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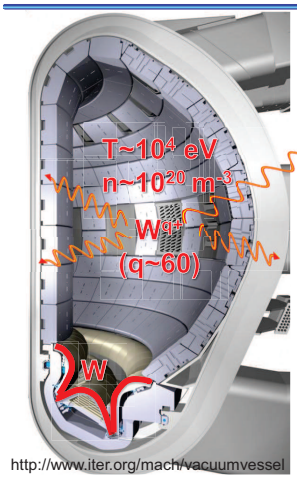
Experimental evaluation of W recombination and Ionization rates/cross-sections

T. Nakano
Japan Atomic Energy Agency

Acknowledgements
Dr. N. Nakamura (Univ. of Electro-Communications)
Dr. H. Ohashi (Toyama Univ.)

Tungsten: a candidate for PFCs in reactors



http://www.iter.org/mach/vacuumvessel

W plasma-facing component

- Merit : high melting point
  : high heat conductivity
  : low sputtering yield
  : low hydrogen (T) retention
  ⇒ safety, economy
- Demerit : melting
  : cracking (Bulk W)
  : **high Z (74)**
  ⇒ accumulation in plasma core
  ⇒ highly radiative ($n_W/n_e < 10^{-5}$)

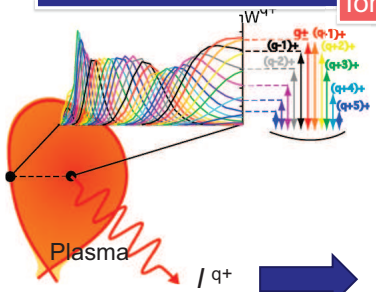
⇒ **W transport in plasmas**

For quantitative transport study, absolute W density is required.

Various W atomic data needed for W density measurement

W spatial / charge state distribution
<= Ioniz/recomb. rates

Ioniz.Eq / Transport model



(Fractional abundance of W^{q+})

$$\frac{nW^{q+}}{nW}$$

nW (total W density)

nW^{q+} (W^{q+} density)

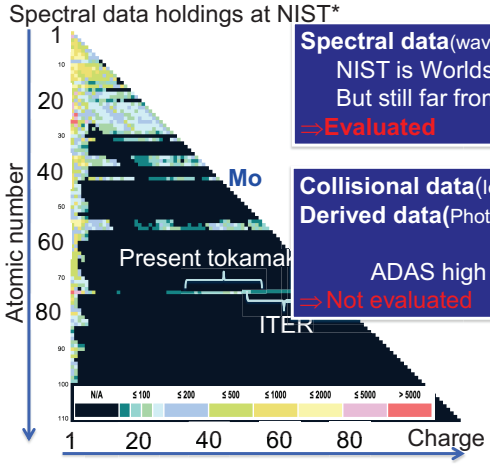
Line identification
<= spectral data

Photon Emission Coefficient
<= excitation rate, A coef, Energy level

Collisional-radiatve model

Availability of W atomic data

Spectral data holdings at NIST*

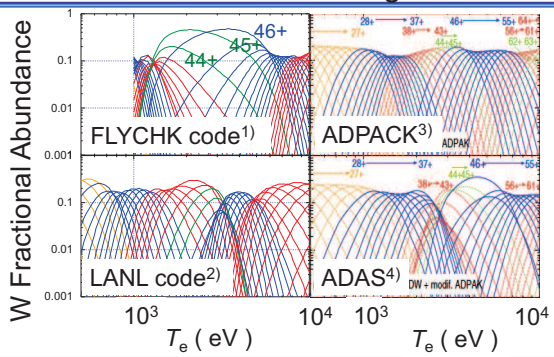


Spectral data(wavelength, Acoef):
NIST is Worlds' standard database
But still far from 'a complete set'
⇒**Evaluated**

Collisional data(Ioniz./recomb. Rates):
Derived data(Photon emission coef, Cooling rates):
ADAS high availability
⇒Not evaluated

*) NIST ASD version5.
http://physics.nist.gov/ASD

W fractional abundance under Ionization equilibrium still different amongst datasets



Uncertainty of collisional data (Ioniz./Recomb. rates) needed
⇒ Evaluation

1)http://nlte.nist.gov/FLY/
2)http://aphysics2.lanl.gov/tempweb/lanl/
3)K. Asmussen, et al., Nucl. Fusion **38** (1998) 967-986.
4)T. Puetterich *et al PPCF* **50** (2008) 085016.

Issue 1: W density measurement

W spatial / charge state distribution
<= Ioniz/recomb. rates

Ioniz.Eq / Transport model

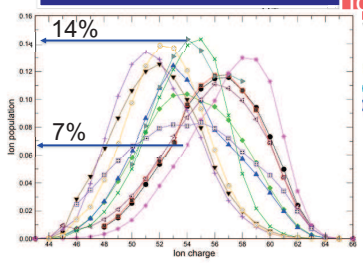


Fig. 11. Ionization distribution of W ions at 7 keV and 10^{14} cm^{-3}.

(Fractional abundance of W^{54+})

$$\frac{nW^{54+}}{nW}$$

nW (total W density)

Factor of 2 deviation

nW^{54+}

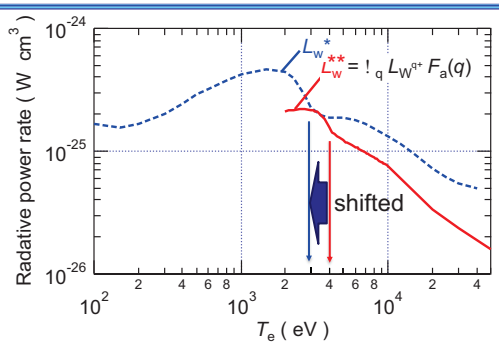
Line identification
<= spectral data

Photon Emission Coefficient
<= excitation rate, A coef, Energy level

Collisional-radiatve model

*H.-K Chung et al., HEDP 9 (2013) 645.

Issue 2: W cooling rate



Shift of the cooling rates originates from ioniz. Eq calculation

*T Puetterich *et al Nucl. Fusion* **50** (2010) 025012
T Nakano et al J. Nucl. Mater **415 (2010) S327

Outline

- Introduction
- Motivation
- Evaluation of W^{44+} ionization / W^{45+} recombination
  - in JT-60U tokamak device (thermal electron)
  - in Tokyo EBIT device (mono-energy electron)
- Suggestion for diagnostic lines in ITER with evaluation method
- Conclusions

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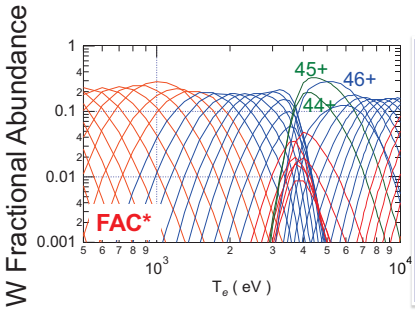
W density ratio calculated under ionization equilibrium



Ionization equilibrium:

$n_W^{44+} S^{44+\to45+} = n_W^{45+} \alpha^{45+\to44+}$

$\Rightarrow$

$$\frac{n_W^{45+}}{n_W^{44+}} = \frac{S^{44+\to45+}}{\alpha^{45+\to44+}}$$

$S = S^{direct} + S^{excit.autoioniz.}$

$\alpha = \alpha^{radiative} + \alpha^{die\text{-}electronic}$

* M.F.Gu, Can. J. Phys. **86** (2008) 675

Constant excitation rate ratio of W^{44+} and W^{45+} useful for direct comparison btw Exp and Theory

Measurement

$$\frac{I^{W45+}(6.2\ nm):\ 4s\,^2S_{1/2} - 4p\,^2P_{3/2}}{I^{W44+}(6.1\ nm):\ 4s4s\,^1S_0 - 4s4p\,^1P_1} = \frac{C_e^{45+}(4s,4p)}{C_e^{44+}(4s,4p)} \cdot \frac{nW^{45+}(4s)}{nW^{44+}(4s)} \cdot \frac{n_e}{n_e}$$

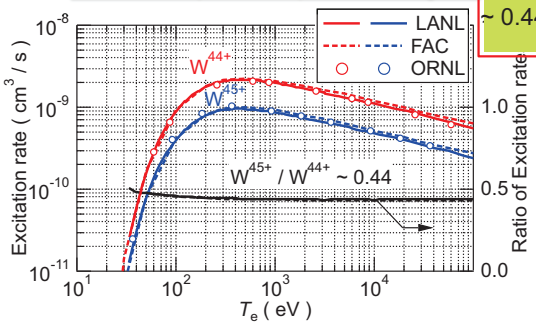
Excitation rate

Ioniz. Equi.

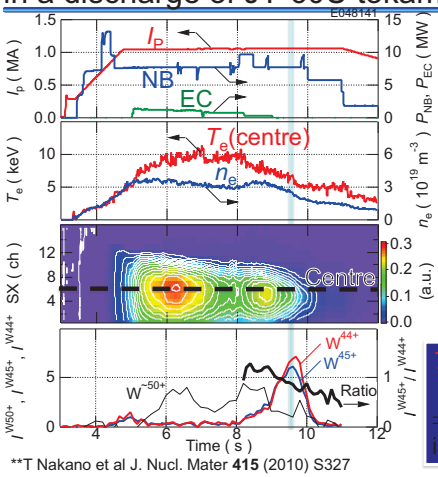
Close excitation energy (199 ev and 204 eV)
$\Rightarrow$ Similar temperature dependence of C_e

~ 0.44 $\quad \frac{S^{44+\to45+}}{\alpha^{45+\to44+}}$ (Ioniz.rate) / (Recomb.rate)

Calculation



Electron temperature scan in a discharge of JT-60U tokamak

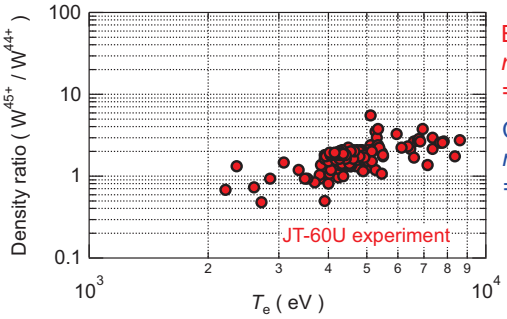


- Negative shear discharge -W accumulation occurs
- T_e decrease from 10 keV to 5 keV
- During T_e decrease, I^{W45+} and I^{W44+} increases, and then decreases

T_e -scan data for W^{45+} / W^{44+}
$\Rightarrow$ Comparison with ionization equilibrium

T Nakano et al J. Nucl. Mater **415 (2010) S327

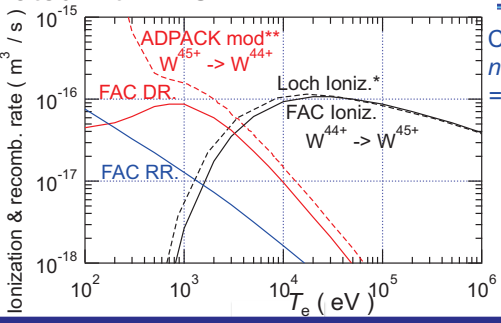
Measured W^{45+}/W^{44+} in JT-60U



Exp:
$n_W^{45+} / n_W^{44+} = I^{45+} / I^{44+} / 0.44$

Cal:
$n_W^{45+} / n_W^{44+} = S^{44+} / \alpha^{45+}$

Ionization/recombination rates calculated with FAC

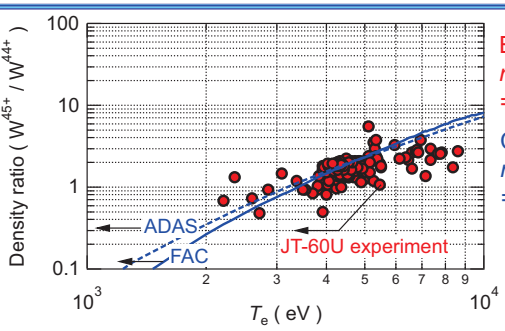


Cal:
$n_W^{45+} / n_W^{44+} = S^{44+} / \alpha^{45+}$

	Present	Ref**	
Ionization	FAC (DW)	Loch code* (DW)	ADAS
Dielectronic Recombination	FAC	ADPACK mod. (0.39 x)	ADAS
Radiative Recombination	FAC	ADPACK mod. (0.39 x)	ADAS

*S Loch *et al.*, *Phys. Rev. A* **72** (2005) 052716 **T Putterich *et al.*, *Plasma Phys. Control. Fusion* **50** (2008) 085016

FAC calculation reproduced measured W^{45+}/W^{44+}*



Exp:
$n_W^{45+} / n_W^{44+} = I^{45+} / I^{44+} / 0.44$

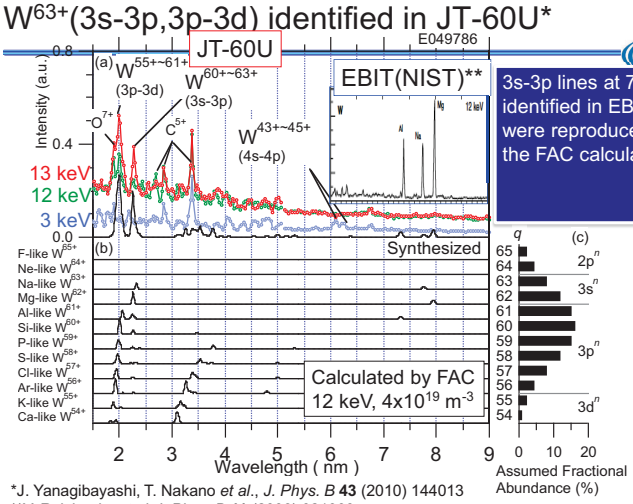
Cal:
$n_W^{45+} / n_W^{44+} = S^{44+} / \alpha^{45+}$

FAC and ADAS agree with JT-60U experimental data within 30%

$\Rightarrow$ Accuracy of S^{44+} to α^{45+} evaluated

*T Nakano et al J. Nucl. Mater **415** (2010) S327
** A. Sasaki and I. Murakami, J. Phys. B **46** (2013) 175701

W^{63+}(3s-3p,3p-3d) identified in JT-60U*



3s-3p lines at 7-8 nm identified in EBIT** were reproduced by the FAC calculation.

*J. Yanagibayashi, T. Nakano *et al.*, *J. Phys. B* **43** (2010) 144013
Y. Ralchenko et al *J. Phys. B* **41 (2008) 021003

Summary

Analysis of intensity ratio of W^{45+} to W^{44+} line in
JT-60U (Maxwellian e distribution) and
EBIT (Mono-energy e)
to evaluate ratios of W^{45+} recombination rates/cross-sections and
W^{44+} ionization rates/cross-sections
by taking advantage of canceling out electron temperature/energy dependence of the rates / cross-sections:

- Rates : quantitative agreement
- Cross-sections : quantitative agreement
  except some DR resonant structures
  ⇒ Needs further analysis.

Suggestion for diagnostic lines for W density in ITER core:
The same evaluation technique can be applied for the ratio of
W^{63+} recombination and W^{62+} ionization rates/cross-sections.