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*NFRI, Gunsan, Korea*

# Population trapping: lost resonance lines in Pm-like Ions

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- EBIT measurement of EUV spectra
- Lost resonance lines and population trapping of meta-stable states in Pm-like spectra
- Summary

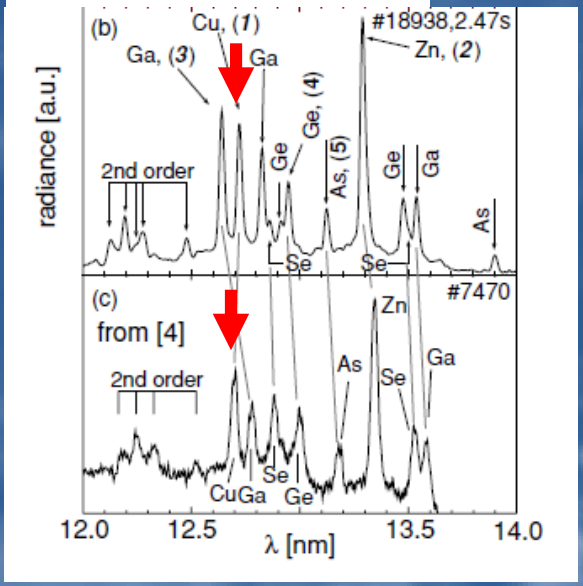
# *ns-np* resonance lines of alkali-like system

- Strong, well isolated in emission spectra
- Simple interpretation of intensities in terms of ion densities
  **→ Particularly useful for plasma diagnostics**
- Li (*n*=2), Na (*n*=3), Cu (*n*=4) sequences have been studied very well and observed in various plasmas

# *ns-np* resonance lines of alkali-like system

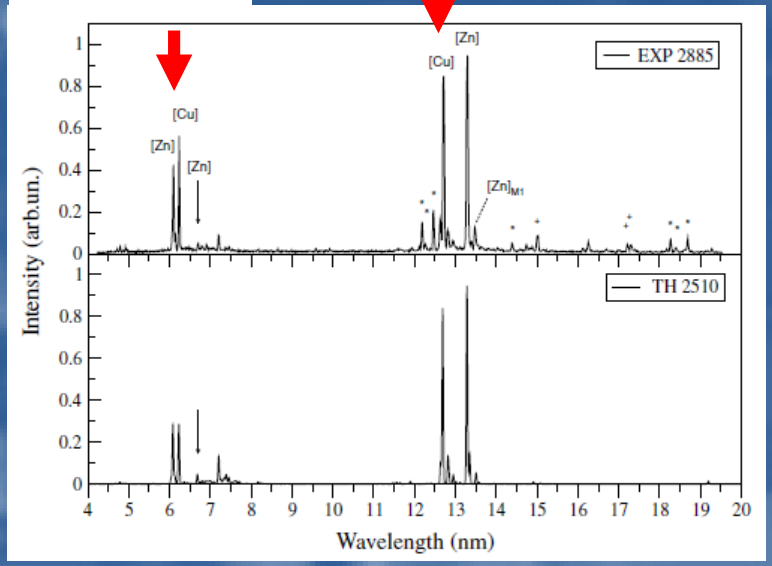
Example. Cu-like $W^{45+}$ resonance lines (4p-4s)

ASDEX-U (tokamak)



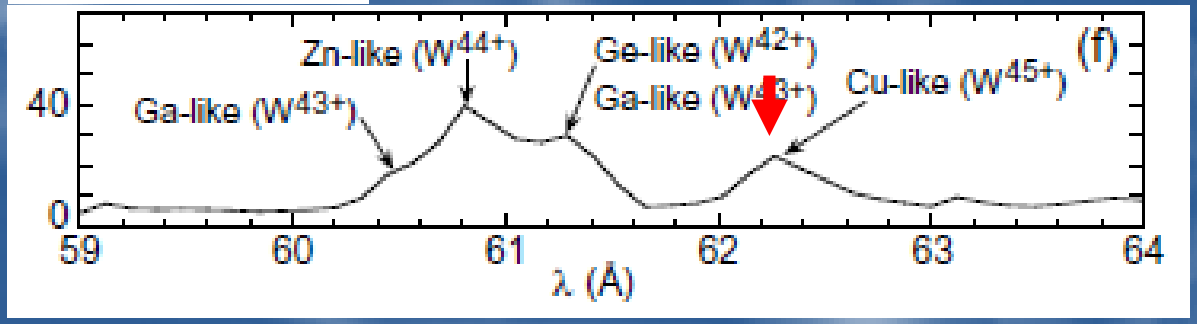

Pütterich et al, JPB 38 (2005) 3071

EBIT(NIST)




Ralchenko et al, JPB 40 (2007) 3861

LHD (stellarator)




Morita et al, AIP Conf. Proc. 1545 (2013) 143

# Pm-like (n=5)?

# Pm-like ions
## theoretical prediction

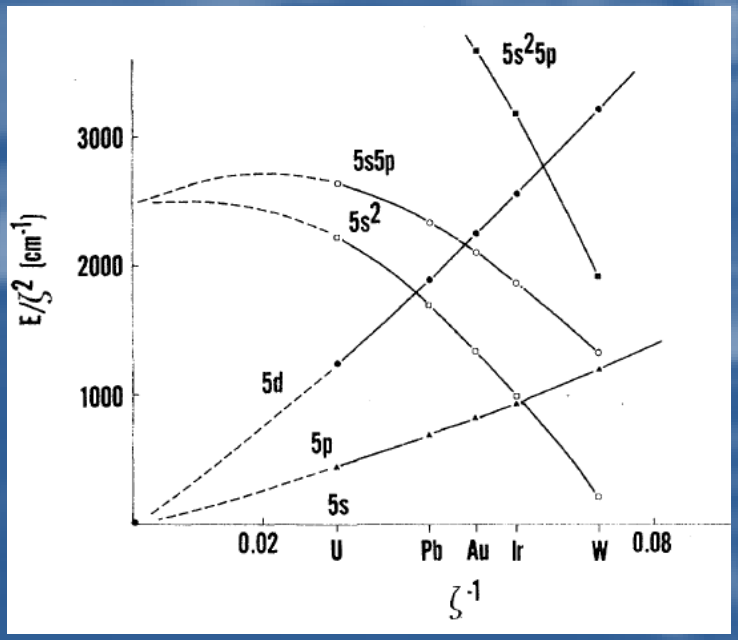
VOLUME 45, NUMBER 26 PHYSICAL REVIEW LETTERS 29 DECEMBER 1980

### Alkalilike Spectra in the Promethium Isoelectronic Sequence

L. J. Curtis and D. G. Ellis
*Department of Physics and Astronomy, The University of Toledo, Toledo, Ohio 43606*

(Received 23 July 1980; revised manuscript received 10 November 1980)

Highly ionized members of the Pm sequence should produce strong resonance lines in the uv spectra of hot plasmas contaminated by heavy elements. These ions for $Z \geq 74$ have an alkali structure with ground configuration $4f^{14}5s$. Hartree-Fock calculations show that in W XIV through U XXXII the dominant resonance lines are the $5s$-$5p$ doublets in the range $\lambda = 100$–$400$ Å. Approximate predictions are given for the doublet wavelengths, line strengths, and mean lives.



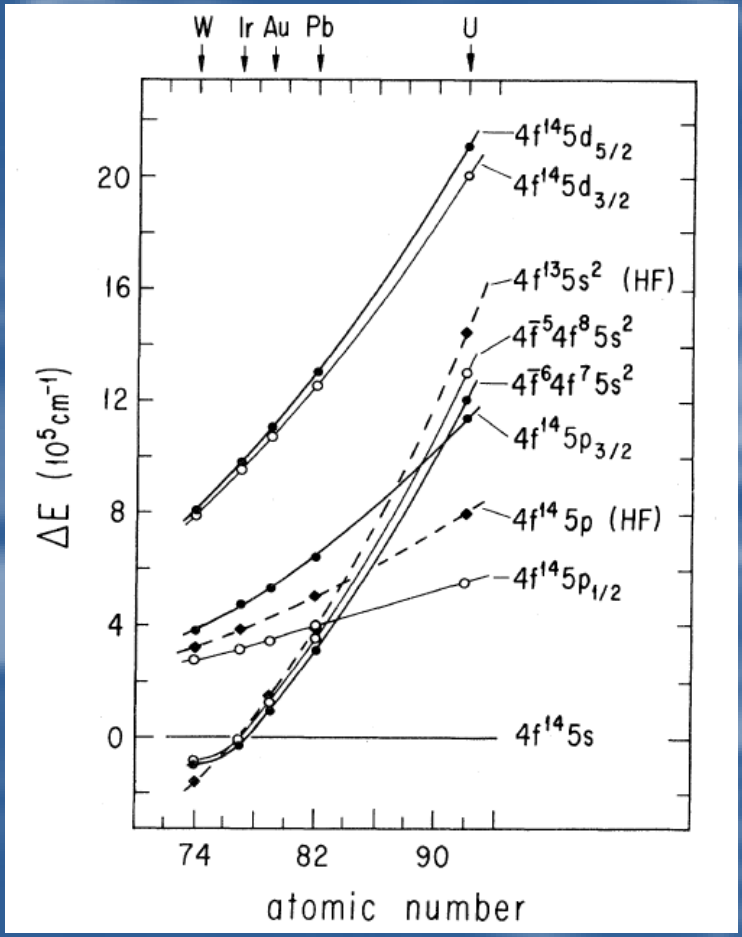

**These ions for $Z \geq 74$ have an alkali structure with ground state configuration $4f^{14}5s$.**

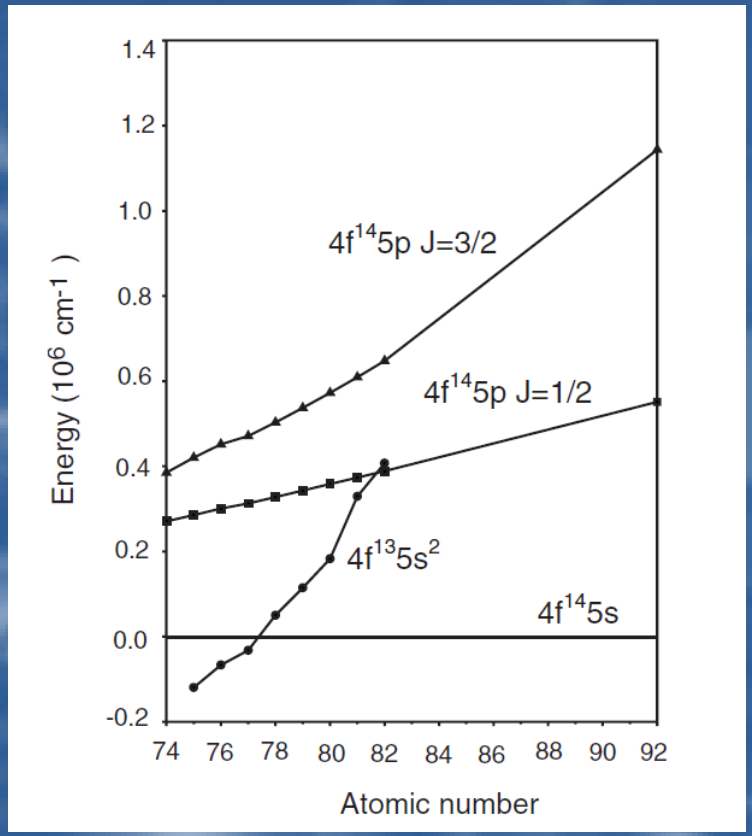
**→ They should produce strong 5p-5s resonance lines.**

# Follow-up of the theoretical prediction

Theodosiou et al. PRA 28 (1983) 1186

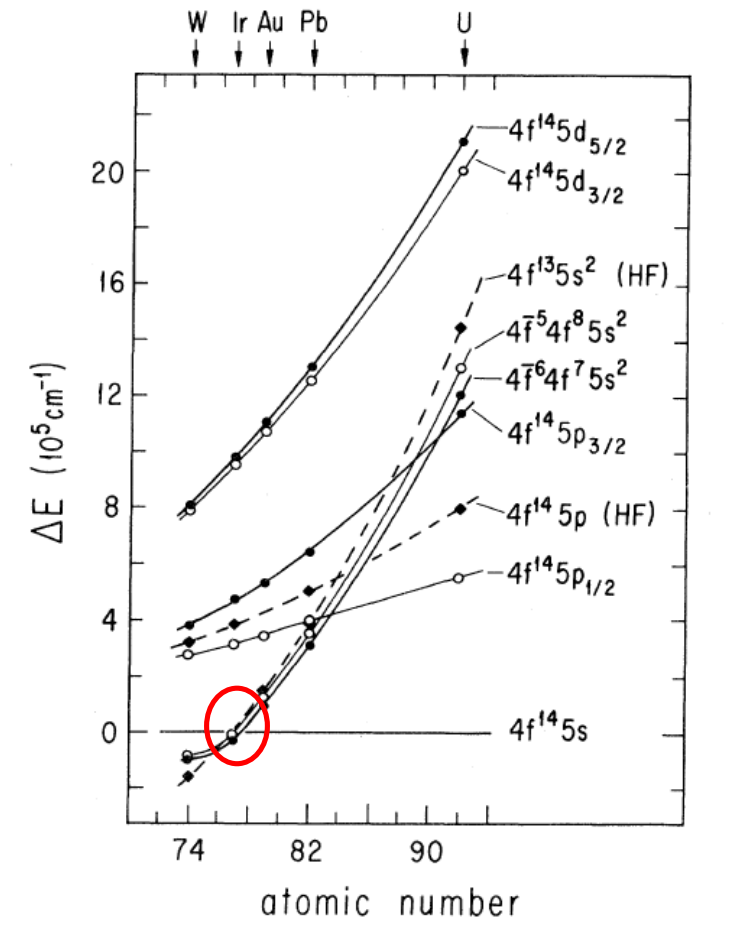
Vilkas et al. PRA 77 (2008) 042510

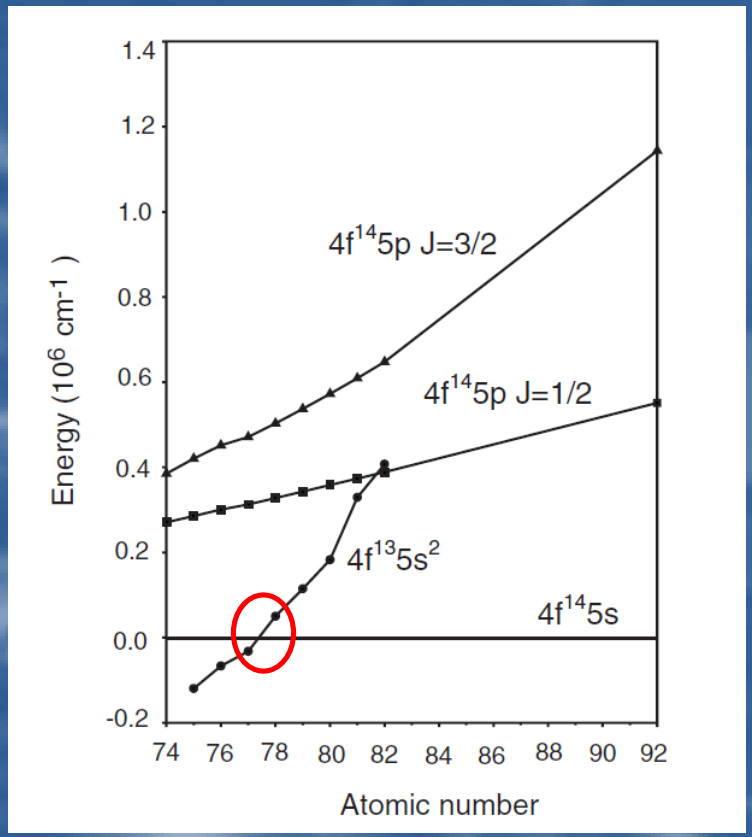


# Follow-up of the theoretical prediction

## Level crossing between $Z = 77$ and 78



# No experimental evidence of the strong 5p-5s resonance line of Pm-like heavy ions !

- Beam foil (Johnson, Träbert, Hutton)
- Tokamak plasma (Fournier)
- Electron-Beam-Ion-Trap (Hutton)
- Charge exchange recombination (Andersson)

In those experiments, ***tentative*** identifications are proposed for $W^{13+}$, $Au^{18+}$, $Pb^{21+}$, $U^{31+}$

# Pm-like ions

## our recent work

PHYSICAL REVIEW A **89**, 010501(R) (2014)

RAPID COMMUNICATIONS

**Spectroscopic study of promethiumlike bismuth with an electron-beam ion trap: Search for alkali-metal-like resonance lines**

Yusuke Kobayashi,[1] Daiji Kato,[2,3] Hiroyuki A. Sakaue,[2] Izumi Murakami,[2,3] and Nobuyuki Nakamura[1]

[1]*Institute for Laser Science, The University of Electro-Communications, Chofu, Tokyo 182-8585, Japan*

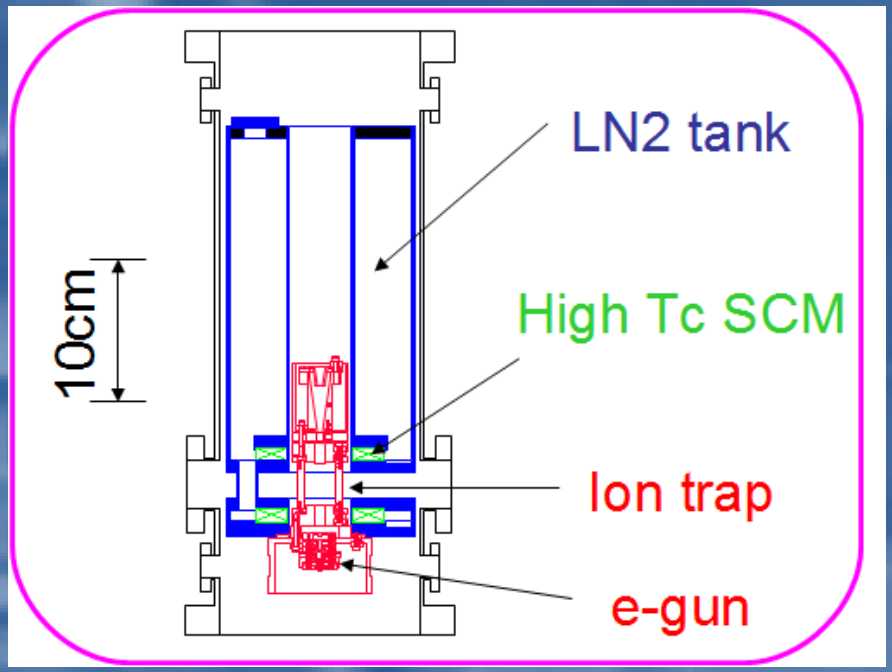
[2]*National Institute for Fusion Science, Toki, Gifu 509-5292, Japan*

[3]*Department of Fusion Science, The Graduate University of Advanced Studies (SOKENDAI), Toki, Gifu 509-5292, Japan*

(Received 17 October 2013; published 27 January 2014)

**The resonance lines are negligibly weak because of population trapping in the $[4f^{13}5s^2]_{7/2}$ metastable state, even though the ground-state configuration is $4f^{14}5s$, as predicted in theories.**

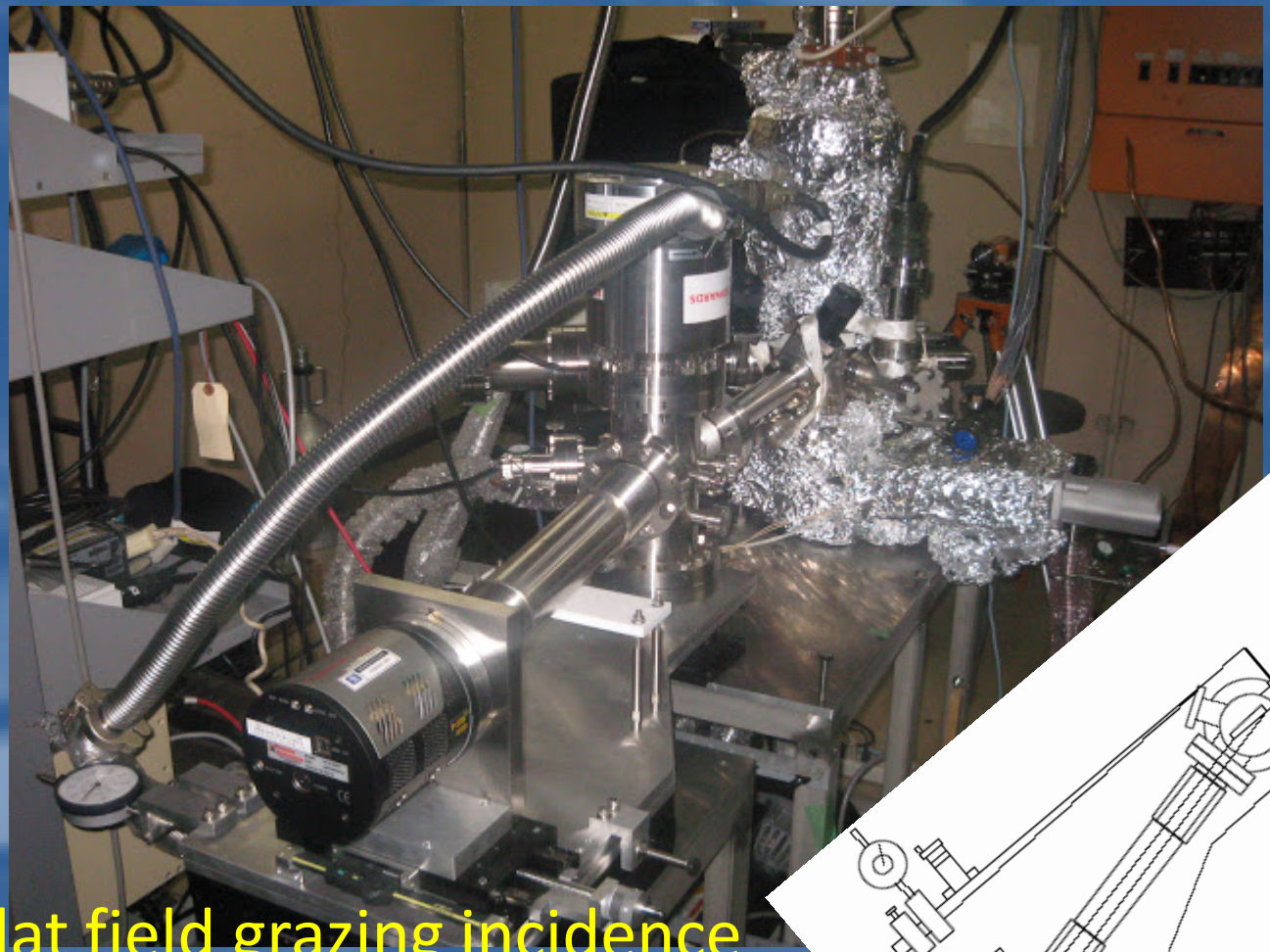
# Compact EBIT (CoBIT) at UEC

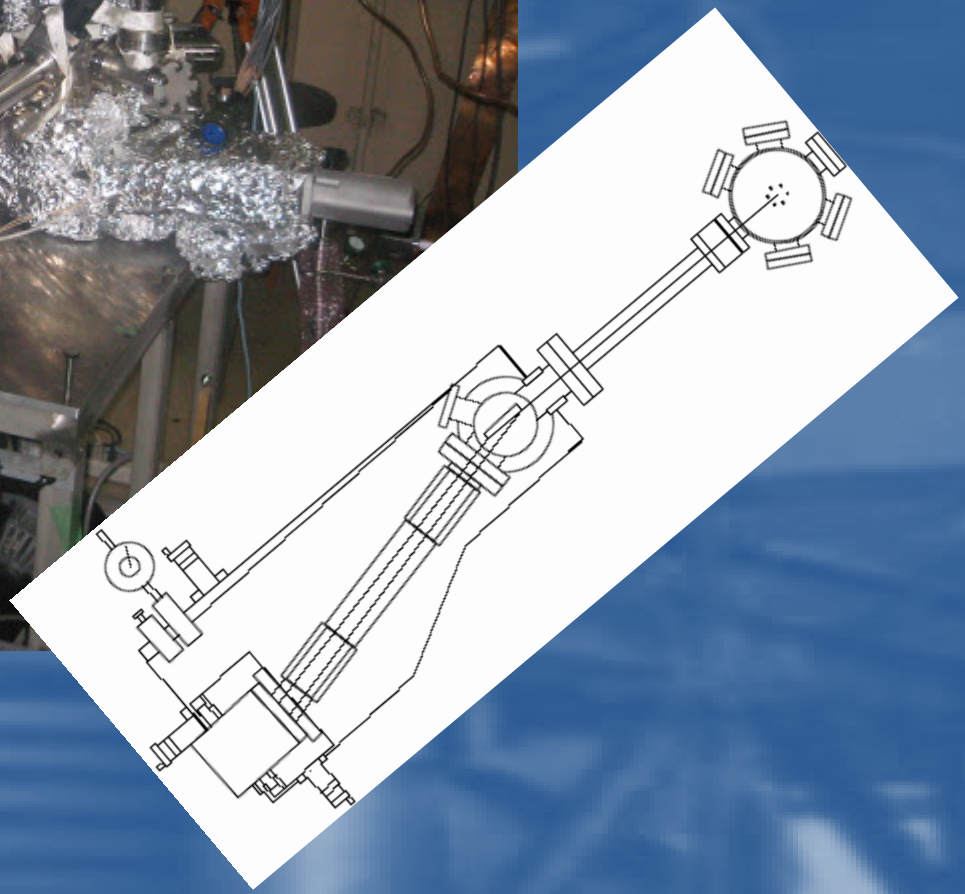



**Specifications**

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

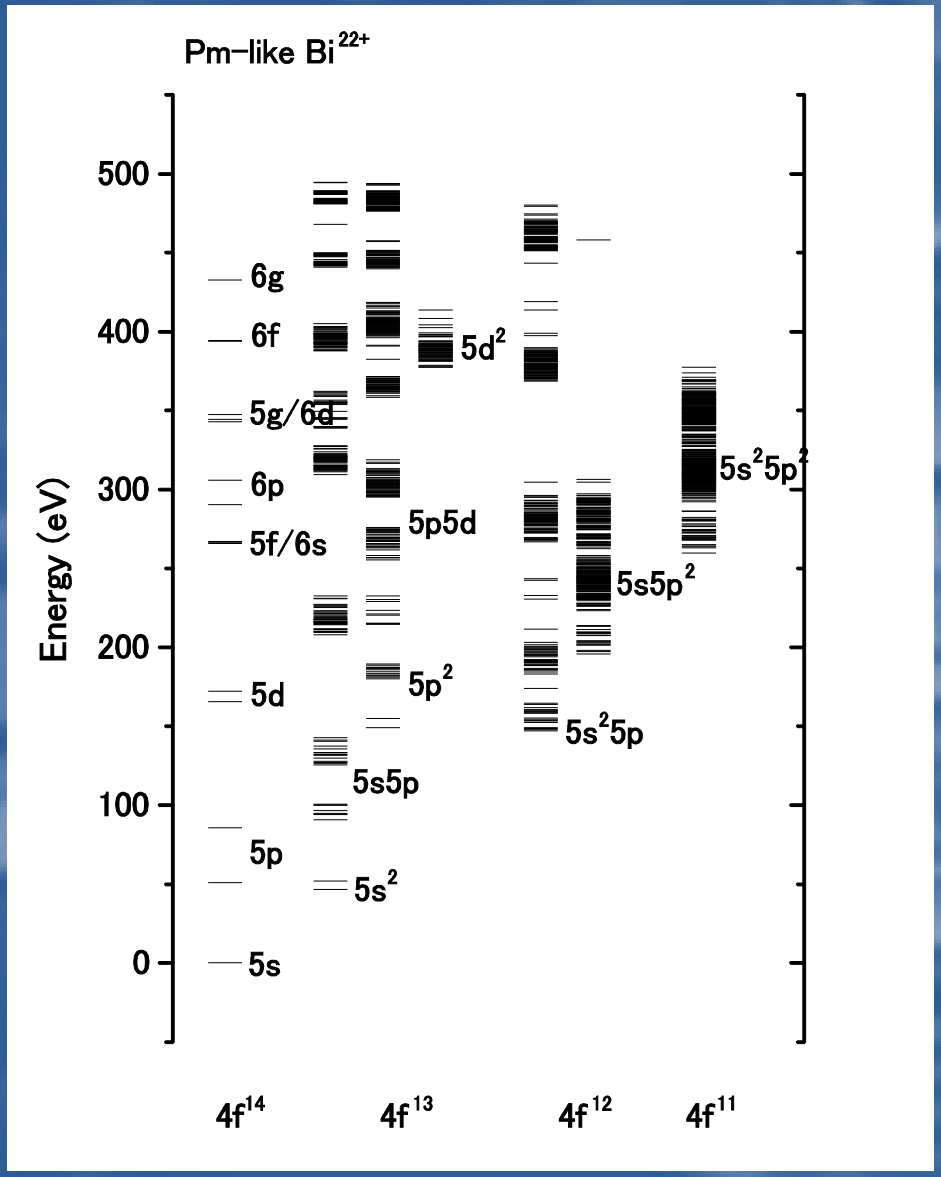
# CoBIT and an EUV spectrometer

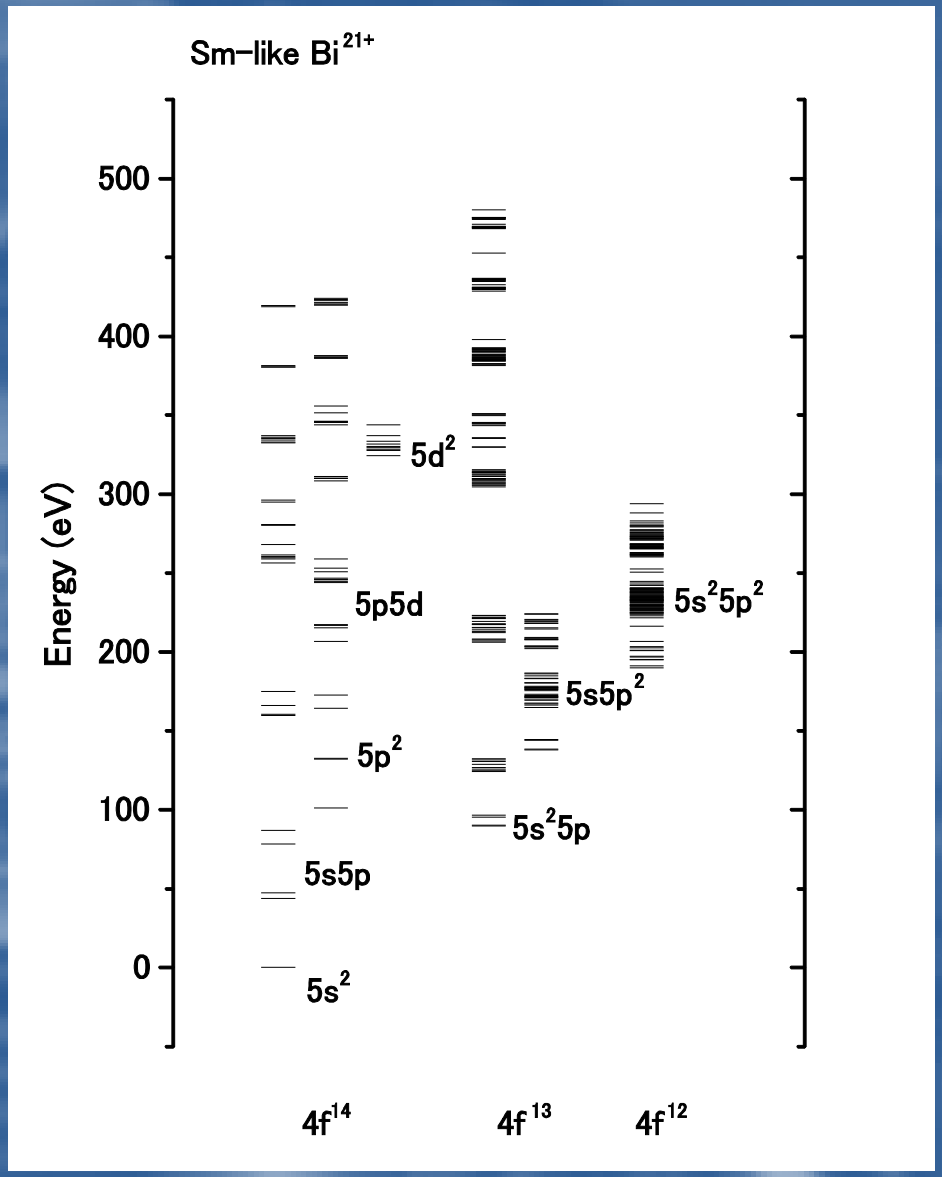




flat field grazing incidence
EUV spectrometer
with a HITACHI grating

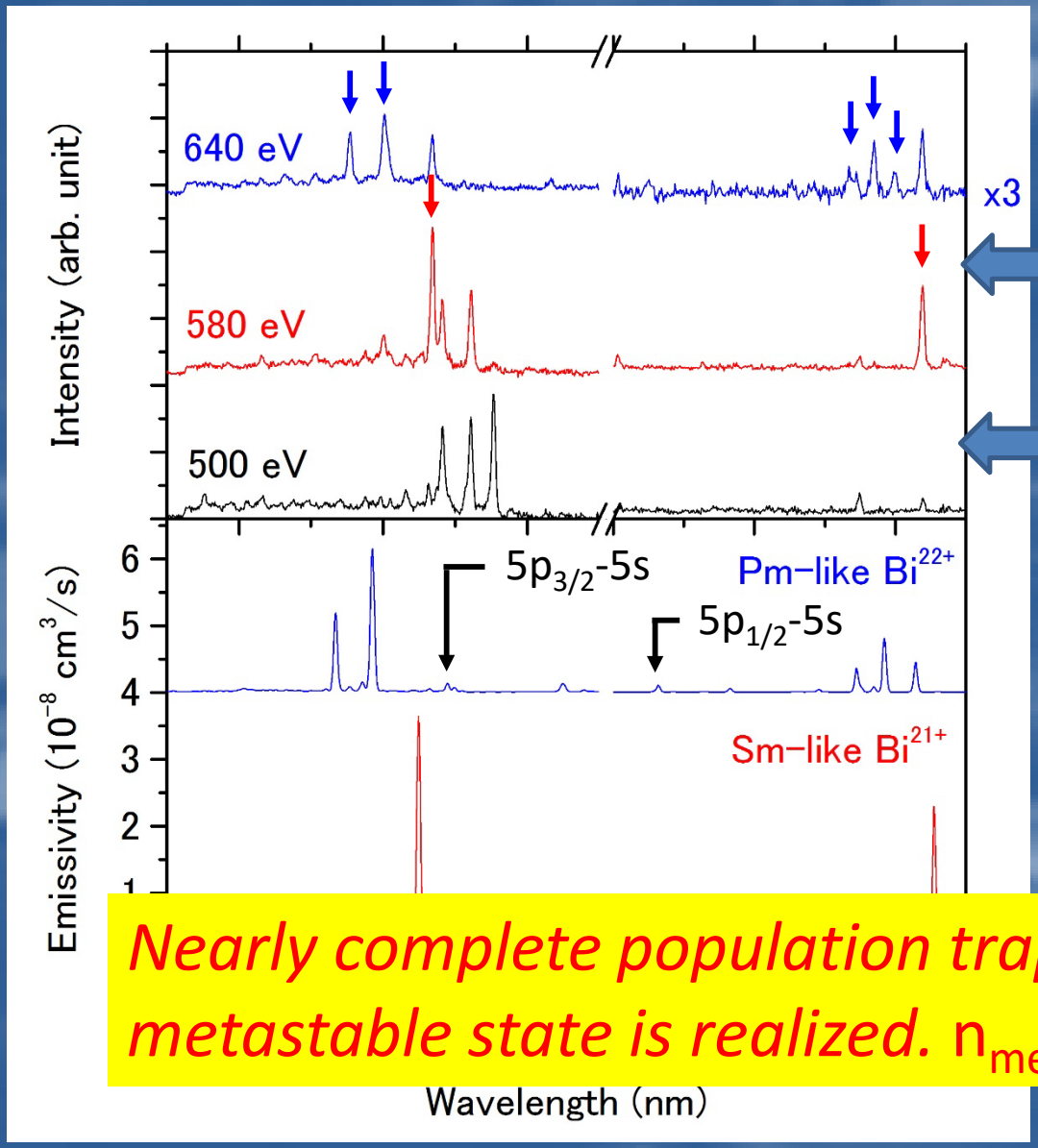
# Atomic levels in CR model

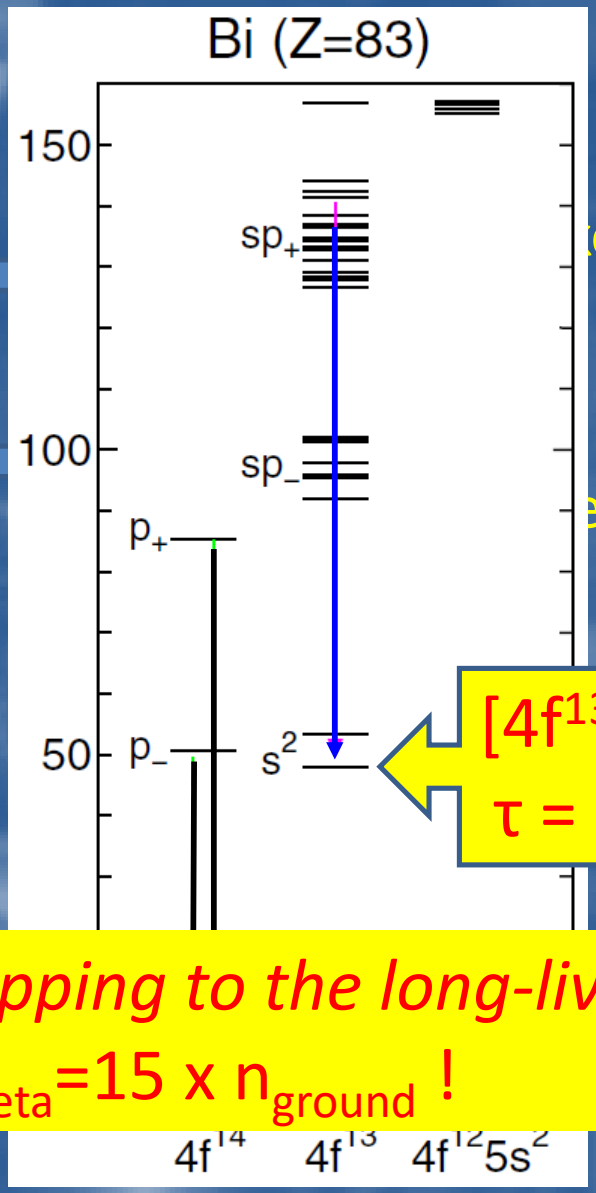


# Bi spectra

## CoBIT measurement and CR model




e (61)

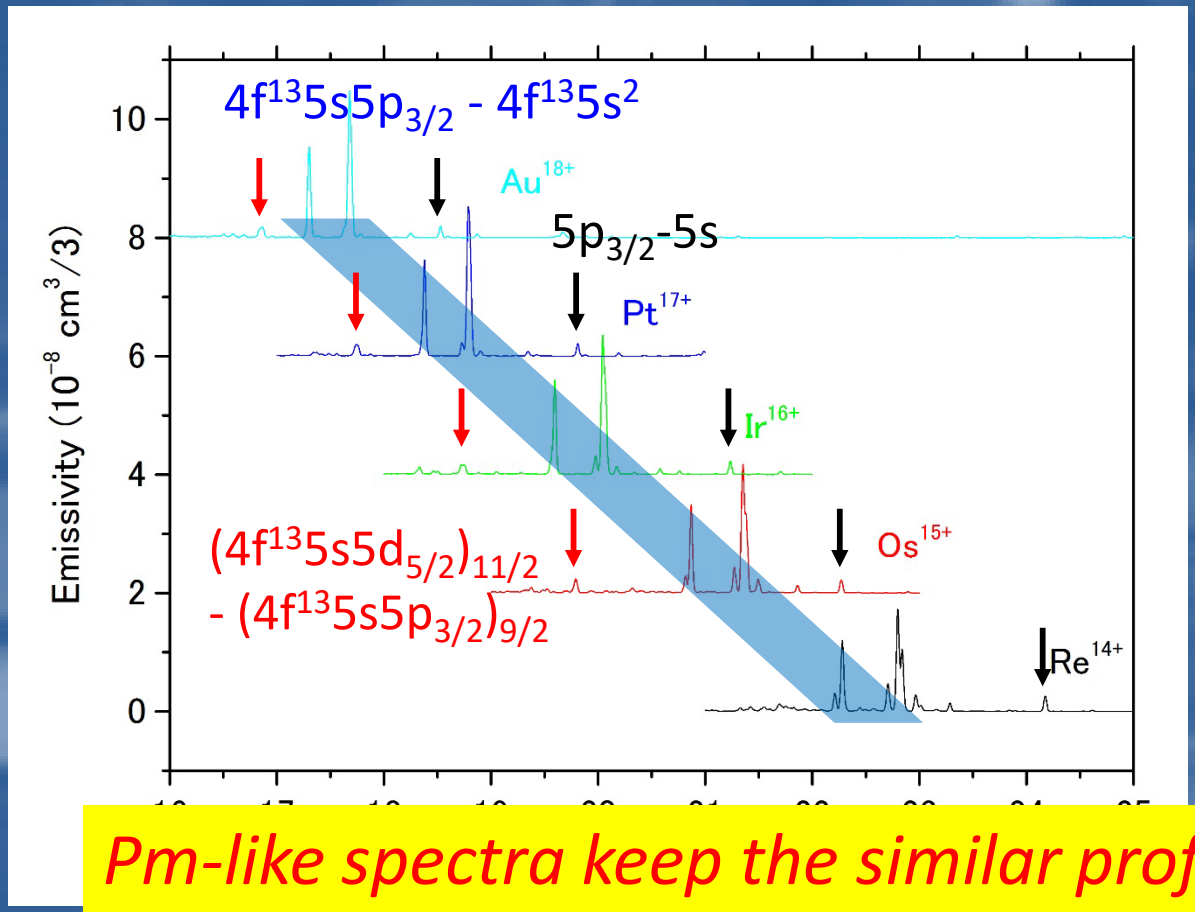
e (62)

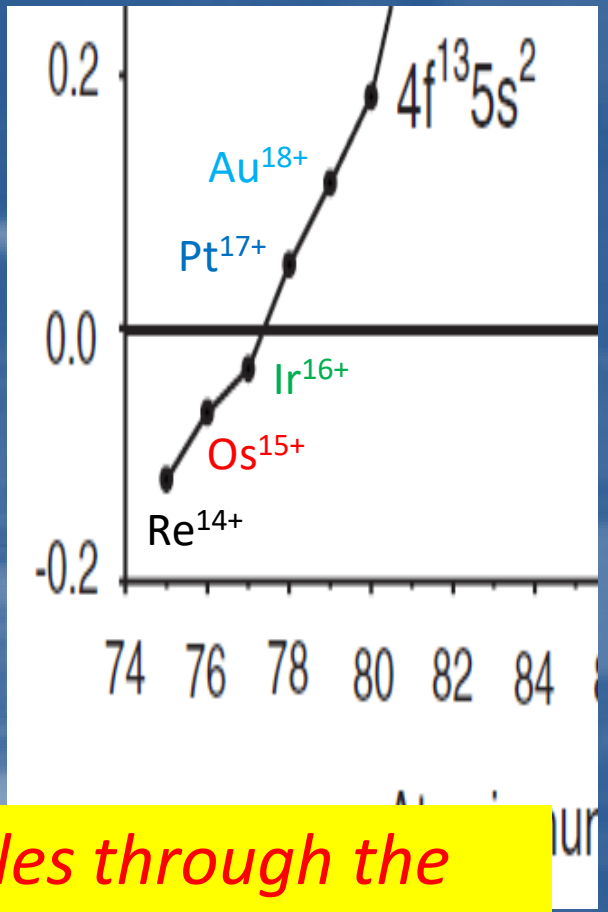
$[4f^{13}5s^2]_{7/2}$
$\tau$ = 64 sec

*Nearly complete population trapping to the long-lived metastable state is realized.* $n_{meta}=15 \times n_{ground}$ !

# Pm-like spectra from Au(Z=79) to Re(Z=75)

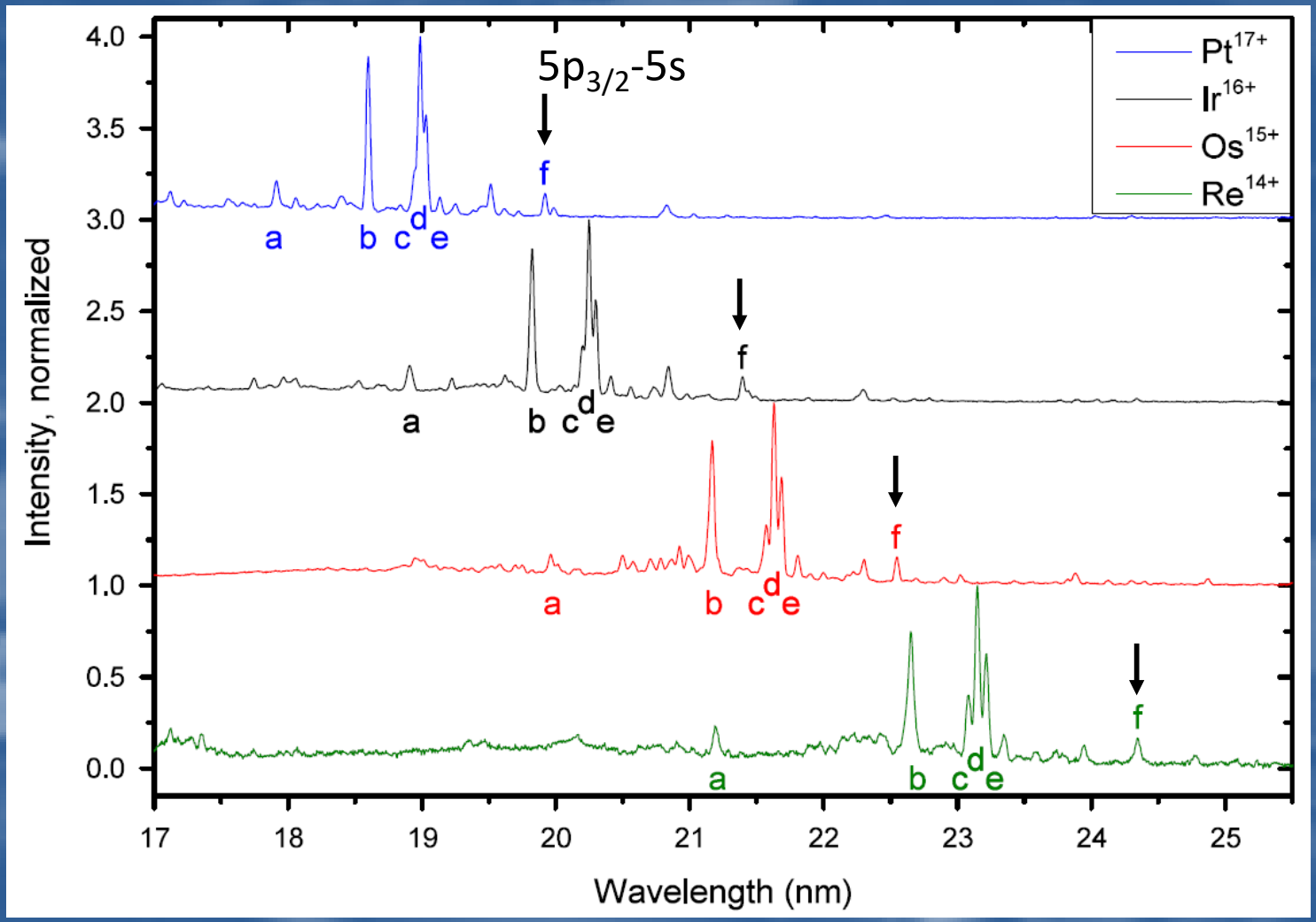
CR model calculation



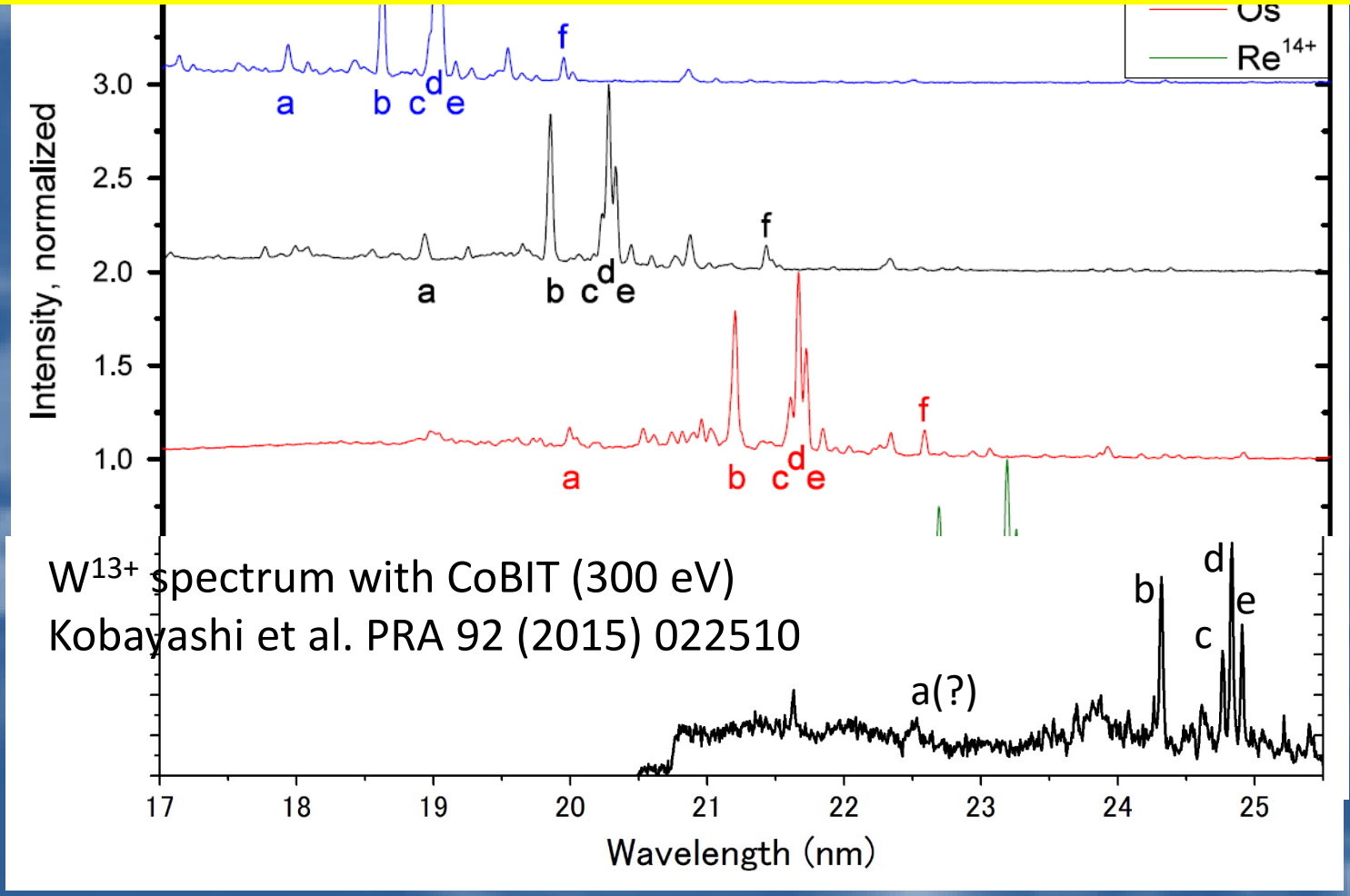

*Pm-like spectra keep the similar profiles through the $4f^{14}5s$ - $4f^{13}5s^2$ energy level crossing. 5p-5s resonance lines are always very weak.*

# Results from Heidelberg EBIT



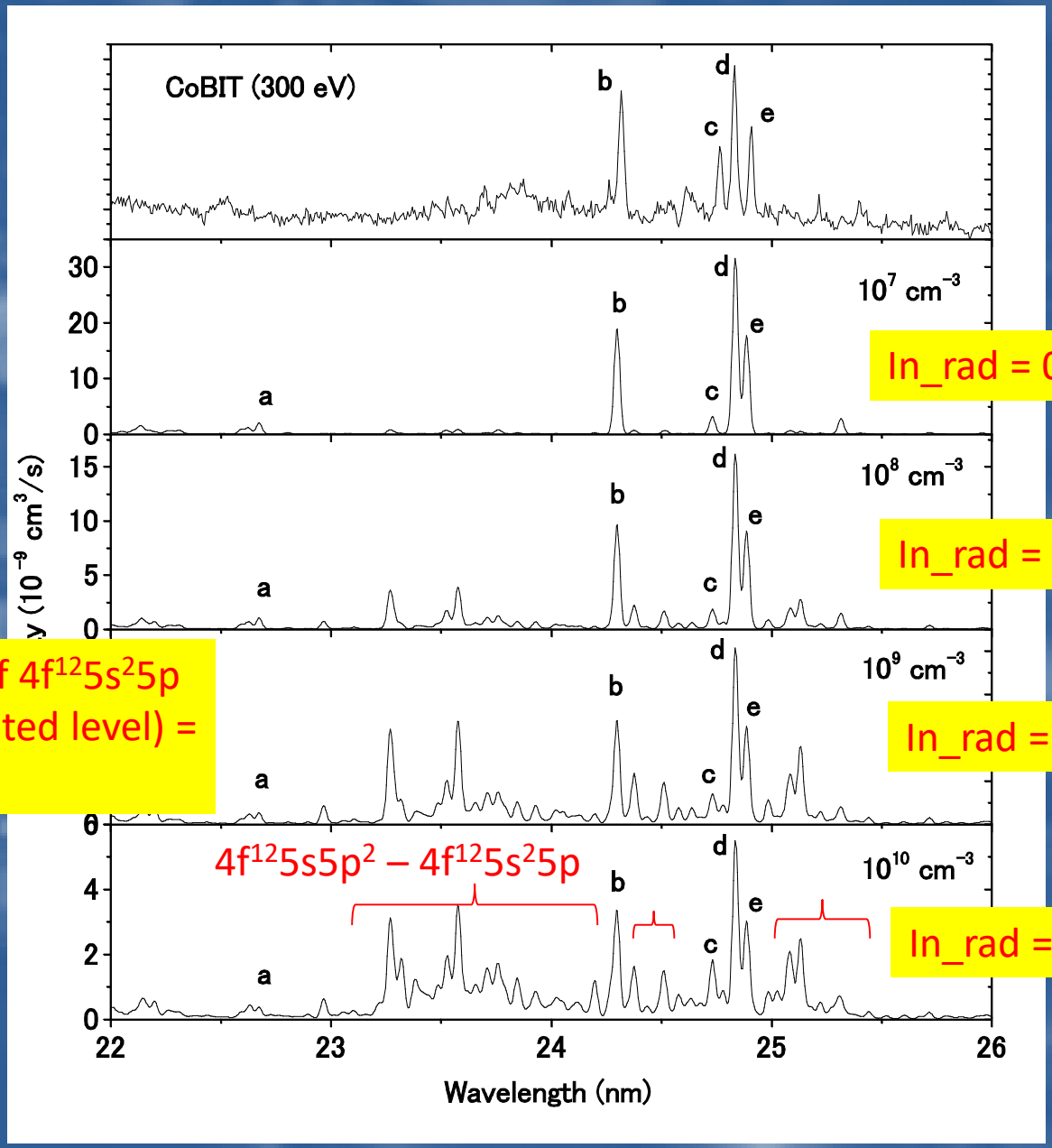

Bekker et al., JPB 48 (2015) 144018

# *W spectrum also looks similar with others. HOWEVER, …*




$W^{13+}$ spectrum with CoBIT (300 eV)
Kobayashi et al. PRA 92 (2015) 022510

# W spectra: CoBIT vs CR model



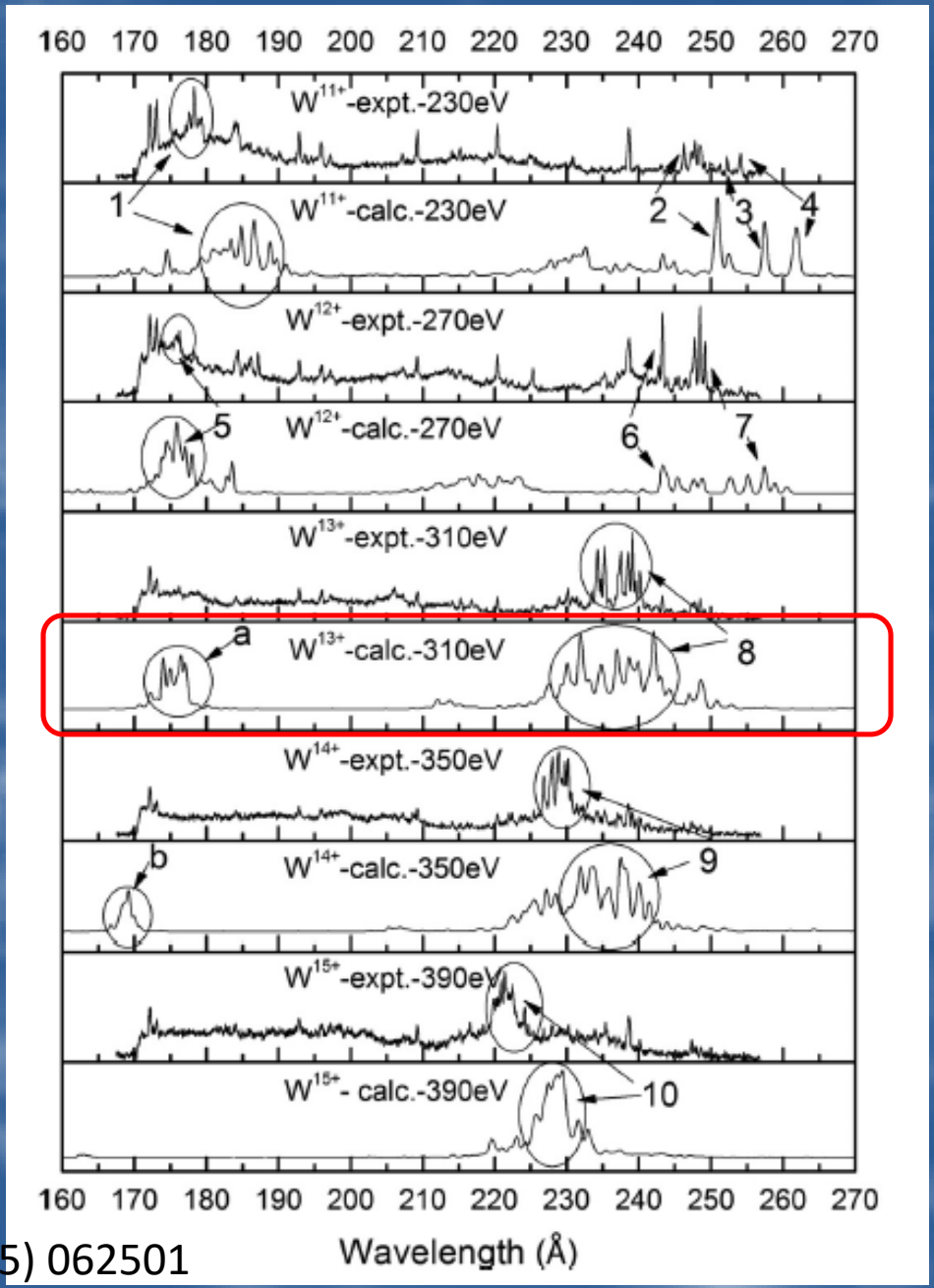

In_rad = 0.07 s-1

In_rad = 1.1 s-1

In_rad = 10 s-1

In_rad = 66 s-1

E2 decay rate of $4f^{12}5s^25p$ (the lowest excited level) = 0.618 s-1




Li et al, PRA 91 (2015) 062501

# Summary

- **Pm-like ions**
  **The resonance 5s-5p transitions are negligibly weak due to the population trapping to the long-lived metastable state.**

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  **The resonance 5s-5p transitions are negligibly weak due to the population trapping to the long-lived metastable state.**
- **Experimental Pm-like spectra are similar for Bi through W, although the level crossing predicted in between.**

# Summary

- Pm-like ions
  The resonance 5s-5p transitions are negligibly weak due to the population trapping to the long-lived metastable state.
- Experimental Pm-like spectra are similar for Bi through W, although the level crossing predicted in between.
- CR model result is reconciled with experimental W spectrum by assuming orders of magnitude smaller electron densities than the expected value.

# Collaborators

**Yusuke Kobayashi (UEC)**

**Izumi Murakami and Hiroyuki A. Sakaue (NIFS)**

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科研費
KAKENHI

Thank you for your kind attention !