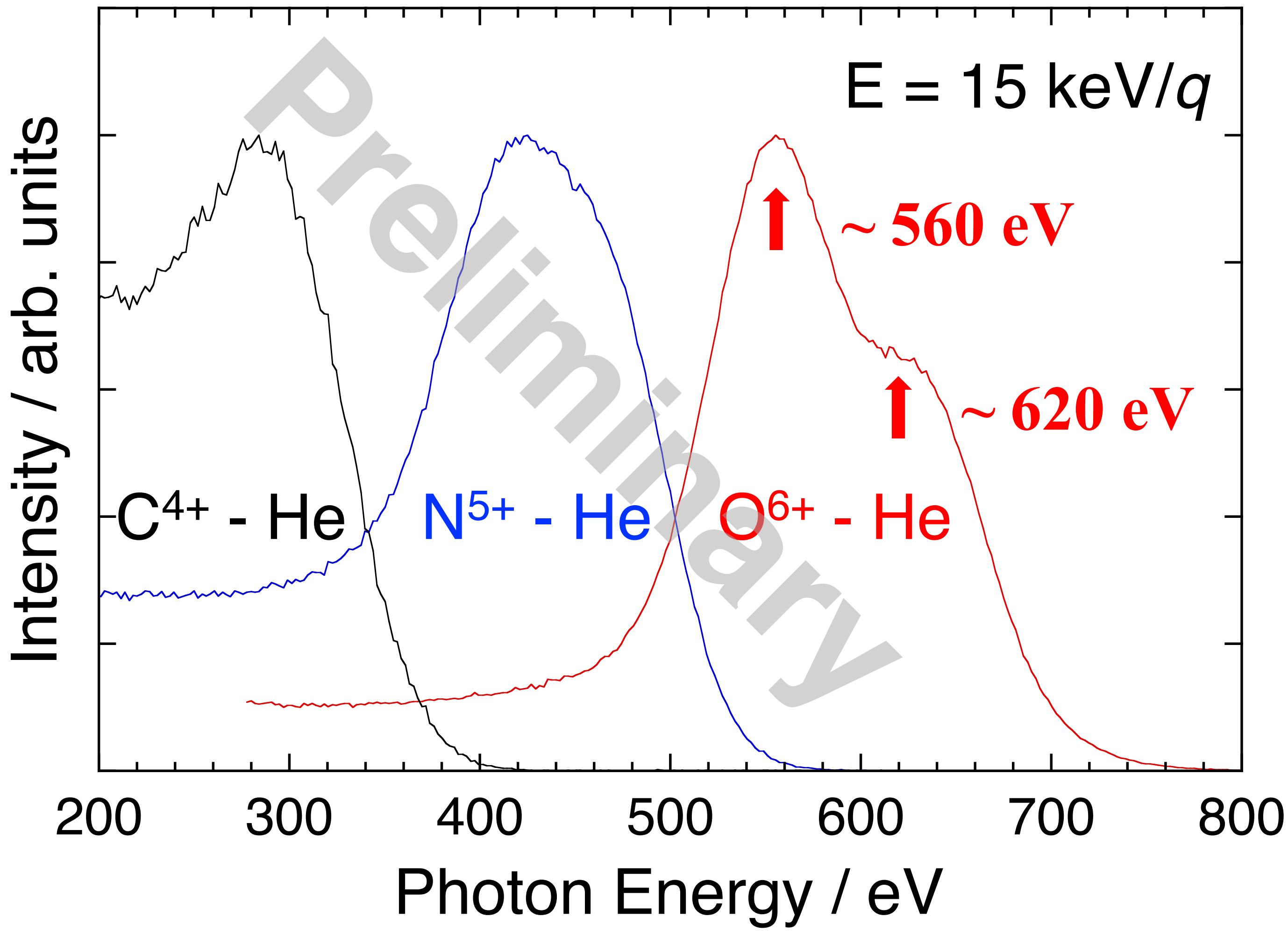
EBIT@UEC

q	IP / eV
+22	1127
+21	642
+20	608
+19	537

IP = Ionization Potential

Meta-stable He-like Ions

Un-expected Soft X-ray emissions in collisions of He-like ions with He



C^{3+} (1s^2 nl) :
< 64 eV

N^{4+} (1s^2 nl) :
< 98 eV

O^{5+} (1s^2 nl) :
< 138 eV

Silicon Drift Detector : ΔE ~ 70 eV

Energy Level Data in NIST ASD

O^{5+}	$1s^2 2s\ ^2S_{1/2}$	: IP = 138.12 eV
	$1s2s(^3S)2p\ ^4P_J$	: 554.24 eV
	$1s2s(^3S)2p\ ^2P_J$	: 562.59 eV
	$1s2s3s\ ^4S_{3/2}$	: 636.03 eV

$h\nu \sim 560$ eV : O^{5+} $1s^2 2s - 1s2s2p$

$h\nu \sim 620$ eV : O^{5+} $1s^2 2s - 1s2s3s$

Why 1s2s*nl* states are produced?

Meta-stable states in a primary ion beam

He-like ions : few % of 1s2s $^3S_1$ from ECRIS

$$O^{6+}(1s2s\ ^3S_1) + He \rightarrow O^{5+}(1s2s\,nl) + He^+$$

$$\rightarrow O^{6+}(1s^2) + e^- \quad \text{: Auger}$$

$$O^{6+}(1s2s\ ^3S_1) + He \rightarrow O^{5+}(1s2s\,nl) + He^+$$

$$\rightarrow O^{5+}(1s^2 2s) + h\nu$$

Influence of 1s2s states on cross section measurements are not clear.

Theoretical Auger and X-ray emission rates

TABLE II. Theoretical Auger and x-ray emission rates (in a.u.[a]) for states of the $1s2s2p$ configuration of Li-like ions of atomic number Z.

State / Z	6 C		7 N		8 O		9		10	
	Auger	x ray	Auger	x ray	Auger	x ray	Auger	x ray	Auger	x ray
$^2P^{(+)}_{1/2}$	1.48(−3)	2.21(−6)	1.65(−3)	4.57(−6)	1.78(−3)	8.46(−6)	1.89(−3)	1.45(−5)	1.98(−3)	2.36(−5)
$^2P^{(-)}_{1/2}$	2.01(−4)	1.72(−5)	2.05(−4)	3.58(−5)	2.06(−4)	6.64(−5)	2.09(−4)	1.13(−4)	2.15(−4)	1.80(−4)
$^2P^{(+)}_{3/2}$	1.48(−3)	2.16(−6)	1.66(−3)	4.38(−6)	1.79(−3)	7.87(−6)	1.89(−3)	1.30(−5)	1.99(−3)	1.99(−5)
$^2P^{(-)}_{3/2}$	1.92(−4)	1.73(−5)	1.90(−4)	3.60(−5)	1.82(−4)	6.70(−5)	1.74(−4)	1.15(−4)	1.66(−4)	1.84(−4)
$^4P_{1/2}$	6.50(−9)	4.19(−11)	1.26(−8)	2.25(−10)	2.13(−8)	9.34(−10)	3.29(−8)	3.24(−9)	4.78(−8)	9.84(−9)
$^4P_{3/2}$	1.73(−9)	1.04(−10)	2.60(−9)	5.57(−10)	3.17(−9)	2.33(−9)	3.07(−9)	8.17(−9)	2.15(−9)	2.48(−8)
$^4P_{5/2}$	2.06(−10)	3.97(−13)	4.45(−10)	1.69(−12)	8.49(−10)	5.73(−12)	1.48(−9)	1.66(−11)	2.43(−9)	4.21(−11)

[a] 1 a.u. $= 27.21$ eV/$\hbar = 4.134\times10^{16}$ sec^{-1}. Numbers in parentheses stand for powers of 10, e.g., $1.48(-3) = 1.48\times10^{-3}$.

Auger < (or <<) X-ray

M. H. Chen *et al*., Phys. Rev. A **27** (1993) 544.

Triplet-Singlet Ratios

Triplet-Singlet ratios in CX

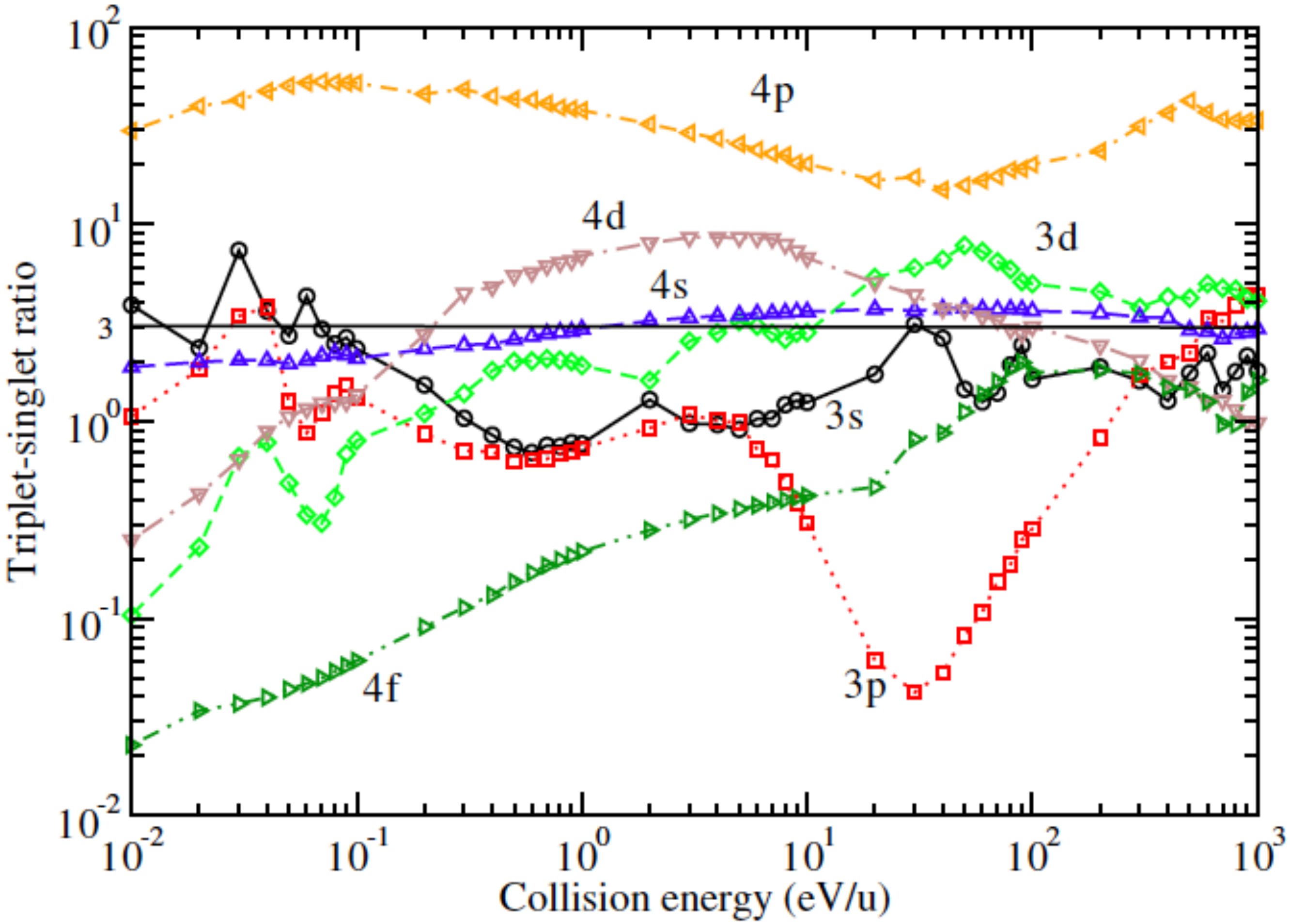


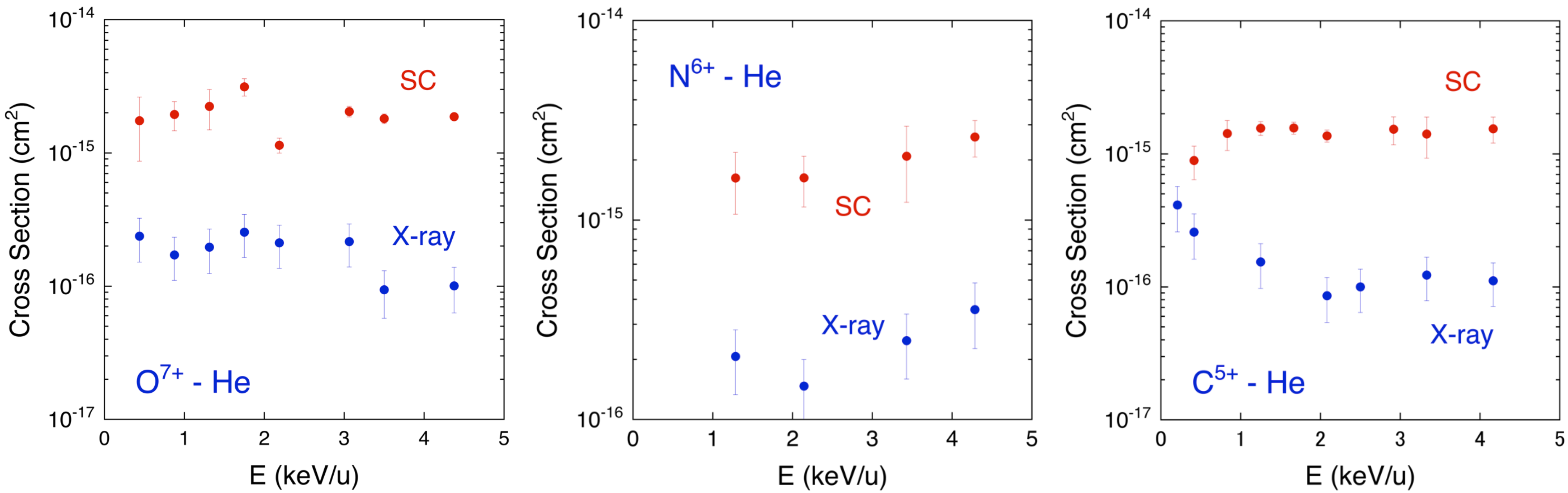
Figure 12. Triplet–singlet ratios obtained from QMOCC results for *n*, *l*-resolved cross sections for C^{5+}+H.

Statistical weights

$$\frac{\sigma_{\mathrm{Triplet}}}{\sigma_{\mathrm{Singlet}}} = 3$$

J. L. Nolte *et al*., J. Phys. B **45** (2012) 245202.

Preliminary Cross Section Data



SC (Single Capture) : H-like → He-like (1s*nl*, Total)

True SC + Transfer Ionization (TI)

X-ray : Emission from He-like

w ($1s^2 \leftarrow 1s2p\ ^1P_1$) + *partially* y ($1s^2 \leftarrow 1s2p\ ^3P_1$)

$$\frac{\sigma_S + \sigma_T}{\sigma_S} > \frac{\sigma_{SC}}{\sigma_{Xray}} > 4$$

Summary

1. **CXS of Ta (instead of W) ions in the EUV region**
   Ta^{q+} : $q = 10 – 20$
2. **The first observation of UTAs in 8 - 20 nm**
3. **Complimentary data from EBITs are required.**
4. **We need theoretical calculation for identification of emission lines.**
5. **Meta-stable states in the primary He-like beams might contribute to the uncertainty of cross section measurements using ECRIS.**
6. **Triplet-Singlet ratios might be far from the statistical weights in charge exchange collisions of H-like ions with neutral targets.**

Collaborators

Nobuyuki NAKUMURA, Univ. of Elecro-Communications

Kunihiro OKADA, Sophia Univ., Tokyo

Gerry O'SULLIVAN, Univ. College Dublin

Ling LIU & Jianguo WANG, IAPCM, Beijing

(Phillip Stancil, Univ. of Georgia)

Present students	**Past students**
Naoki NUMADATE	**Hirofumi SHIMAYA**
Yoshiyuki UCHIKURA	**Takuya ISHIDA**
Kento SHIMADA	**Takuma KANDA**
Takuto AKUTSU	**Hayato OHASHI**

Thank you for your attention.

Go raibh maith agat.

謝 謝

감사합니다

御静聴ありがとうございました。