Observation and Identification of Tungsten Spectra Observed with an Electron Beam Ion Trap:
Benchmarking atomic structure calculations

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Contents

- Electron beam ion trap (EBIT)
  compact EBIT (CoBIT)
- Observation and identification of previously unreported lines
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Electron beam ion trap (EBIT)

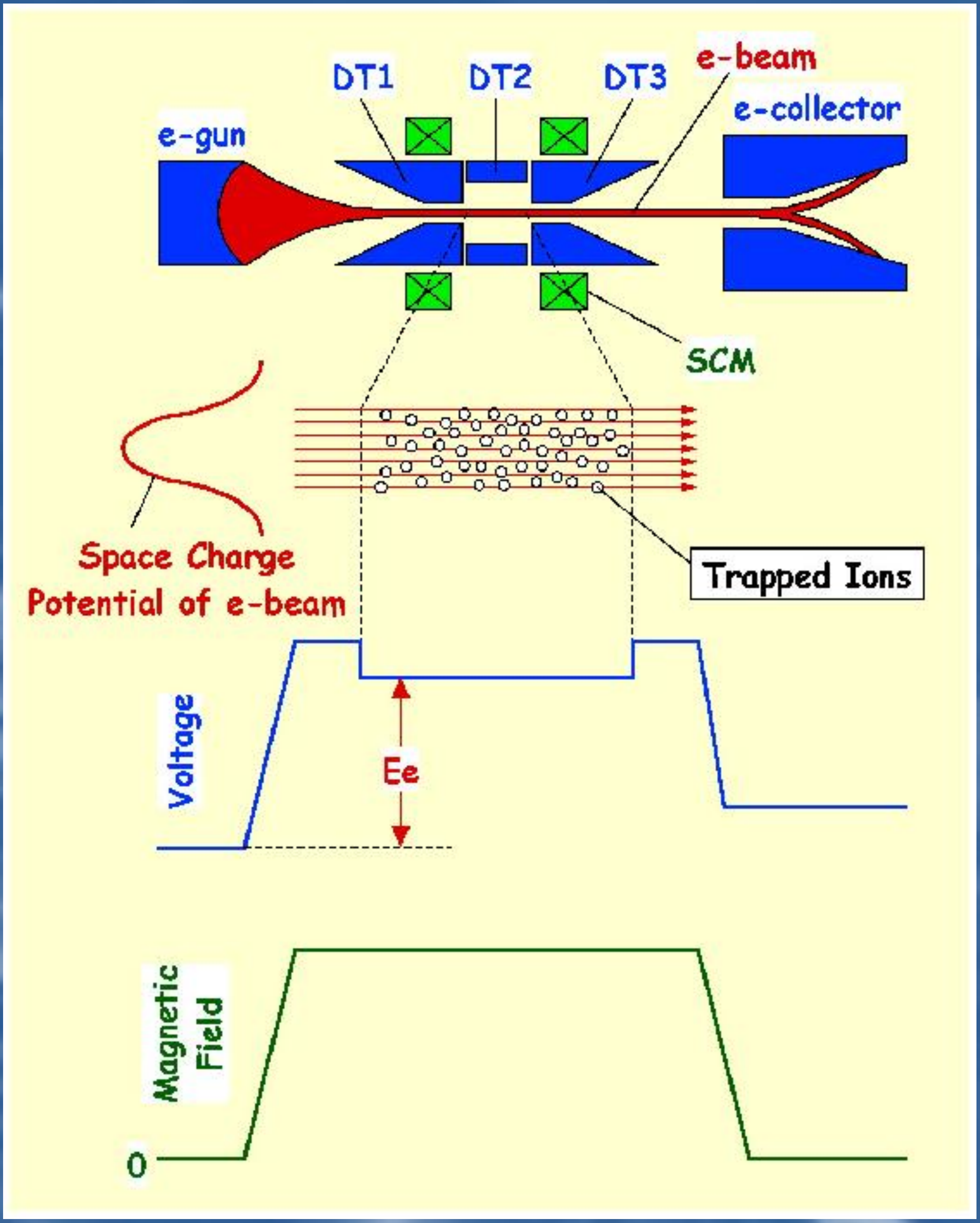
A Penning-like trap + a high energy e-beam.

Axial potential applied to the drift tube (DT) and the space charge of the electron beam confines the ions.

Highly charged ions are produced through successive electron impact ionization with a high density electron beam compressed by a strong magnetic field.

Radiation from the trapped ions can be observed through the observation slits opened at the middle of the ion trap.

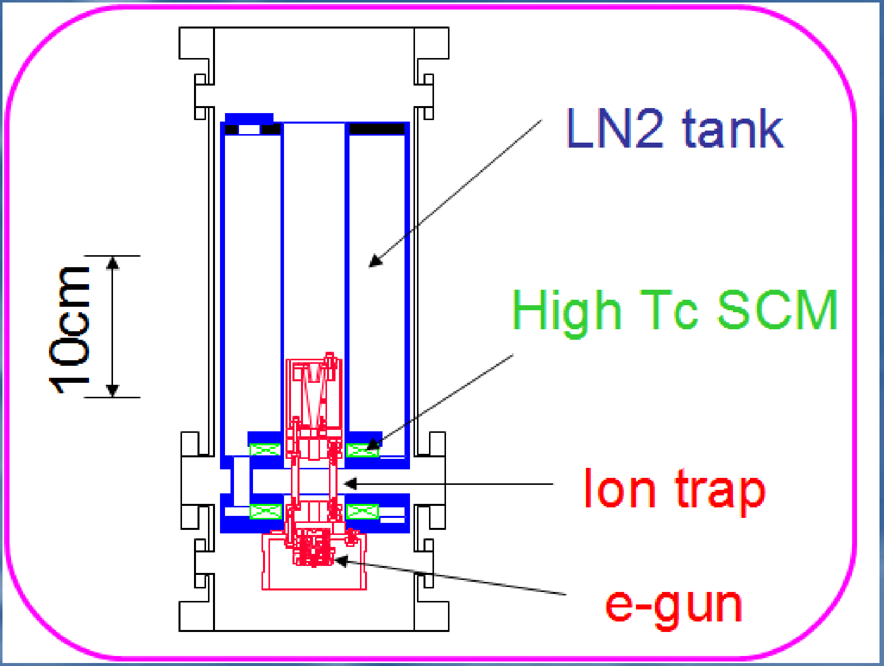
The ions can be extracted axially through the electron collector.



Spectroscopy with an EBIT

- **Ionization and excitation with an unidirectional mono-energetic electron beam**
  - in contrast with plasma spectroscopy -
  - Narrow charge state distribution with a coronal plasma condition.→ Advantage in the identification of previously unreported lines.
  - Energy dependence, Excitation function, Resonance processes.
  - Anisotropy, Polarization.
  - Capable of arbitrary changing energy, current, electron density.
    → Well-defined plasma.
    → Good benchmark spectra for plasma models.
  - Thin line-shape source → slit-less configuration.

Compact EBIT (CoBIT) since 2008

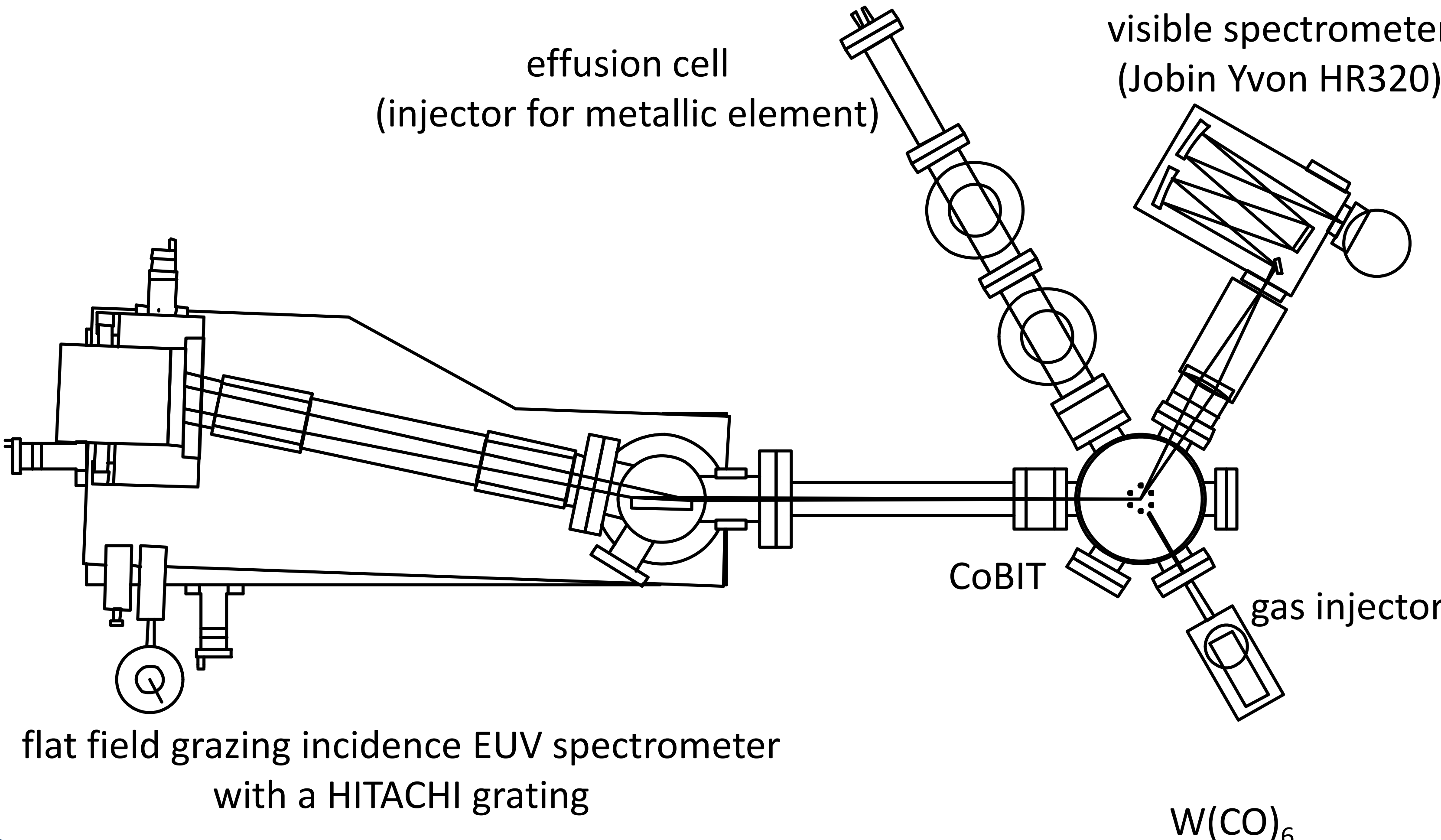


<u>Specifications</u>

e-beam energy	100 - 2500 eV
e-beam current	20 mA (max)
Magnetic field	0.2 T (max)
Temperature	77 K (High-Tc SCM)

Acknowledgement: NINS collaboration project

Experimental setup for CoBIT



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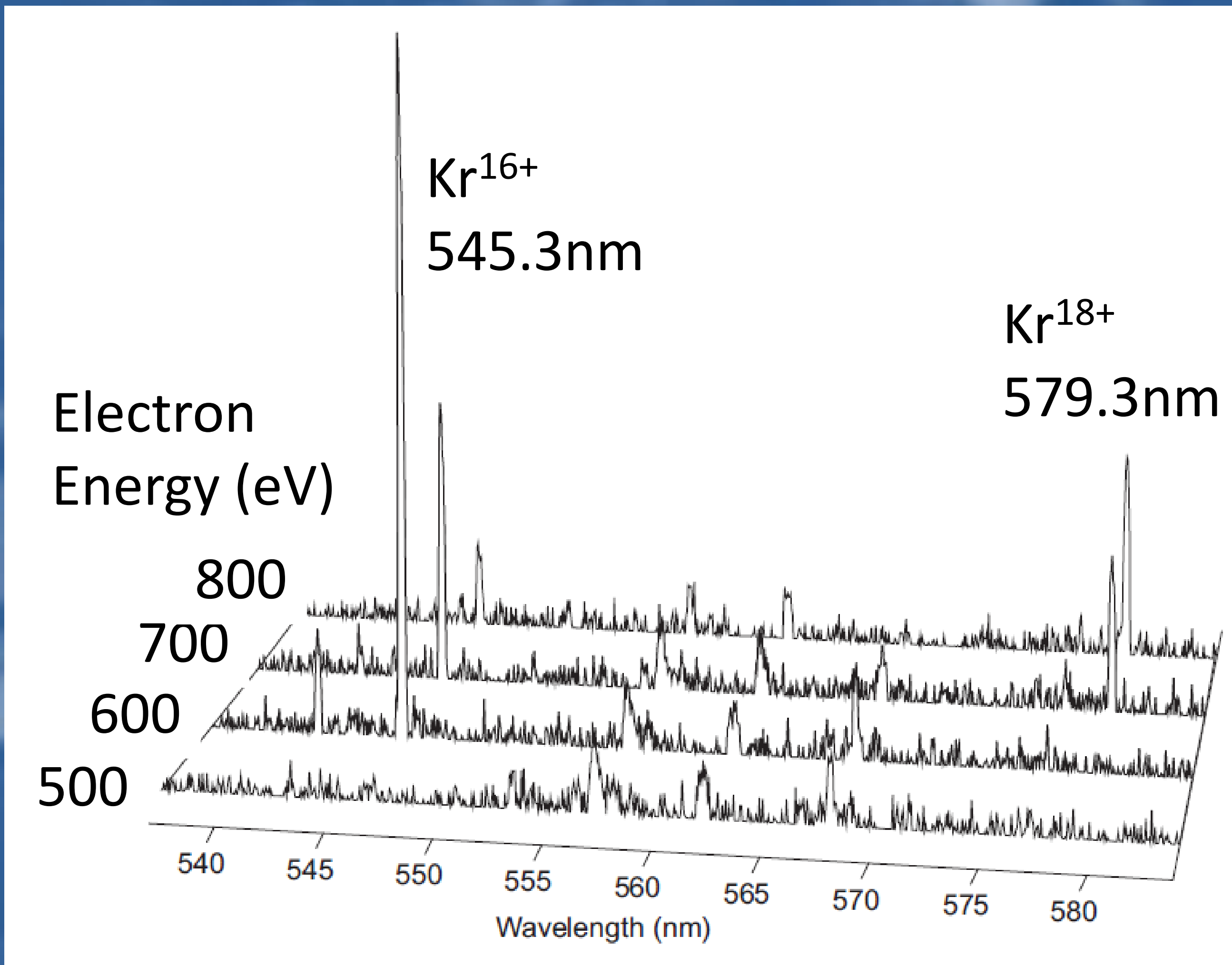
The first result from CoBIT: Observation of known visible lines of Kr



Ionization energy

$Kr^{15+} \rightarrow Kr^{16+}$ 538 eV

$Kr^{16+} \rightarrow Kr^{17+}$ 588 eV

$Kr^{17+} \rightarrow Kr^{18+}$ 640 eV

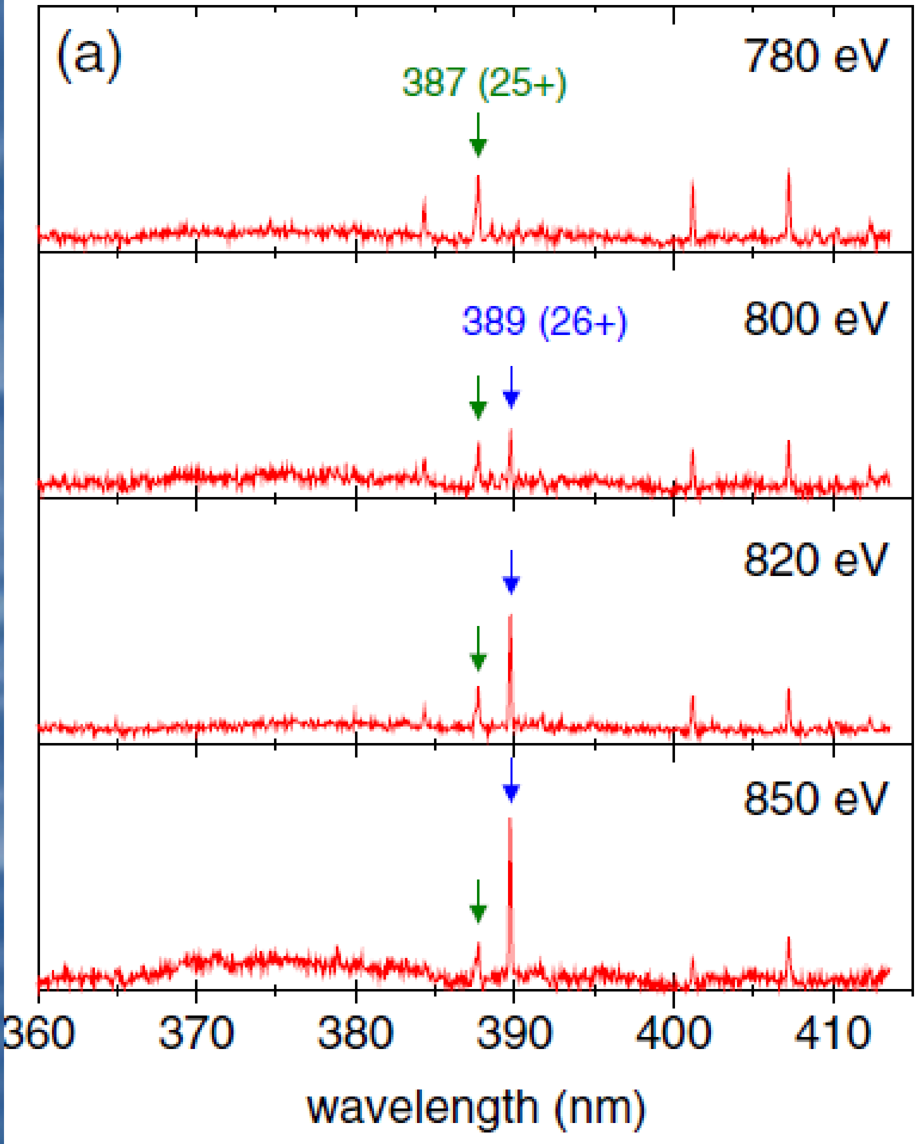
Nakamura et al., RSI 79 (2008)

The first tungsten result from CoBIT: Previously unreported visible line in W^{26+}

Cd-like W^{26+}: $4f^2$
M1 transitions in the ground state configuration:
$^3H_5 – {}^3H_4$: 389.41(6) nm

Ionization energy
$W^{25+} \rightarrow W^{26+}$: 784 eV

Komatsu et al.
Phys. Scr. T144 (2011) 014012



The W data status at that time

PHYSICAL REVIEW A, VOLUME 63, 042513

Magnetic dipole transitions in titaniumlike ions

H. Watanabe,[1] D. Crosby,[2] F. J. Currell,[1,3] T. Fukami,[4] D. Kato,[1] S. Ohtani,[1,4] J. D. Silver,[2] and C. Yamada,[1,4]
[1]*Cold Trapped Ions Project, ICORP, Japan Science and Technology Corporation (JST), Tokyo 182-0024, Japan*
[2]*Clarendon Laboratory, University of Oxford, Oxford, OX1 3PU, United Kingdom*
[3]*The Queen's University of Belfast, Belfast, BT7 1NN, United Kingdom*
[4]*University of Electro-communications, Tokyo 182-8585, Japan*
(Received 12 May 2000; revised manuscript received 22 November 2000; published 21 March 2001)

TABLE I. Wavelengths of the $(3d^4)^5D_2$-$^5D_3$ transition in Ti-like ions. Wavelengths are values in air.

	This work (nm)	
Z	Measured	Calculated
74 (W)	362.67(5)	362.47

The only one visible (UV) line in highly charged tungsten reported up to that time.

Subsequent studies: A lot of previously-unreported lines

Plasma and Fusion Research: Rapid Communications Volume 7, 1201158 (2012)

Visible Transitions in Highly Charged Tungsten Ions: 365 - 475 nm

Akihiro KOMATSU[1)], Junpei SAKODA[1)], Maki MINOSHIMA[1)], Hiroyuki A. SAKAUE[2)], Xiao-Bin DING[3)], Daiji KATO[2)], Izumi MURAKAMI[2)], Fumihiro KOIKE[4)] and Nobuyuki NAKAMURA[1,2)]

[1)]*Institute for Laser Science, The University of Electro-Communications, Tokyo 182-8585, Japan*
[2)]*National Institute for Fusion Science, Gifu 509-5292, Japan*
[3)]*Coll. of Phys. and Elect. Eng., North West Normal University, Lanzhou 730070, China*
[4)]*School of Medicine, Kitasato University, Sagamihara, Kanagawa 252-0373, Japan*

(Received 27 November 2012 / Accepted 4 December 2012)

Komatsu et al.
Plasma Fusion Res. 7, 1201158 (2012).

Subsequent studies:
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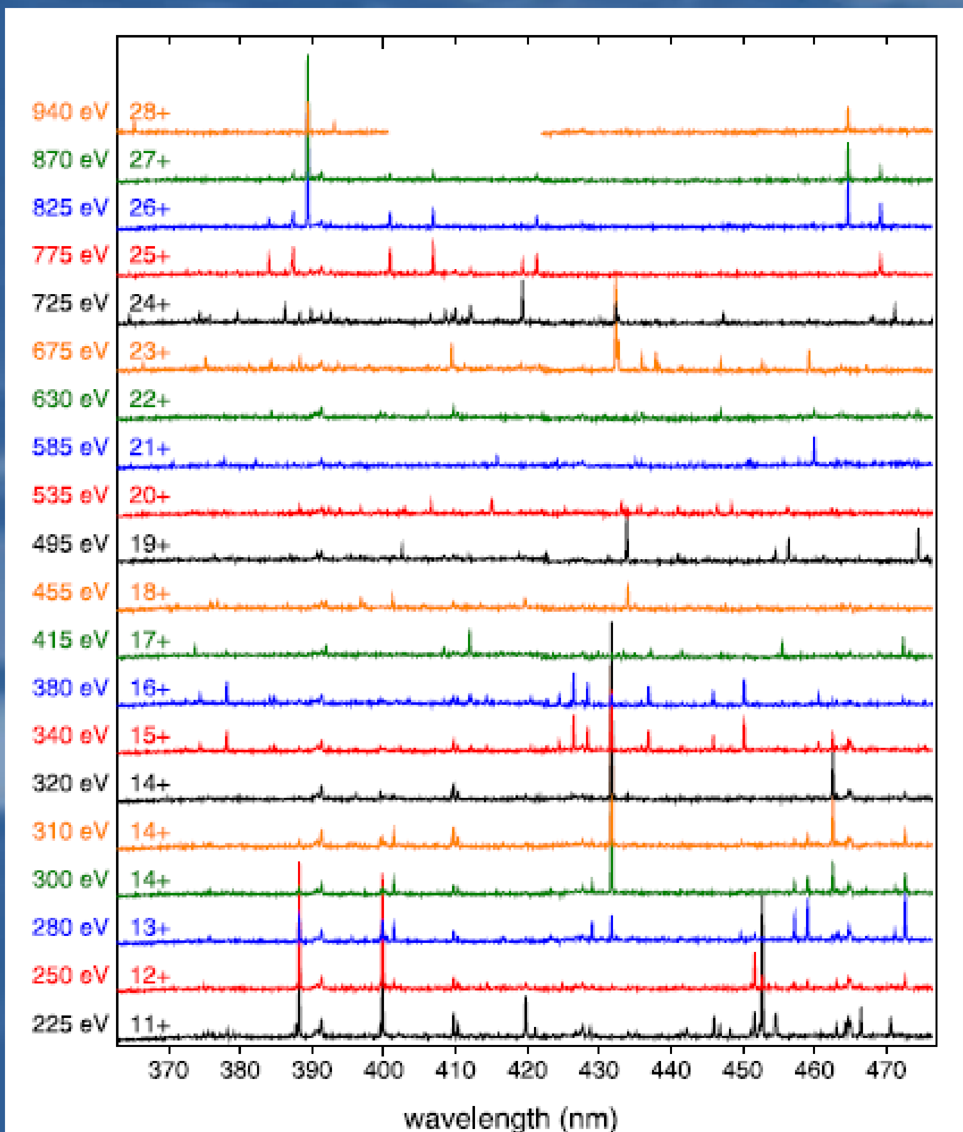
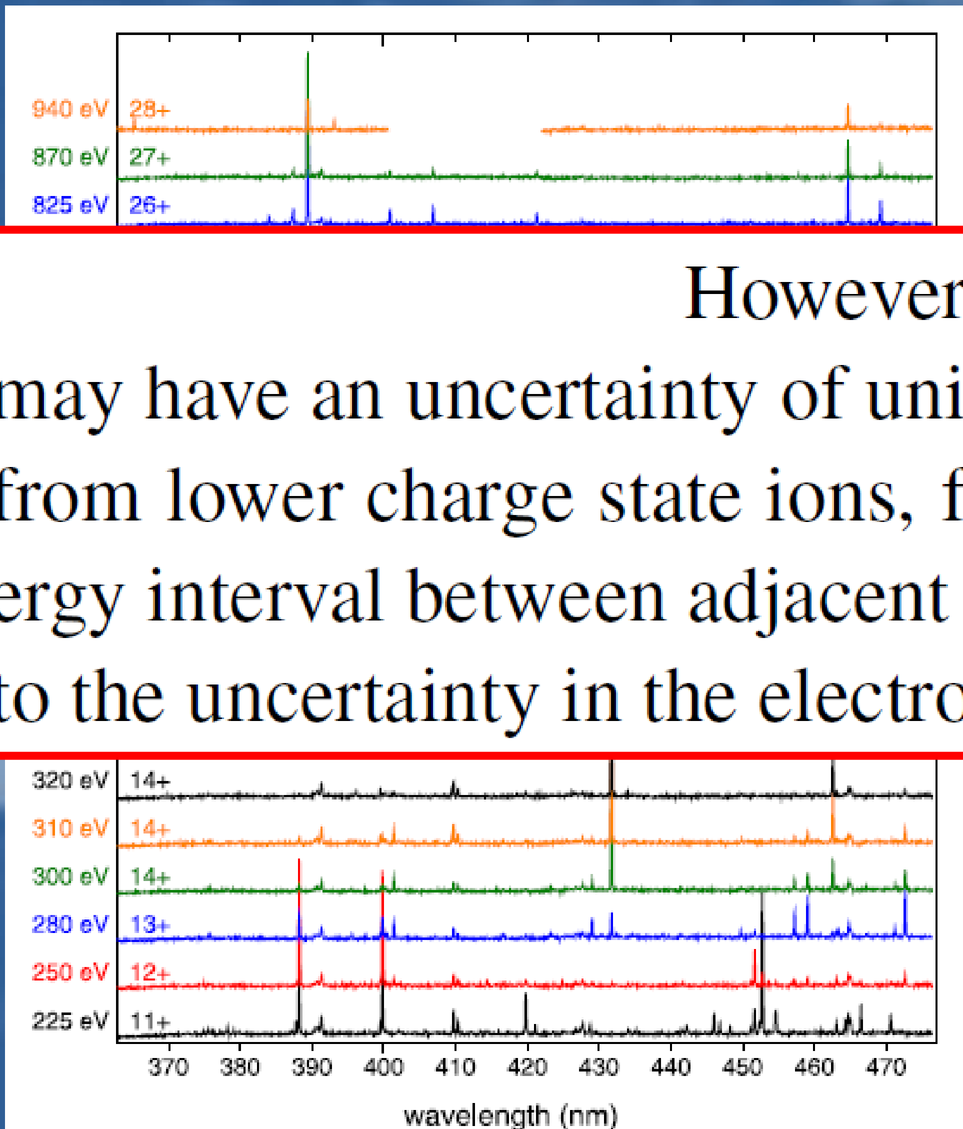


q	wavelength (nm)
28	365.25*, 393.06*
26	389.41*, 464.68*, 501.99*
25	383.99*, 387.3*†, 400.88*, 406.92*, 421.28*, 451.15, 467.59, 469.21*, 493.62
24	364.58, 374.34, 375.70, 379.64, 386.23, 389.89, 392.62, 406.49, 408.58, 409.97, 412.2†, 419.35*, 425.17, 447.36, 467.80, 468.22, 471.18
23	366.48, 375.18, 381.25‡, 388.27, 389.19‡, 393.69‡, 409.44*, 411.28‡, 432.32*, 432.66, 437.90, 438.30, 441.52, 449.46, 459.25
22	384.32, 446.95
21	382.21, 385.16‡, 415.83, 424.17, 442.69, 444.58, 450.70, 451.17, 459.99, 463.50, 468.39
20	388.25, 402.91, 406.62, 415.06†, 422.05, 425.27, 433.14, 435.21‡, 435.82, 438.02, 448.47, 462.40
19	376.38‡, 402.52, 418.90‡, 433.89, 441.06, 456.43, 474.49
18	375.90, 376.85, 396.83, 397.42‡, 401.22, 419.68, 434.01
17	373.69, 391.93, 423.65‡
16	455.52‡, 472.39
15	372.41‡, 374.39, 378.14, 384.15, 384.76, 412.17, 414.29, 420.52, 424.45, 426.47, 428.43, 436.92, 450.23
14	462.59‡
13	457.26, 459.08, 472.68
12	401.38, 451.68
11	388.19, 399.81, 428.79‡, 446.04, 452.77, 454.64, 466.48
8	387.15, 405.73

Subsequent studies:
A lot of previously-unreported lines



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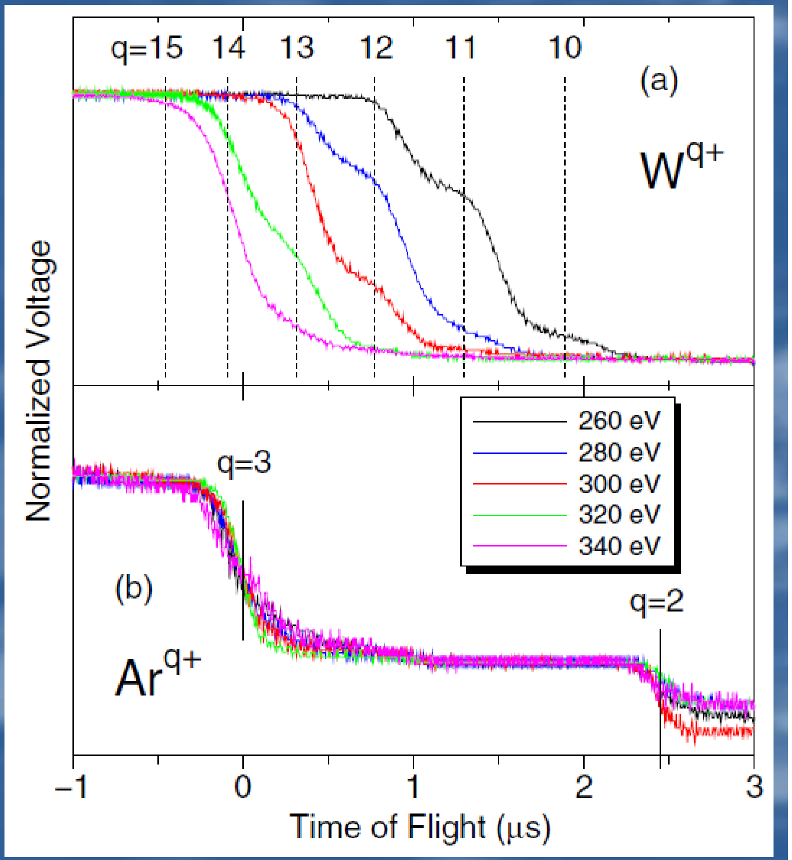
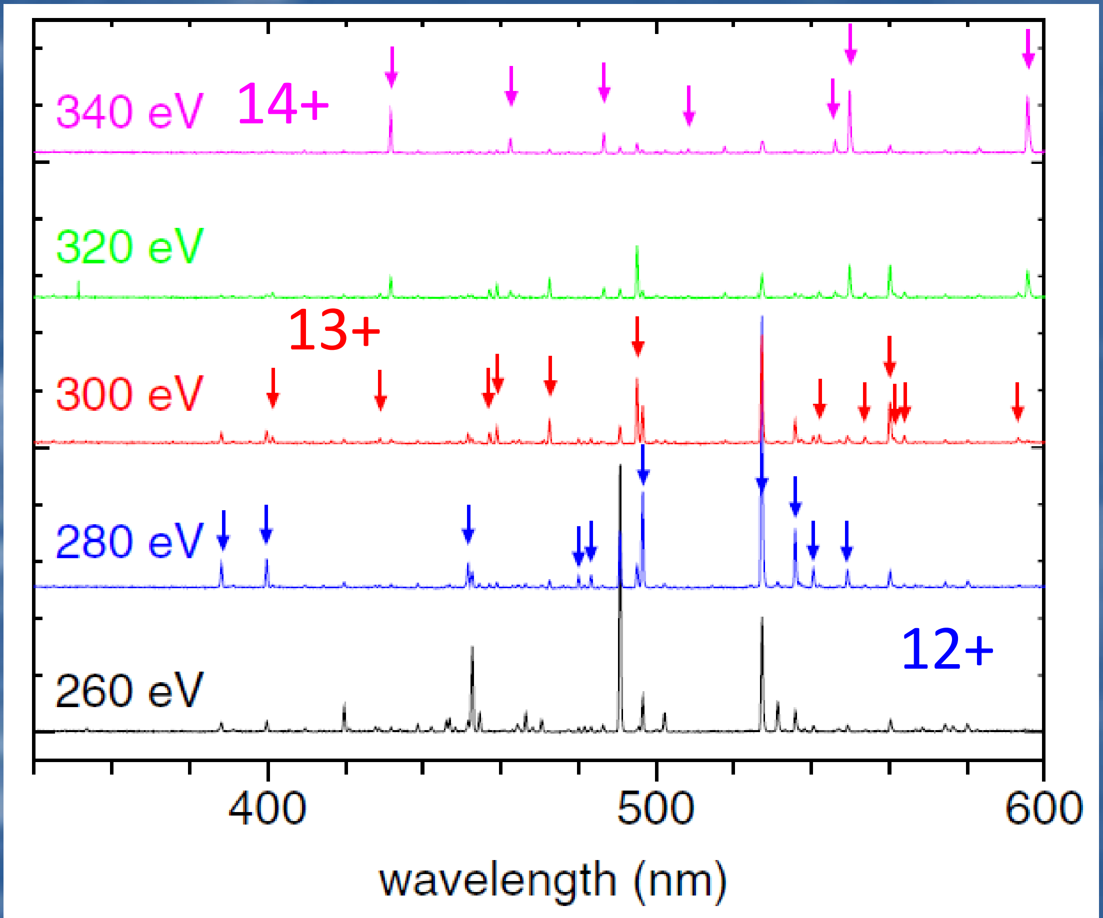
However, the assigned charge states may have an uncertainty of unity especially for weak lines from lower charge state ions, for which the ionization energy interval between adjacent charge states is comparable to the uncertainty in the electron energy.

Charge state verification
1. TOF analysis of ions in the trap

TOF results



Visible spectra



Charge state verification
1. TOF analysis of ions in the trap

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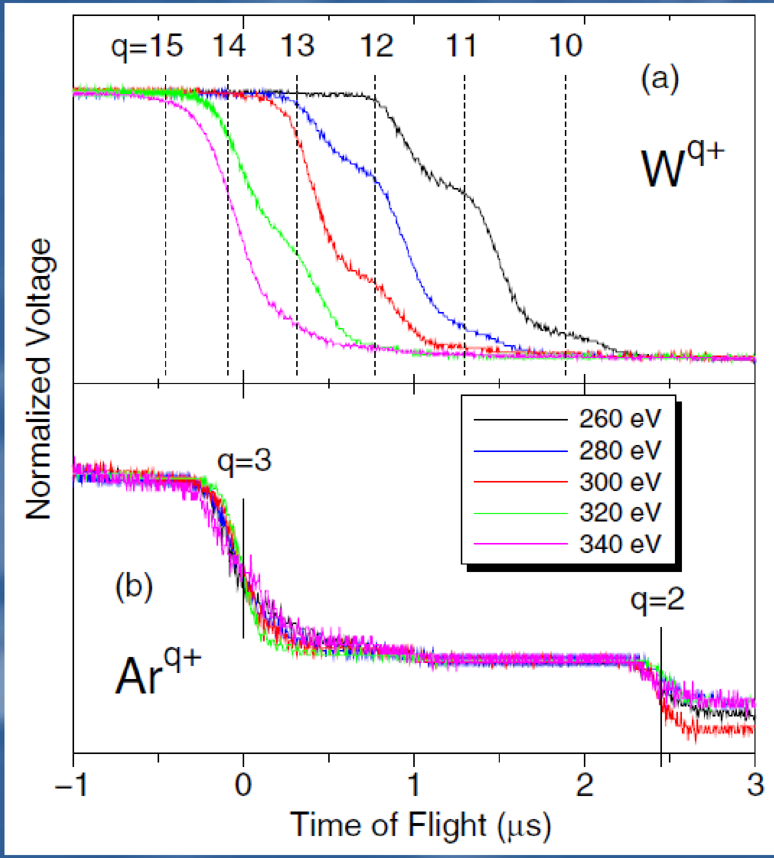
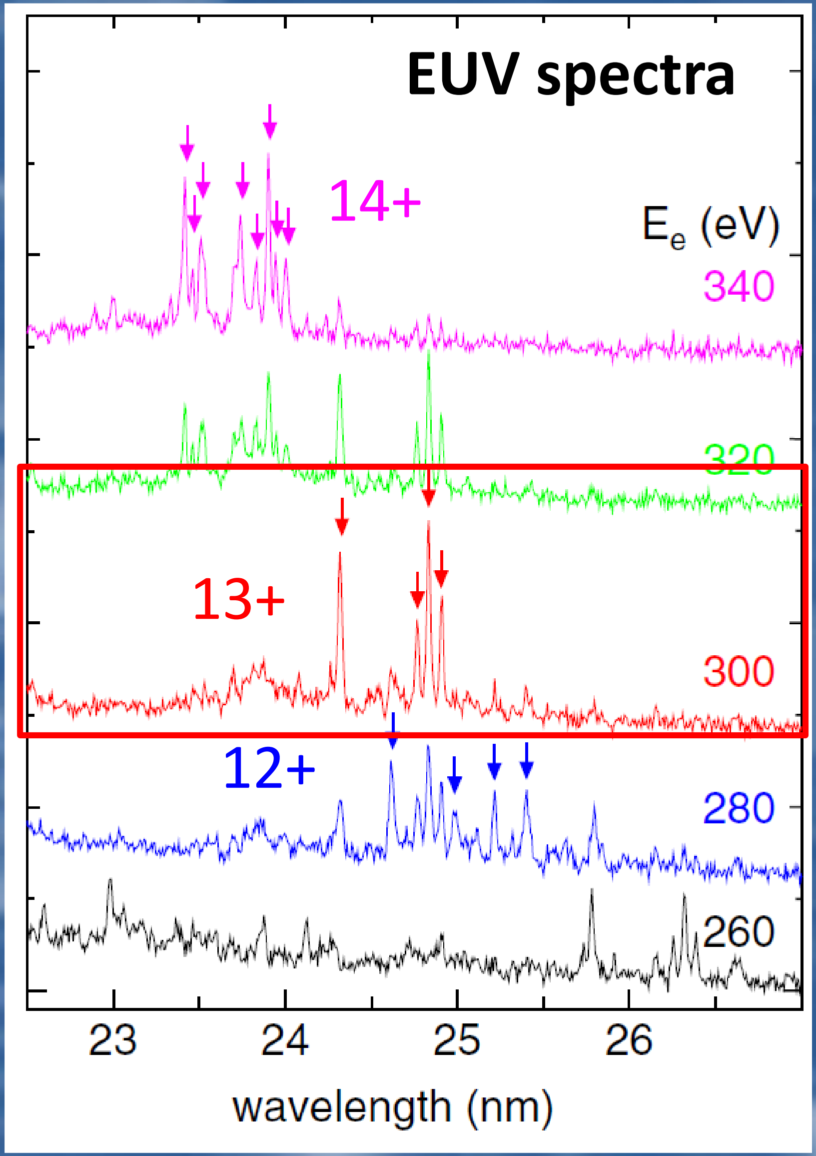
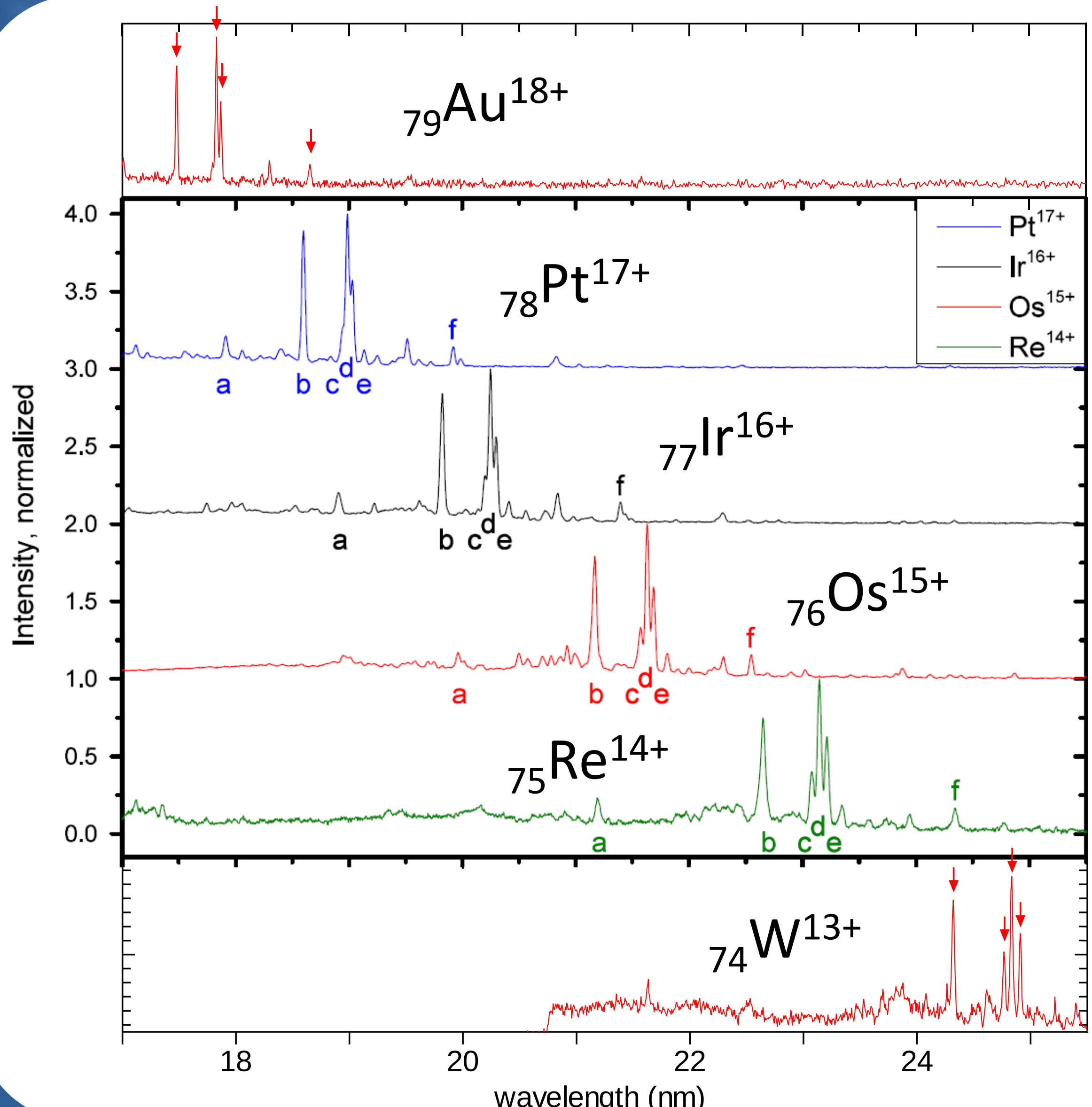
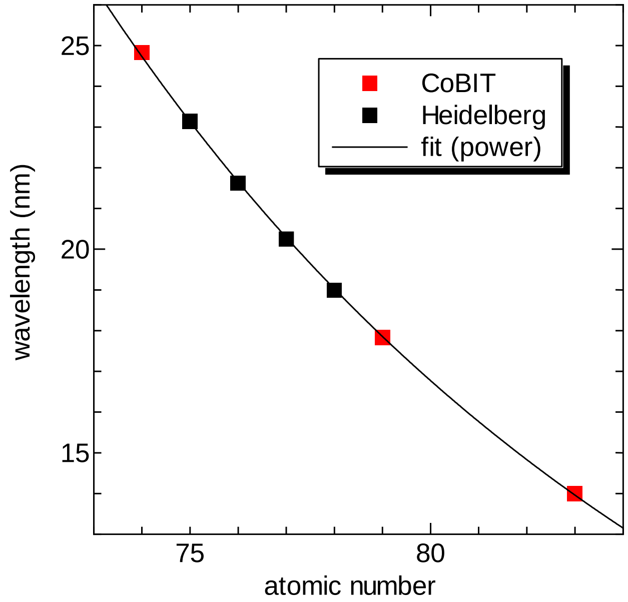




Charge state verification
2. Atomic number dependence (ex. Pm-like)





Z=74,79,83: CoBIT
Z=75-78: Heidelberg
(Bekker, JPB 48)

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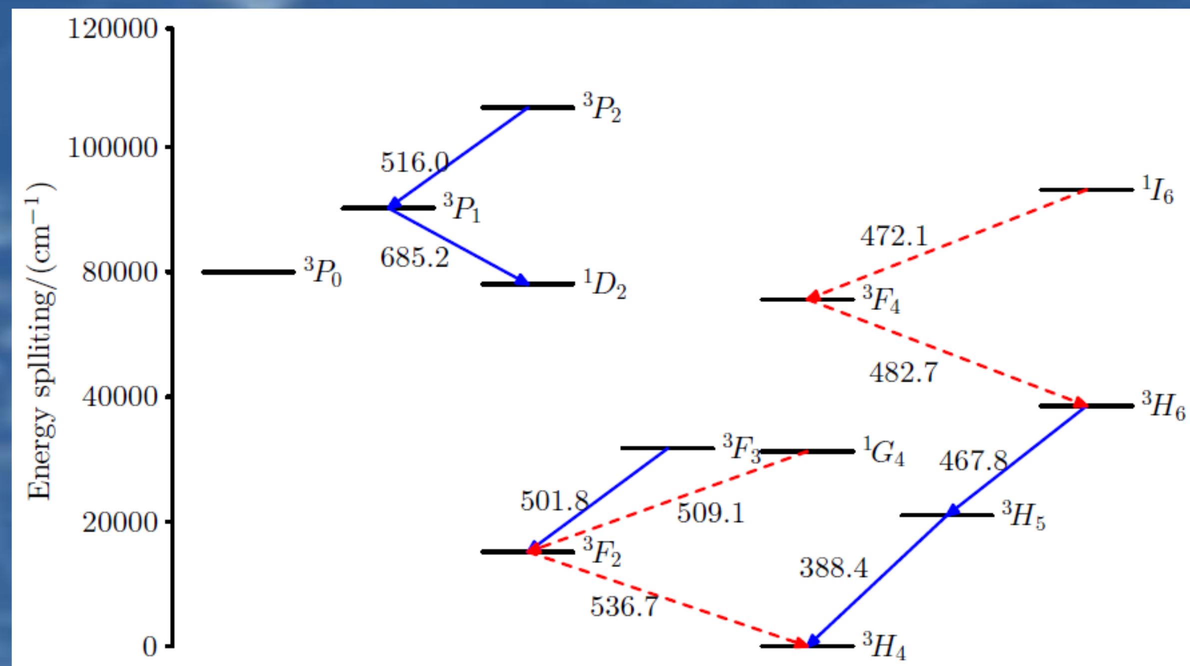
The energy level of Cd-like W26+

27+ (4f)

Fine structure in the ground state configuration



6,722,000 cm^{-1}

Ding et al., J. Phys. B 44 (2011) 145004

26+ ($4f^2$)

Benchmarking calculations for some identified lines

Wavelength of M1 transitions between ground state fine structure levels of Cd-like W26+ ($4f^2$).

Upper–lower	$\lambda_{The.}$ (nm)	$\lambda_{Obs.}$ (nm)	Rate (s^{-1})
$^3H_5 \rightarrow {}^3H_4$	388.43	389.41	3.94(2)
$^3H_6 \rightarrow {}^3H_5$	467.79	464.41	2.05(2)
$^3F_3 \rightarrow {}^3F_2$	501.80	501.99	1.75(2)

Ding et al., J. Phys. B 44 (2011) 145004

Benchmarking calculations for some identified lines

Wavelength (nm) of M1 transitions between fine structure levels in Pm-like W13+ ($4f^{13}5s^2$).

TABLE IV. Wavelength λ (nm in air) and transition probability A (s^{-1}) for the $[4f^{13}5s^2]_J$ ($J = 7/2{-}5/2$) transition in promethiumlike tungsten.

Ion	λ_{exp}	λ_{th}				A
W^{13+}	560.25	567.8[a]	538[b]	568[c]	552[d]	83.9[a]

[a]Present result with GRASP2K.
[b]Hartree-Fock relativistic calculation with COWAN [28].
[c]Relativistic many-body perturbation theory with the Flexible Atomic Code (FAC) [15].
[d]Relativistic configuration interaction with FAC [15].

Kobayashi et al., PRA 92 (2015) 022510

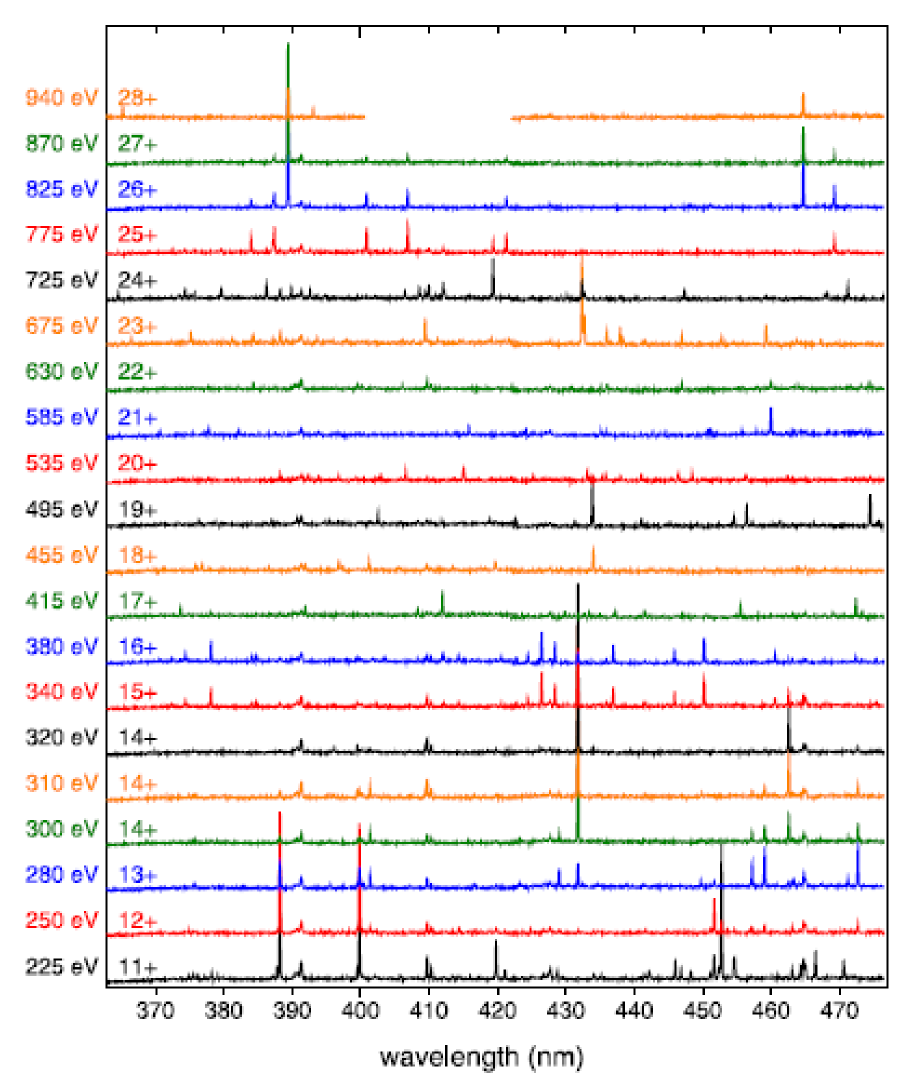
Benchmarking calculations for some identified lines

Fine structure splitting of the ground state in W7+ ($4f^{13}5p^{6}$).

	year	exp or th	energy (cm^{-1})	
Kramida [5]	2009	theory	17440 ± 60	
Berengut [14]	2009	theory	18199	
Ryabtsev [6]	2015	exp	17410 ± 5	indirect
Mita (present)	2016	exp	17402.5 ± 0.9	direct

Mita et al., submitted to ATOMS
https://arxiv.org/abs/1611.01261

However…
A lot of lines are still awaiting their identification.



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Summary

- A compact EBIT, CoBIT is a powerful device for observing and identifying previously unreported lines of highly charged tungsten ions.
- A lot of previously unreported lines have been observed in the EUV and visible ranges.
- Charge state assignment has been done based on
  - electron energy dependence,
  - TOF analysis of the ion in the trap,
  - atomic number dependence,
  - charge state dependence.
- Some transitions have been identified, which can be used for benchmarking calculations.
- However, it is generally difficult to identify the transitions for many electron systems due to the complicated electronic structure.

Collaborators

NIFS: I. Murakami, D. Kato, H. A. Sakaue

NWNU: Chenzhong Dong, Xiaobin Ding

Thank you for your attention.