EUV spectra from the NIST EBIT

D. Kilbane and G. O'Sullivan

Atomic and Molecular Plasma Physics group, UCD, Ireland

J. D. Gillaspy, Yu. Ralchenko and J. Reader

National Institute of Standards and Technology,

Gaithersburg, MD 20899, USA

The 17th ADAS WORKSHOP

23 – 25 September 2012

Château de Cadarache

Outline

Motivation

EBIT

- Experimental set up
- Collisional-radiative modeling of plasma

EUV Spectra

- Gadolinium
- Dysprosium
- Tungsten

‘Potential lowering’ of $4f^n$ ions

Summary

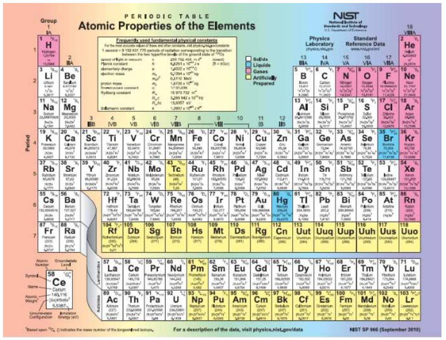
Motivation

Atomic and Plasma Theory

- Hf, Ta, W, Au ions

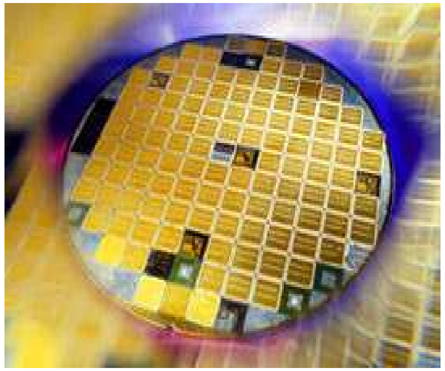
  advance atomic / plasma codes

  predict trends in atomic structure



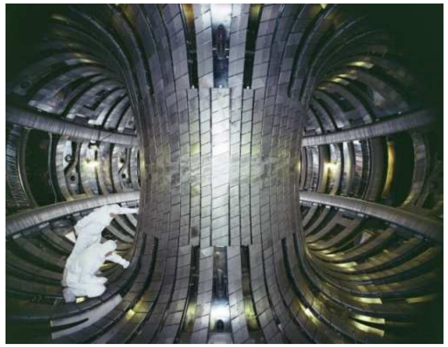
Next-Generation Lithography

- Modeling of sources at 6.x nm



ITER

- Diagnostics of hot plasmas in fusion devices



NIST Electron Beam Ion Trap (EBIT)

EBIT creates, traps and excites HCI

Electron beam

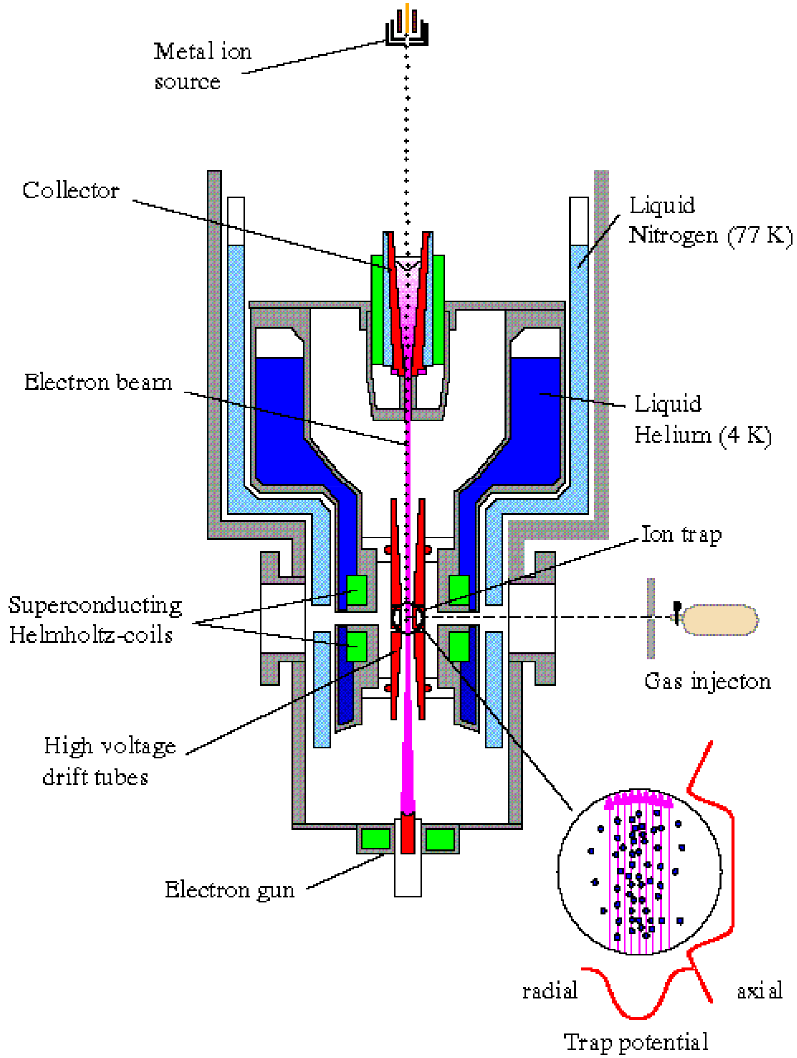
- collides with, ionizes and excites atoms
- monoenergetic, width ~60 eV
- tuneable, 1 - 30 keV
- radius ~30 μm
- density ~10^{11} cm^{-3}

Ions are trapped

- radially by space charge
- axially by electrodes and magnetic field

EUV radiation

- from the ions is observed with a flat field grazing incidence spectrometer



Gillaspy *Phys. Scr. T* **71** 99 (1997)
Blagojević *et al. Rev. Sci. Instrum.* **76** 083102 (2005)

http://physics.nist.gov/ebit

Collisional-Radiative Modeling

All important physical processes in the EBIT plasma

Atomic Data –
Flexible Atomic Code (FAC)

- Relativistic potential to solve the Dirac eqn (CI and QED):

  energy levels, radiative decay rates, radiative recombination cross sections

- e^- ion collisions are treated with distorted wave/Coulomb Born-exchange approx:

  electron impact excitation, de-excitation, ionization cross sections

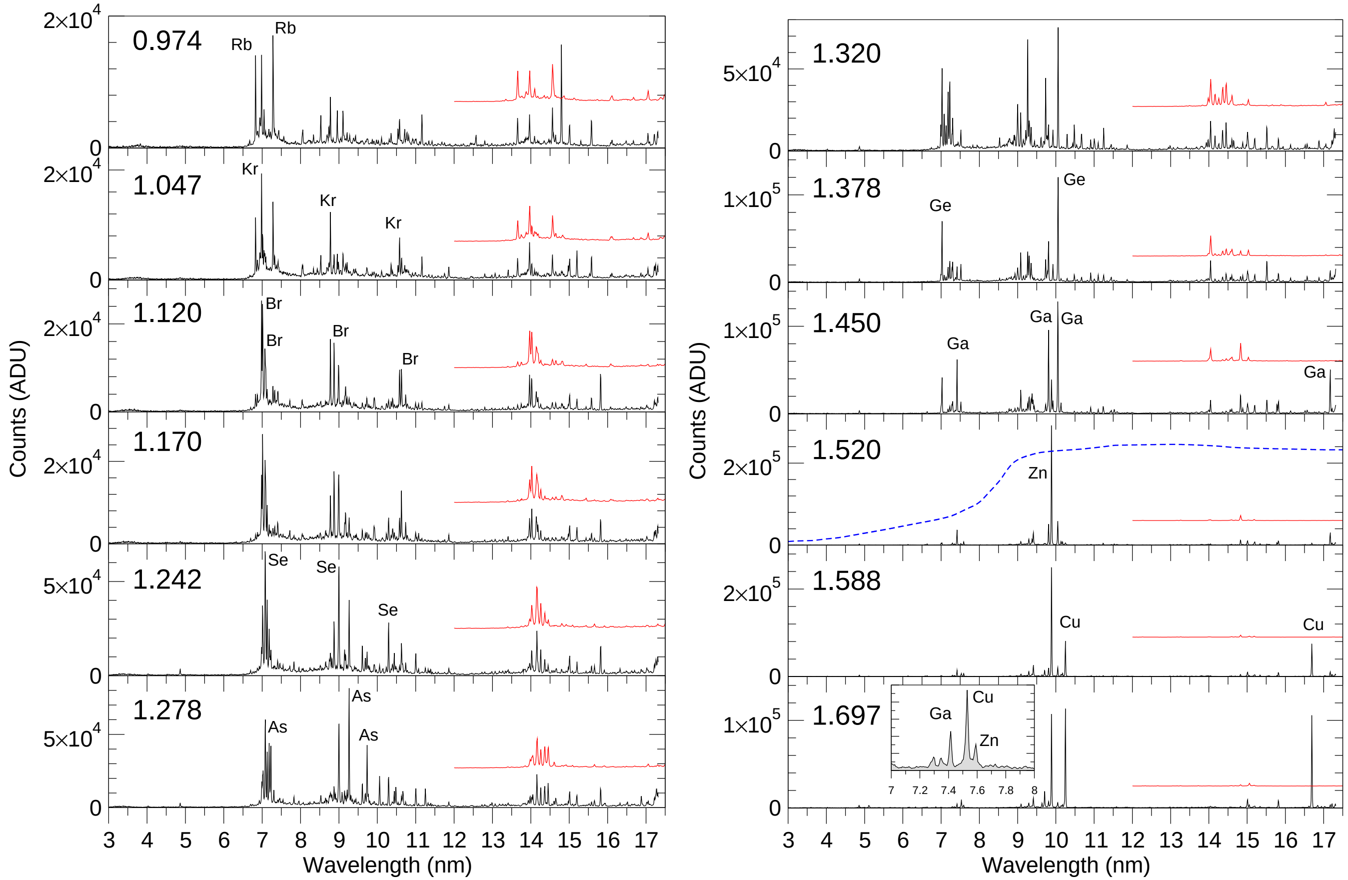
CR model –
NOMAD

- non-Maxwellian time-dependent CR plasma code
- ~10^3 levels/ion
  typically 6-8 ions
  several million transitions
  runs in minutes
- **one free parameter** – charge exchange CX between ions and neutrals

Gu *Can. J. Phys.* **86** 675 (2008)
Ralchenko and Maron *J. Quant. Spectrosc. Radiat. Transfer* **71** 609 (2001)

EBIT Spectra of Gd

Rb-like to Cu-like gadolinium ion spectra



Ion	IP (eV)
Rb-like	936
Kr-like	1100
Br-like	1142
Se-like	1189
As-like	1233
Ge-like	1320
Ga-like	1369
Zn-like	1481
Cu-like	1531

Kilbane *et al.* accepted *Phys. Rev. A* (2012)
Rodrigues *et al. At. Data Nucl. Data Tables* **86** 117 (2004)

EBIT Spectra of Gd

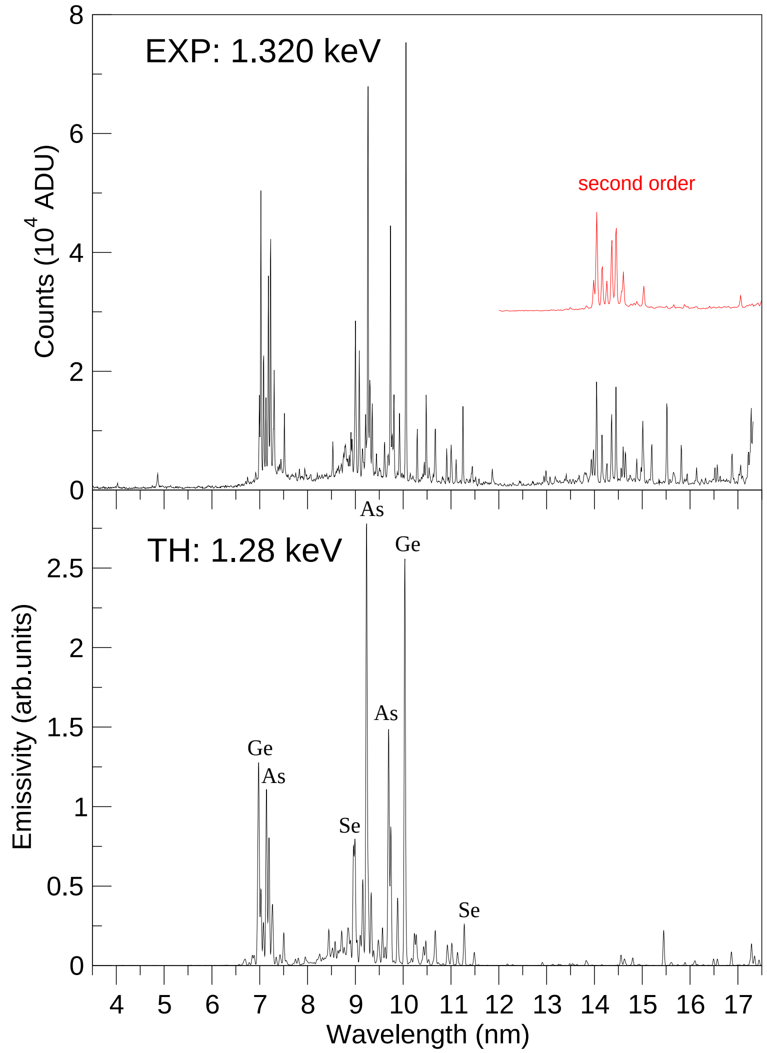
Ge-like Gd ion

CR database of singly + doubly excited $4s^24p^2$, $4p^4$, $4s^24d^2$, $4s4p^3$, $4s^24p4d$, $4s^24p4f$, $4s4p^24d$, $4s4p^24f$, $4s^24p5l$, $4s4p^25l$, $4s^24p6l$, $4s4p^26l$

Energy levels of all singly, doubly, triply and quadruply excited n=4 complex $4s4d^3$, $4s4f^3$, $4d^4$, $4f^4$ $4p^24d^2$, $4p^24f^2$ and $4p^24d4f$

CR database is updated with new energies of the lowest levels

Excellent agreement between measured and simulated spectra e.g. Se, As, Ge-like



Kilbane *et al.* accepted *Phys. Rev. A* (2012)

Gadolinium Data Tables

59 new lines:
4s-4p, **4p-4d** and **4d-4f** transitions ranging from 6.630 nm to 17.279 nm (mostly E1)

Ion	Lower level		Upper level		Experiment		Theory	
	Conf.	State	Conf.	State	Current	Previous	Current	Previous
Gd^{33+} [Ga]	$4s^24p$ [1]	$(4p_-)_{1/2}$	$4s4p^2$ [7]	$((4s_+,4p_-)_1,4p_+)_{1/2}$	9.807	9.811(20)[f]	9.7664	9.655[f]
Gd^{34+} [As]	$4s^24p^3$ [1]	$(4p_+)_{3/2}$	$4s4p^4$ [9]	$(4s_+,4p_+^2)_{3/2}$	9.732		9.6954	
Gd^{28+} [Kr]	$4p^6$ [1]	$(4p_+^4)_0$	$4p^54d$ [7]	$(4p_+^3,4d_+)_2$	9.726		9.6932	
Gd^{35+} [Cu]	$4p$ [3]	$(4p_+)_{3/2}$	$4d$ [5]	$(4d_+)_{5/2}$	9.704	9.7026(15)[d], 9.7074(15)[c]	9.6999	9.6962[d], 9.6958[n]
Gd^{30+} [Se]	$4s^24p^4$ [1]	$(4p_+^2)_2$	$4p^34d$ [11]	$(4p_+,4d_+)_4$	9.684		9.6719	
Gd^{35+} [Cu]	$4d$ [5]	$(4d_+)_{5/2}$	$4f$ [7]	$(4f_+)_{7/2}$	9.636	9.6349(15)[d], 9.6398(15)[c]	9.6598	9.6419[n], 9.6426[d]
Gd^{30+} [Se]	$4s^24p^4$ [1]	$(4p_+^2)_2$	$4s4p^5$ [12]	$(4s_+,4p_+^3)_1$	9.609		9.5688	
Gd^{34+} [Zn]	$4s4p$ [5]	$(4s_+,4p_+)_1$	$4s4d$ [14]	$(4s_+,4d_+)_2$	9.409	9.4085(20)[e]	9.3897	9.3651[e]
Gd^{33+} [Ga]	$4s^24p$ [2]	$(4p_+)_{3/2}$	$4s4p^2$ [11]	$(4s_+,4p_+^2)_{3/2}$	9.376		9.3183	
Gd^{32+} [Ge]	$4s4p^3$ [7]	$(4s_+,4p_+)_1$	$4s4p^24d$ [33]	$(4s_+,4d_+)_2$	9.352		9.3317	
Gd^{32+} [Ge]	$4s^24p^2$ [3]	$(4p_-,4p_+)_2$	$4p4d$ [15]	$(4p_-,4d_+)_3$	9.300		9.2711	
Gd^{31+} [As]	$4s^24p^3$ [1]	$(4p_+)_{3/2}$	$4p^24d$ [10]	$(4d_+)_{5/2}$	9.262		9.2345	
Gd^{29+} [Br]	$4p^5$ [1]	$(4p_+^3)_{3/2}$	$4p^44d$ [11]	$(4p_+^2,4d_+)_{1/2}$	9.172		9.1315	
Gd^{30+} [Se]	$4s^24p^4$ [2]	$(4p_+^2)_0$	$4p^34d$ [15]	$(4p_+,4d_+)_1$	9.146		9.1050	
Gd^{27+} [Rb]	$4p^64d$ [1]	$(4d_-)_{3/2}$	$4p^54d^2$ [23]	$((4p_+^3,4d_-)_2,4d_+)_{5/2}$	9.105		9.0503	

'Forbidden lines'

Kr-like (9.726 nm) (M2)
$4p^6(4p^4_+)_0 – 4p^54d(4p^3_+,4d_+)_2$

Se-like (9.684 nm) (M2)
$4s^24p^4(4p^2_+)_2 – 4p^34d(4p_+,4d_+)_4$

Se-like (7.826 nm) (M2)
$4s^24p^4(4p^2_+)_2$
$– 4p^34d((4p_-,4p^2_+)_{3/2},4d_-)_0$

Spectra were calibrated with known lines of Ba, Xe, C and O ions – accuracy 0.003 nm

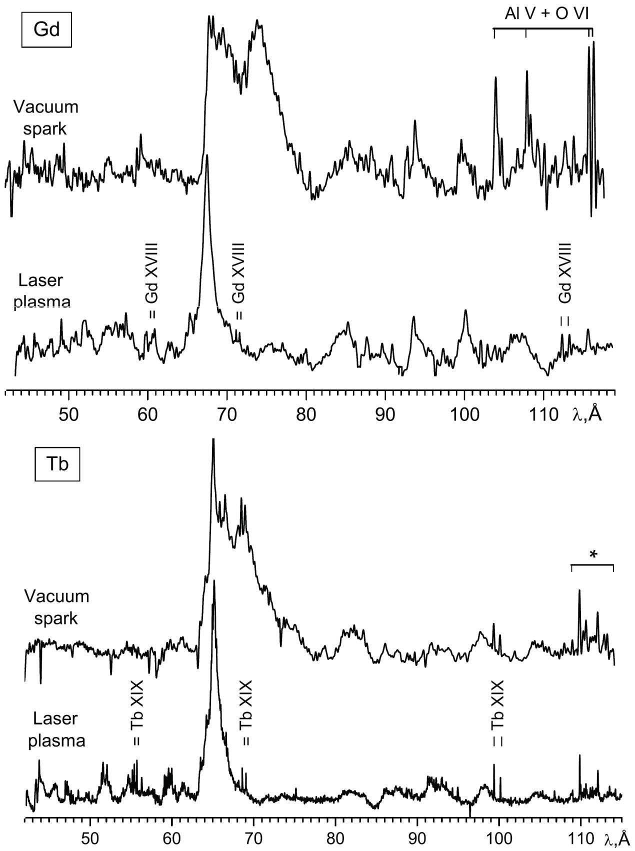
Cu-like lines

NIST EBIT	NIFS
9.086 nm	9.091(2) nm
7.527 nm	7.524(2) nm

Kilbane *et al.* accepted *Phys. Rev. A* (2012)
Suzuki *et al. J. Phys. B* **45** 135002 (2012)

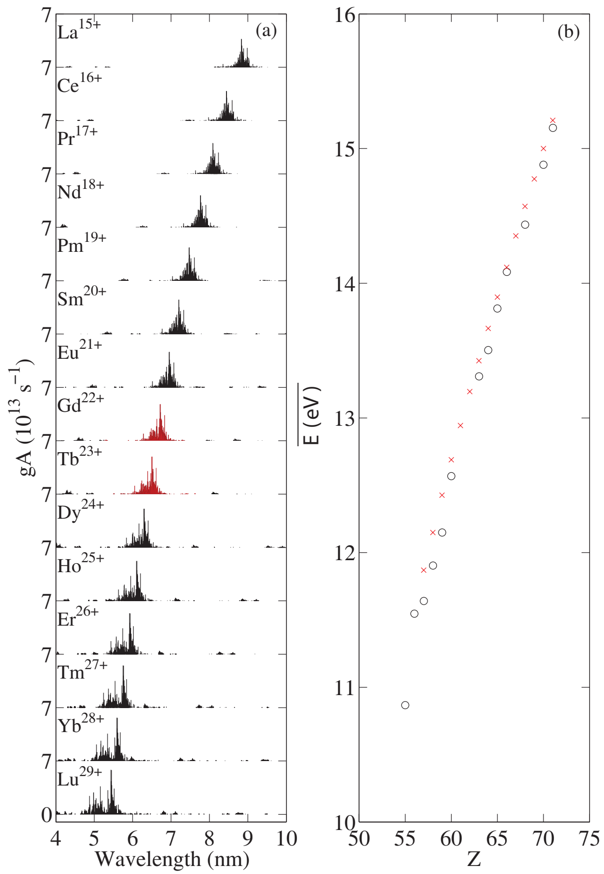
Next-Generation EUV Lithography at 6.x nm

Churilov identified **Gd and Tb** in LPPs and spark discharges



4d-4f + 4p-4d UTAs

Intense emission due to overlap of many open 4d and 4f subshell ions



Churilov *et al. Phys. Scr.* **80** 045303 (2009)

Kilbane and O'Sullivan *Phys. Rev. A* **82** 062504 (2010)

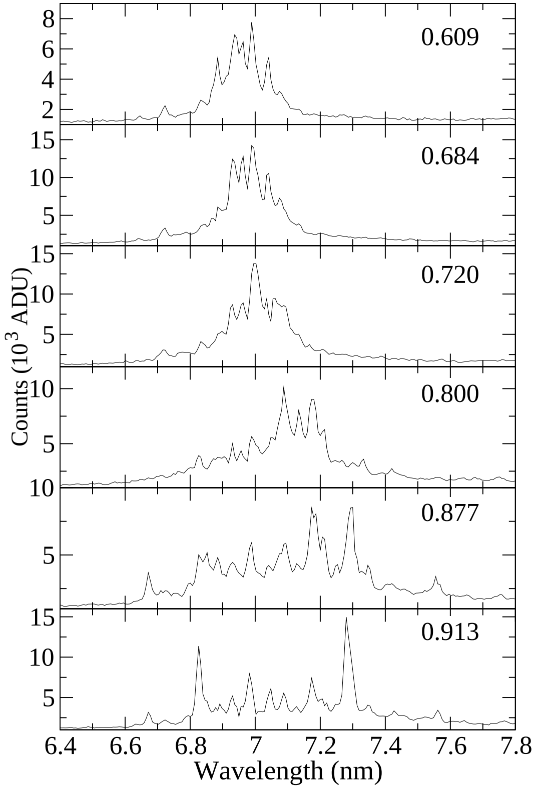
Spectra of Gd and Dy at 6.x nm

Gadolinium

Ag-like
$4d^{10}4f – 4d^{9}4f^{2}$
6.7423, 6.7465,
6.7884 nm

Pd-like
$4d^{10} – 4d^{9}4f$
6.7636 nm

Gd Ion	IP (eV)
Ag-like	358
Pd-like	565
Rh-like	601

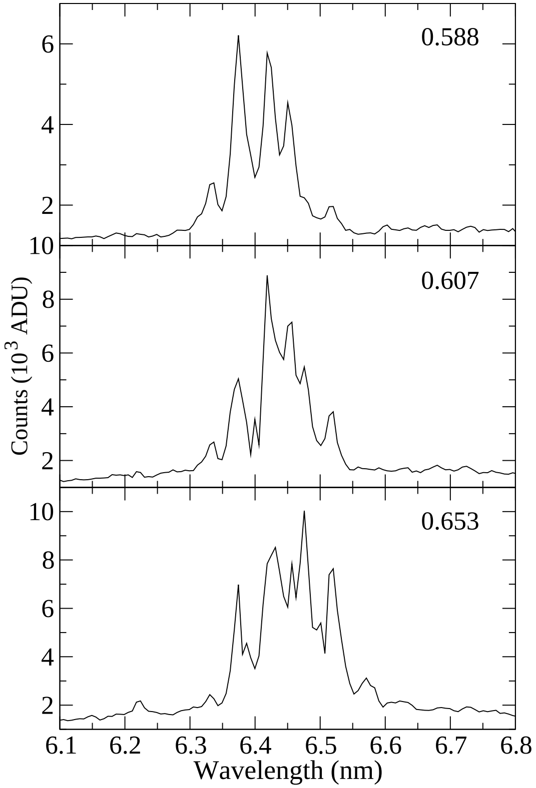


Dysprosium

Ag-like
$4d^{10}4f – 4d^{9}4f^{2}$
6.6437, 6.5967,
6.2587, 6.3125 nm

Pd-like
$4d^{10} – 4d^{9}4f$
6.2778 nm

Dy Ion	IP (eV)
Ag-like	423
Pd-like	664
Rh-like	702



Note: Very low current ~5 mA at 0.609 keV

Absence of strong resonant transitions

Sugar *et al. J. Opt. Soc. Am. B* **10** 799, 1321, 1977 (1993)

Rodrigues *et al. At. Data Nucl. Data Tables* **86** 117 (2004)

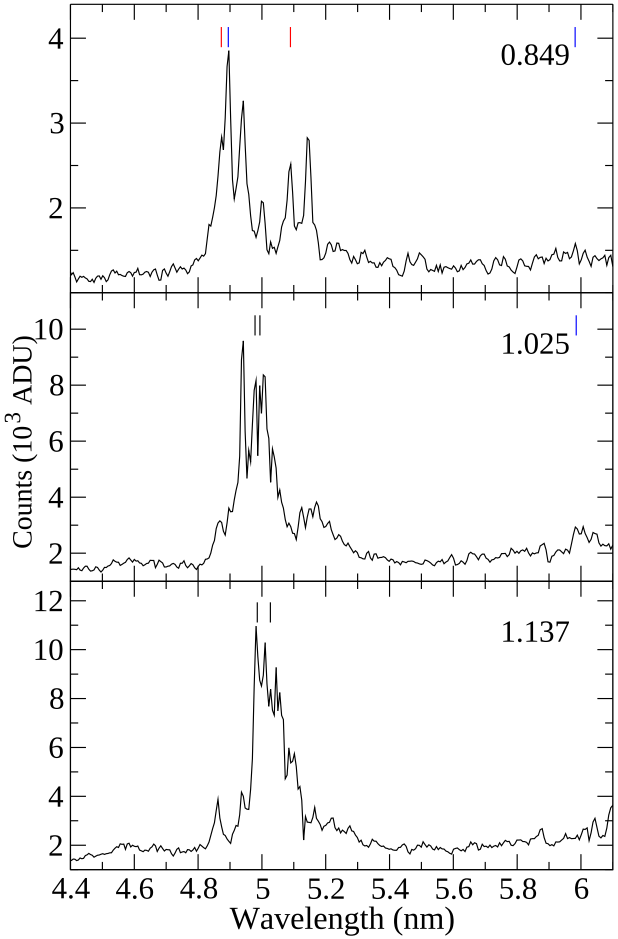
Spectra of W

Ag-like $4d^{10}4f – 4d^{9}4f^{2}$
5.1457, 5.0895, 4.8729, 4.9403 nm

Pd-like $4d^{10} – 4d^{9}4f$
4.8948, 5.9852 nm

Rh-like $4d^{9} – 4d^{8}4f$
4.9856, 4.9785, 4.9938, 5.0265 nm

W Ion	IP (eV)
Ag-like	881.4
Pd-like	1132.2
Rh-like	1179.9



Strong resonant transitions observed at lower beam energies in Pd-like ions

Note: Feature observed at ~4.5 nm at 1.03 and 1.15 keV at the Berlin EBIT is absent

Sugar *et al. J. Opt. Soc. Am. B* **10** 799, 1321, 1977 (1993)

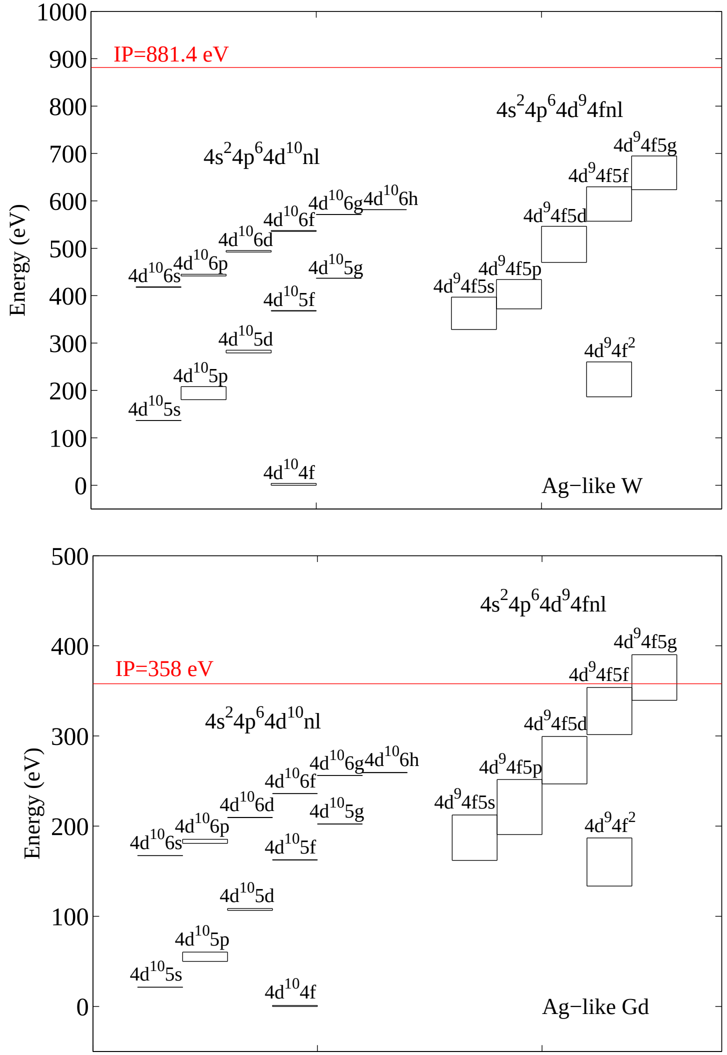
Kramida and Shirai *At. Data Nucl. Data Tables* **95** 305 (2009)

Biedermann *et al. Phys. Scr. T* **92** 85 (2001)

‘Potential Lowering’ of 4f^n ions

Metastable states

- Many low lying excited states of Ag-like ions are populated by collisions
- These metastable states remain well populated
- Beam energy required to generate excited states of Pd-like ions is reduced



Summary

EUV spectra of Gd, Dy and W ions from the NIST EBIT

- 59 new lines identified in Rb-like to Cu-like gadolinium
- ‘Potential lowering’ observed in $4f^{n}$ ions
- Uses:
  - validate atomic / plasma codes
    predict trends in atomic structure
  - model EUV sources for next-generation lithography
  - diagnostics of hot plasmas in fusion devices
    such as ITER

Thanks

The Atomic Spectroscopy Group at NIST

Acknowledgement:

This work was supported by Science Foundation Ireland under grant number 07/IN.1/I1771 and in part by the Office of Fusion Energy Sciences of the U.S. Department of Energy.