Dielectronic Recombination of W^{18+}: Theory vs Storage Ring Measurements

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Motivation

- Dielectronic recombination (DR) establishes the ionization balance in non-LTE plasmas and contributes to line emission e.g. DR satellites.

- For ITER and ITER-like devices we need to consider W and its brethren. The highest charge-state likely to be seen in ITER is nominally 60+.

- Tungsten $\sim 20+$ is seen at the null point of the separatrix at JET.

- Previously, (ADAS 2012) reported-on DR of $W^{20+}(4d^{10}4f^8\ {}^7F_6)$:
experiment (Schippers et al. PRA83, 012711, 2011) and
theory (Badnell et al. PRA85, 052716, 2012).

Recall (1): W^{20+}

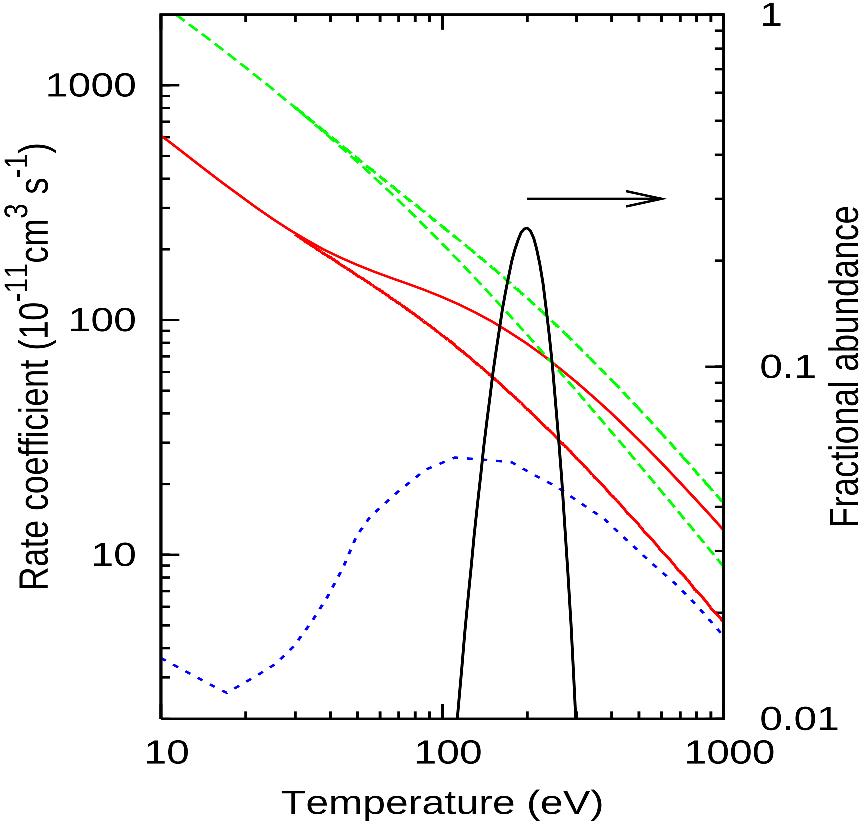

Fig 1. W^{20+} total Maxwellian DR rate coefficients: experiment Schippers et al. (2011) to 140 eV and with theory top-up for resonances above 140 eV (long-dashed green curves); theory Badnell et al. (2012) IC all resonances and to 140 eV only (solid red curves), and ADAS (Foster, Ph.D. Thesis 2008) (short-dashed blue curve). A possible fractional abundance of W^{20+} in a magnetic fusion plasma is shown also (solid black curve).

Recall (2): W^{20+}

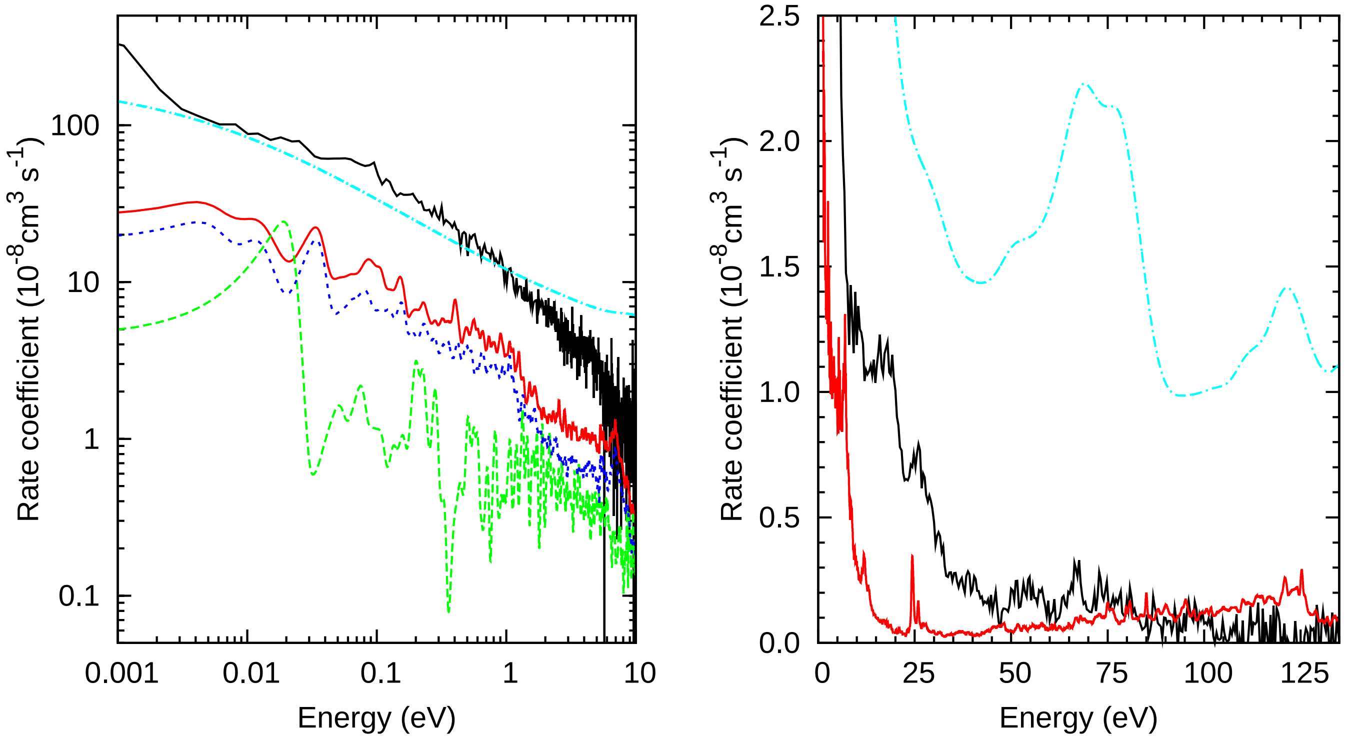

Fig 2. W^{20+} merged-beams DR rate coefficients: experiment Schippers et al. (2011) (solid black curve); theory Badnell et al. (2012) partitioned total (dot-dashed cyan curve), IC total (solid red curve), LS total (long-dashed green curve), and IC $4\mathrm{d} \rightarrow 4\mathrm{f}$ only (short-dashed blue curve).

DR of $W^{18+}(\mathbf{4d^{10}4f^{10}\ {}^5I_8})$

We use AUTOSTRUCTURE (Badnell 2011) to carry-out configuration average, LS- and intermediate coupling calculations — including partitioning.

We consider $\Delta n = 0$ and $\Delta n = 1$ promotions of $4d$ and $4f$ electrons.

The complexity of the open f-shell restricts us to one-electron promotions plus dielectronic capture into autoionizing states of W^{17+}.

There are many more autoionizing states present which result from multiple-electron promotions (plus capture) but they are 'forbidden' to the ground state under a single 2-body operator.

The same open f-shell complexity mixes/redistributes the dielectronic capture (inverse autoionization A) over many more autoionizing states, effectively making them accessible from the ground state.

Such 'forbidden' capture states can typically radiatively stabilize at a rate R comparable with that for the 'allowed' capture.

A Simple Model

What does this mean for DR?

Recall,

$$\mathrm{DR} \propto \frac{AR}{A+R} \tag{1}$$

and so the weaker process controls the rate:

If $A \ll R$

$$\mathrm{DR} \propto \frac{A}{A/R+1} \approx A\,. \tag{2}$$

If $R \ll A$

$$\mathrm{DR} \propto \frac{R}{1+R/A} \approx R\,. \tag{3}$$

So, if the autoionization rate A, corresponding to the allowed dielectronic capture, satisfies

$$A \ll R\,, \tag{4}$$

initially, then the total DR is merely redistributed by any (unitary) mixing transformation, and

$$\mathrm{DR} \propto A \tag{5}$$

still, both with-and-without mixing.

However, if initially

$$A \gg R\,, \tag{6}$$

so

$$\mathrm{DR} \propto R\,, \tag{7}$$

then following complete redistributive mixing of A, so that $A \ll R$ again, we have the total

$$\mathrm{DR} \propto A \tag{8}$$

and enhanced by a factor

$$A/R\,. \tag{9}$$

compared to the unmixed result.

Redistribution, Partitioning & Damping

We use a Breit-Wigner distribution to partition our autoionization rates, as suggested by statistical theory (Flambaum et al. 1994):

$$A \leftarrow L(E)A \tag{10}$$

and

$$L(E) = \frac{\Gamma/(2\pi)}{E^2 + \Gamma^2/4}\,, \tag{11}$$

where E is the 'de-tuning' energy and Γ is the spreading width (~ 10 eV for the open f-shell). We use a uniform logarithmic set of 'bin' energies for E.

The above model is valid close to threshold only. As we move higher in energy, more-and-more alternative autoionization into excited-states pathways open-up and suppress the DR again ($A + R \not\approx R$).

Thus, the total autoionization width needs to be recomputed at each bin energy (for each dielectronic capture).

W^{18+} (New)

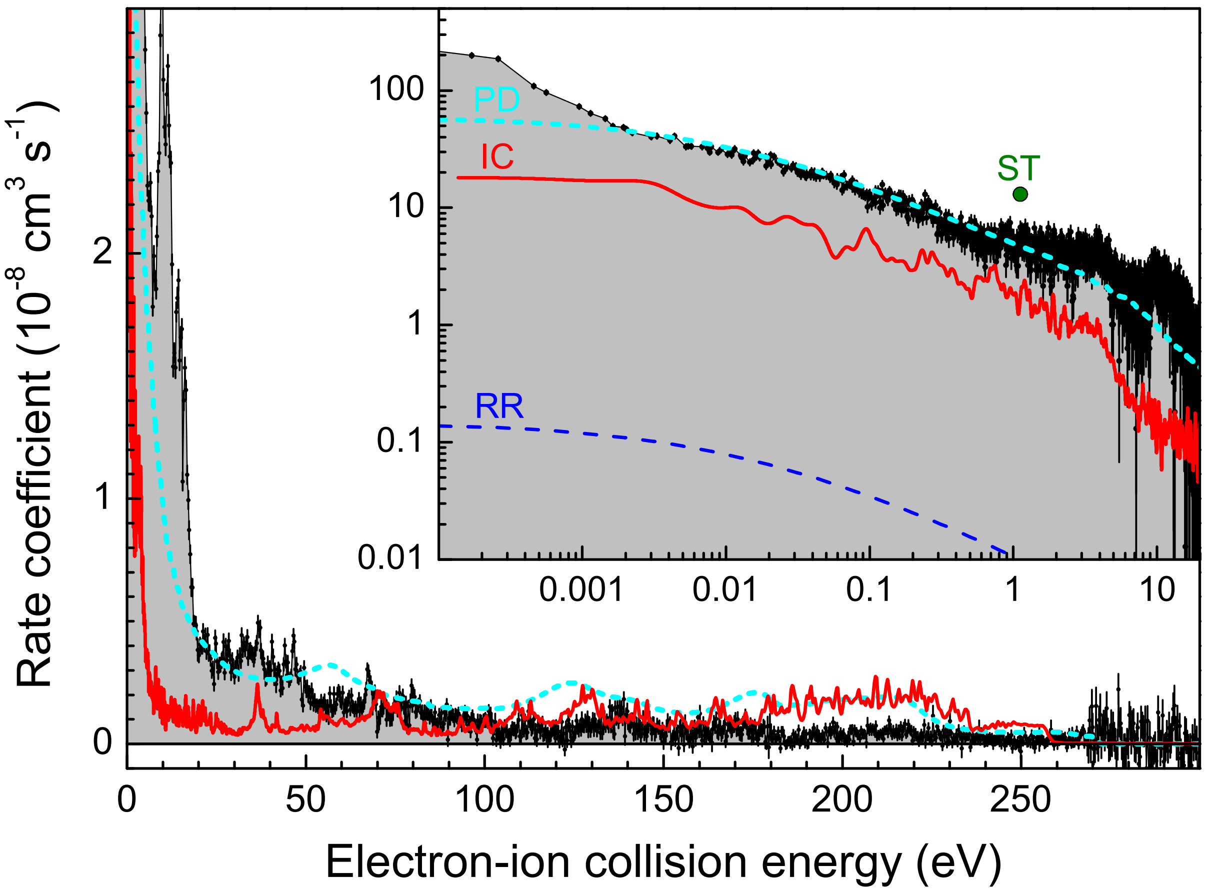

Fig 3. Merged-beams recombination rate coefficients for W^{18+} (Spruck et al. Phys.Rev.A At Press, 2014). Symbols with error bars: measured; solid curve (IC): present intermediate-coupling results; short-dashed curve (PD): present partitioned and damped results; circle (ST): from the statistical theory by Dzuba et al. (2012).

W^{18+} (New)

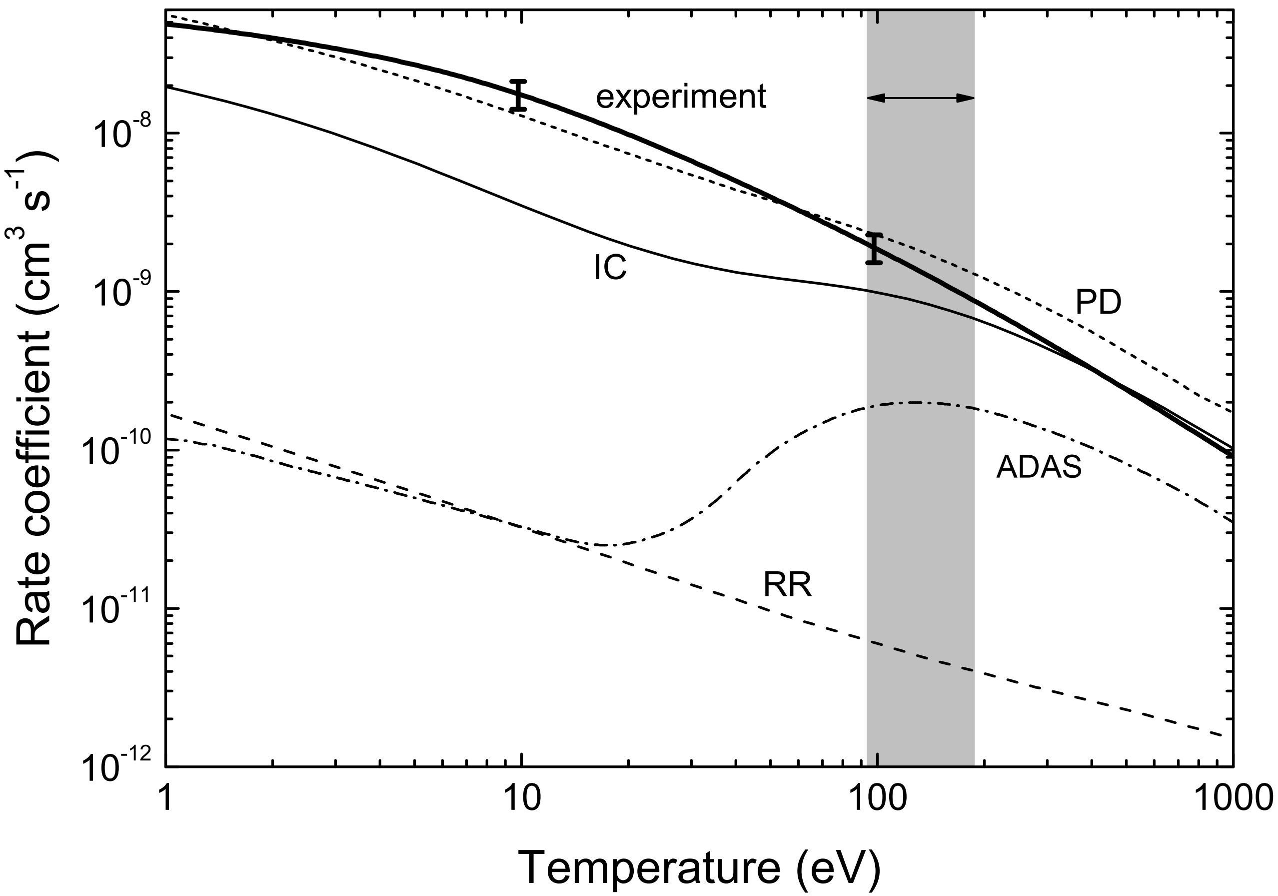

Fig 4. Plasma recombination rate coefficients for W^{18+} (Spruck et al. Phys.Rev.A At Press, 2014). Thick solid curve: experimentally derived rate coefficient; thin solid curve: IC theory; short-dashed curve (PD) partitioned and damped calculation; Dot-dashed curve: ADAS plasma recombination rate coefficient (Foster 2008).

W^{20+} (Revisited)

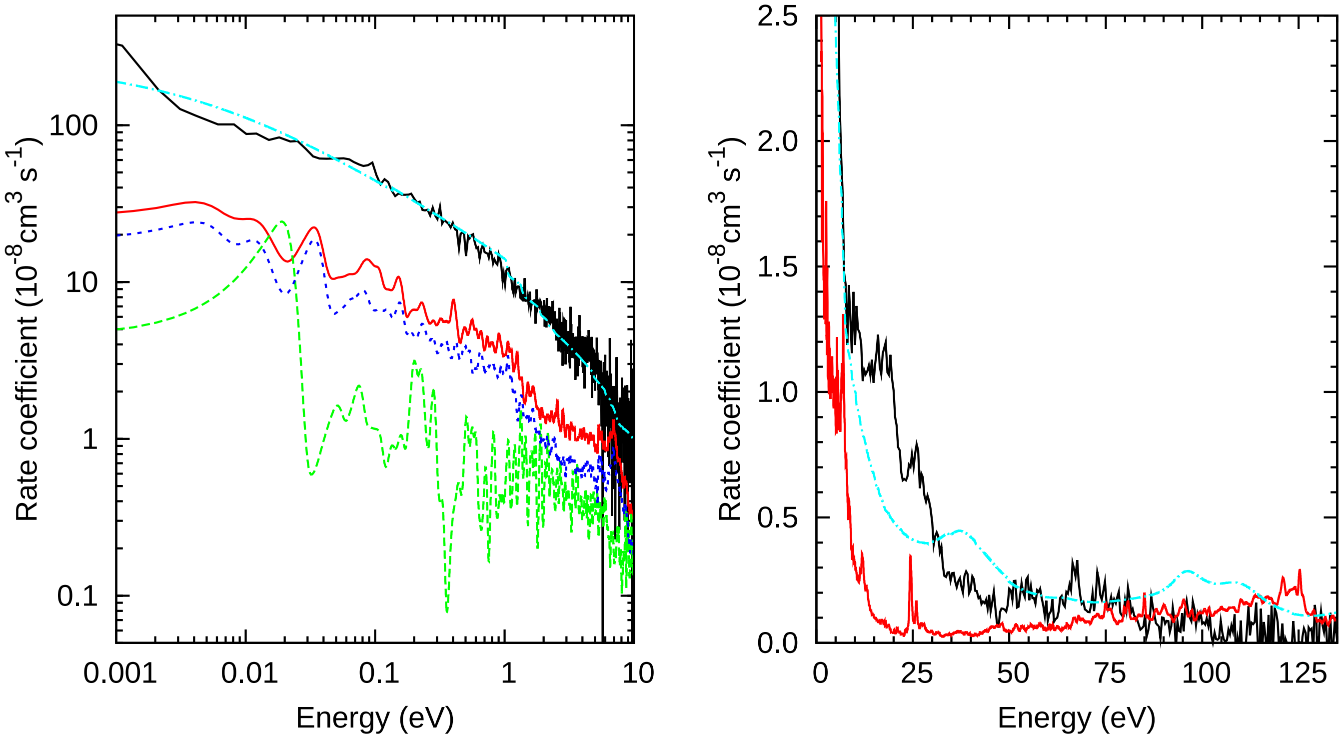

Fig 5. W^{20+} merged-beams DR rate coefficients: experiment Schippers et al. (2011) (solid black curve); theory Badnell et al. (2012, & unpublished) partitioned and damped total (dot-dashed cyan curve), IC total (solid red curve), LS total (long-dashed green curve), and IC $4\mathrm{d} \rightarrow 4\mathrm{f}$ only (short-dashed blue curve).

Follow-up

ADAS 2012 Workshop:

- CR modelling to assess density effects and revise ionization balance for W with open f-shell;$\times$ DR of adjacent ions expected to be similar.✓
- Experiments on adjacent ions being analyzed (Schippers, private communication).✓(19+ almost finished.)
- Can the validity of the model calculation be extended to higher energy?✓✓

Follow-on

ADAS 2014 Workshop:

- We have a good handle on total DR. But CR modelling requires final-state resolved partials. We have the answer, viz. the hybrid *adf09* specification (discussed at ADAS 2012). The question is, where do we put the redistributed DR?

- EPSRC funded (EP/L021803/1) 'Atomic Process for Magnetic Fusion Plasmas: DR of the Tungsten Isonuclear Sequence' — starting shortly (Simon Preval) at Strathclyde, and Martin at JET.

Podziękowania!