
New set of radiative atomic data for the six Ytterbium-like ions (Ta IV - Pt IX) of interest to nuclear fusion diagnostics

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1. Introduction

- Ionic impurities in the fusion plasma
- Plasma diagnostics

2. HFR+CPOL preliminary results

- Pseudo-relativistic Hartree-Fock method with the core polarization corrections (HFR+CPOL)
- Model + least squares adjustment
- The configuration interactions and the core-valence correlations
- Radiative decay rates

3. MCDHF preliminary results

- Multiconfigurational Dirac-Hartree-Fock (MCDHF) method
- Model and convergence
- Radiative decay rates (comparisons)

Introduction

Ionic impurities in the fusion plasma

- Divertor will be made of tungsten: high fluxes of heat and particles (neutrons)
- Transmutation products after few years irradiation time: rhenium, osmium, tantalum, hafnium, iridium and platinum → impurities
- Brittleness of pure tungsten → alloying elements (tantalum, rhenium, titanium or vanadium)

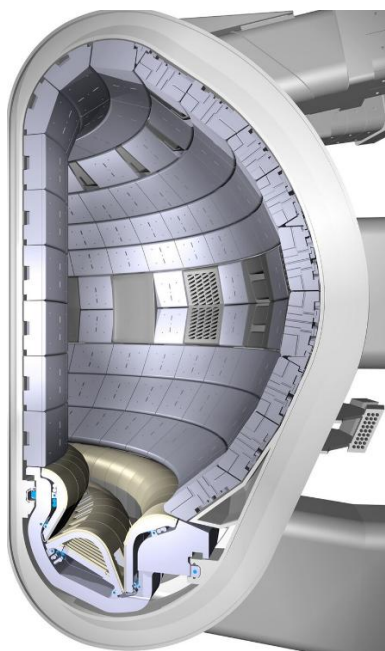
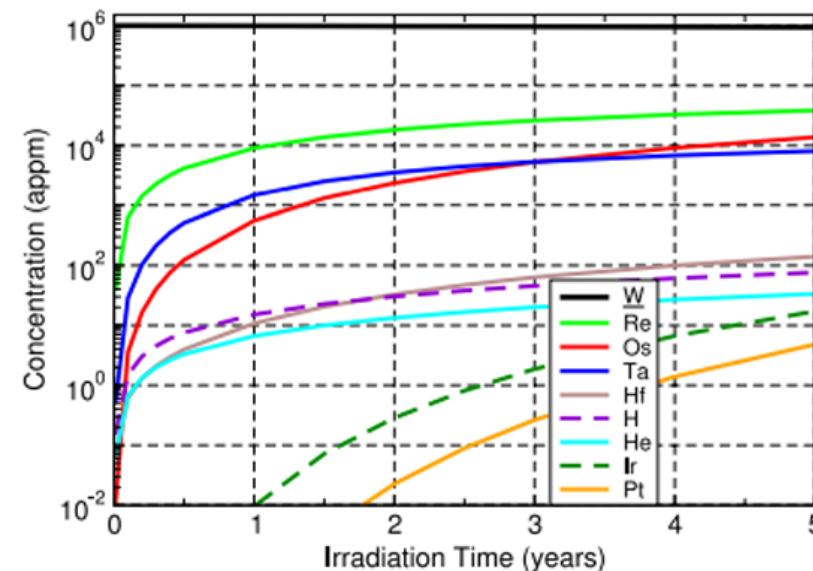


Illustration of the inside of the Tokamak.
(<https://encyclopedia.pub/entry/37629>)



Evolution of the concentration (Atomic Part Per Millions) of all the elements produced by the transmutation of W for a five-years irradiation [Gilbert, M. R and Sublet, J.Ch , 2011]

Plasma diagnostics

- Ionic impurities will contribute to the radiation losses/enable to diagnose the fusion plasma
- From observed intensity ratio and radiative parameters [HJ. Kunze, 2009] :

$$\blacktriangleright \frac{\varepsilon_Z(p \rightarrow q)}{\varepsilon_Z(p' \rightarrow q')} = \frac{\lambda_{p'q'}}{\lambda_{pq}} \frac{A_Z(p \rightarrow q)}{A_Z(p' \rightarrow q')} \frac{A_Z(p' \rightarrow)}{A_Z(p \rightarrow)} \frac{X_Z(g \rightarrow p)(T_e)}{X_Z(g \rightarrow p')(T_e)} \Rightarrow T_e$$

$$\blacktriangleright \frac{\varepsilon_Z(p \rightarrow q)}{\varepsilon_Z(p' \rightarrow q')} = \frac{\lambda_{p'q'}}{\lambda_{pq}} \frac{A_Z(p \rightarrow q)}{A_Z(p' \rightarrow q')} \frac{A_Z(p' \rightarrow)}{A_Z(p \rightarrow)} \frac{X_Z(g \rightarrow p)(T_e)}{X_Z(g \rightarrow p')(T_e)} \left[1 + n_e \frac{X_Z(p' \rightarrow)}{A_Z(p' \rightarrow)} \right] \Rightarrow n_e$$

HFR+CPOL results

HFR method

General procedure [Cowan, R. D., 1981]

- Solve $H\Psi = E\Psi$ where $H = \sum_{i=1}^N \left(-\frac{1}{2} \Delta_i + V(r_i) \right)$ (central field approximation)
- $H_i \varphi_i = E_i \varphi_i \rightarrow \varphi_i(r_i, \theta_i, \phi_i, s_i) = \frac{1}{r_i} P_{n_i l_i}(r_i) Y_{l_i}^{m_i}(\theta_i, \phi_i) \sigma_{m_{s_i}}(s_i)$
- $P_{n_i l_i}(r_i) ? \rightarrow$ solve Hartree-Fock equations (Self-Consistent Field method)
- HF equations obtained by variational principle on the average energy of each electronic configuration

- Atomic State Functions (ASFs) :
$$\Psi(\alpha, P, J, M_J) = \sum_{r=1}^{n_c} c_r \Phi(\alpha_r, P, L_r, S_r, J, M_J)$$

Configuration State Functions (CSFs) are built thanks to Slater determinants

HFR+CPOL method

Core polarisation correction

- Valence electron correlations represented by configuration interactions (CI) and other correlations by core-polarisation potential
- Quinet, P. et al [1999, 2002]: pseudo potentiel have one-body and two-body part :

$$\text{➤ } V_{P1} = -\frac{1}{2}\alpha_D \sum_{i=1}^N \frac{r_i^2}{(r_i^2 + r_c^2)^3} \text{ and } V_{P2} = -\alpha_D \sum_{i>j} \frac{\vec{r}_i \cdot \vec{r}_j}{[(r_i^2 + r_c^2)(r_j^2 + r_c^2)]^{3/2}}$$

- α_D : dipole polarisability; r_c : ionic core radius

HFR+CPOL Model

Valence-Valence interactions

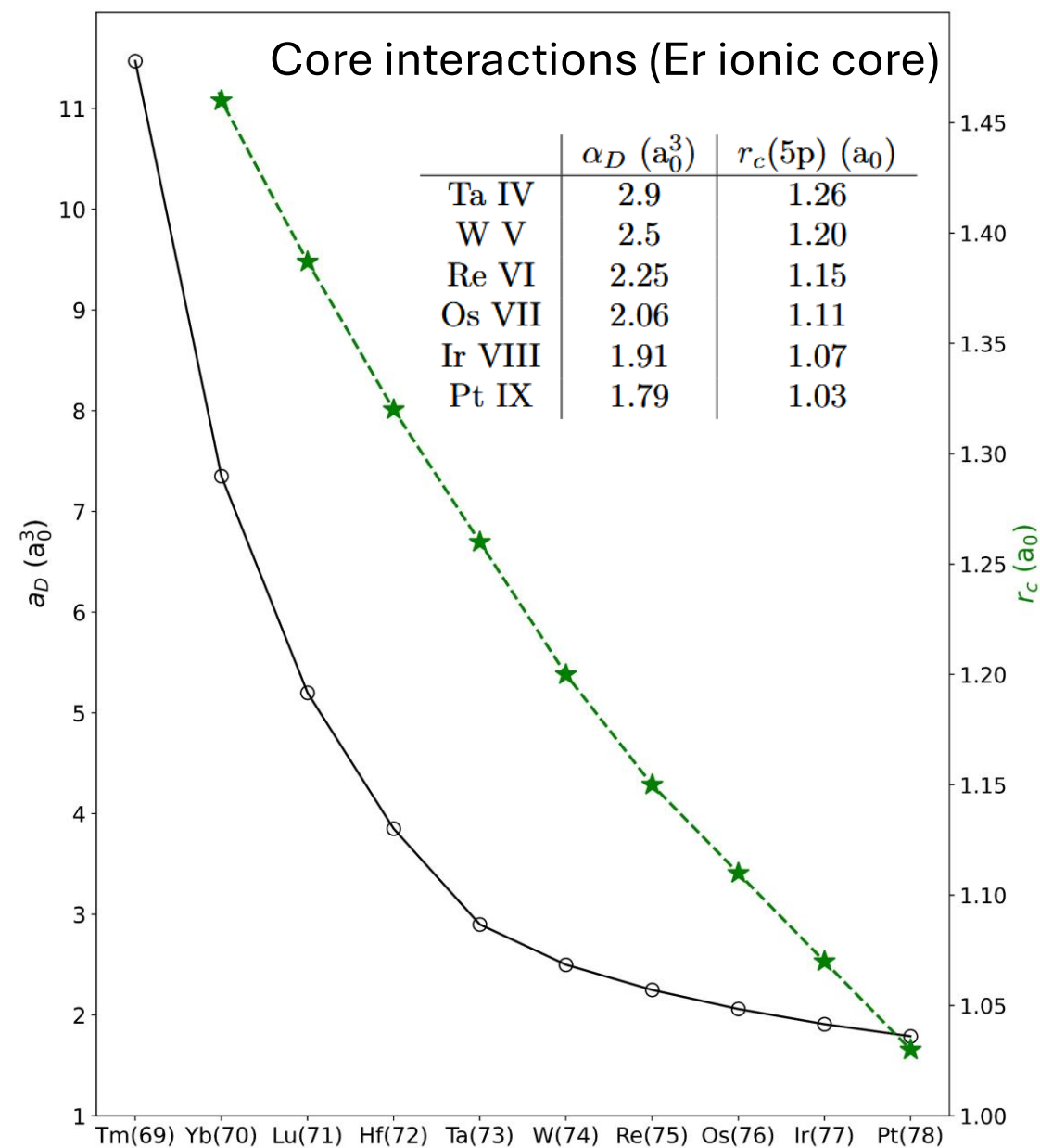
Even parity

$5d^2$ $6p6f$
 $5d6s$ $6p7f$
 $5d7s$ $6d^2$
 $6s^2$ $6d7s$
 $5d6d$ $6d7d$
 $5d7d$ $7s^2$
 $6s7s$ $7p^2$
 $6s6d$ $7s7d$
 $6s7d$ $7p5f$
 $6p7p$ $7p6f$
 $6p^2$ $7p7f$
 $6p5f$

Odd parity

$5d6p$ $6p6d$
 $6s6p$ $6p7d$
 $5d7p$ $6d7p$
 $5d5f$ $6d5f$
 $5d6f$ $6d6f$
 $5d7f$ $6d7f$
 $6s7p$ $7s5f$
 $6s5f$ $7s6f$
 $6s6f$ $7s7f$
 $6s7f$ $7s7p$
 $6p7s$ $7s7d$

[Yoca et al, 2012]



Least squares method

- Minimise difference between computed energy levels and observed ones with spin-orbit and Slater parameters

- Accuracy of the fit: $\sigma = \left[\frac{\sum_k (E^k - T^k)^2}{N_k - N_p} \right]^{1/2}$, where E^k : energy eigenvalues; T^k : observed energies; N_k : number of fitted levels; N_p : number of fitted parameters

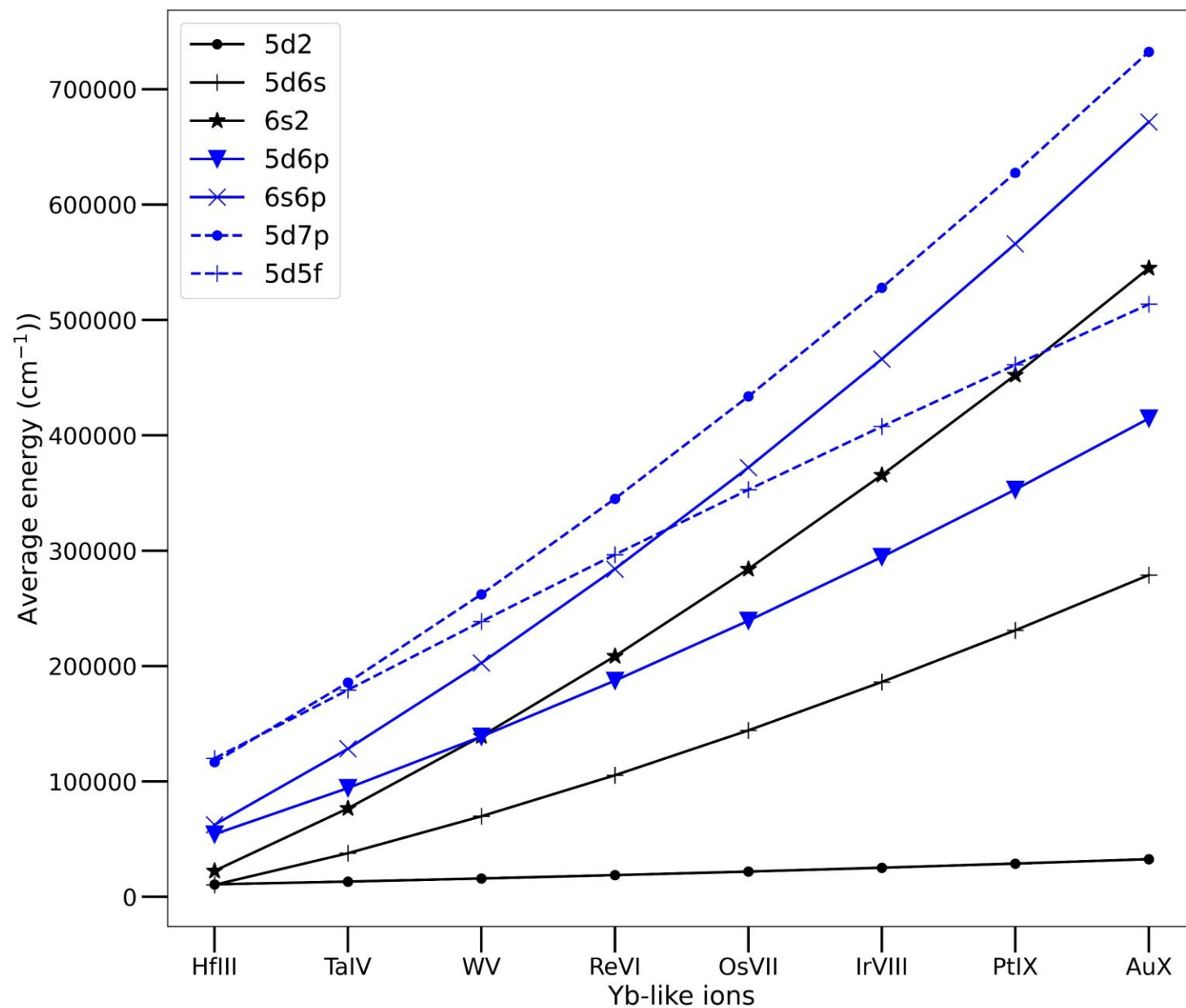
- HFR+CPOL model :

	Even parity			Odd parity			
	nbr of fitted levels	$\sigma_{HFR+CPOL}$ (cm ⁻¹)	$\sigma_{HFR(CV)}$ (cm ⁻¹)	nbr of fitted levels	$\sigma_{HFR+CPOL}$ (cm ⁻¹)	$\sigma_{HFR(CV)}$ (cm ⁻¹)	
Ta IV	14	22	24	47	106	118	
W V	13	26	31	46	123	141	
Re VI	13	30	37	29	347	253	
Os VII	13	31	40	30	779	139	
Ir VIII	13	35	47	29	1216	571	
Pt IX	13	38	53	28	3363	422	5d7p odd configuration not observed

[Churilov, S.S. et al, 1996 ; Meijer, F.G and Metsch, 1978 ; Kildiyarova, R.R et al, 1996 ; Kramida , A. et al, 2024 ; Sugar, J. et al, 1994 ; Yoca, S.E et al, 2012 ; Van het Hof, G.J. et al, 1995 ; Kildiyarova, R.R et al, 1995 ; Kildiyarova, R.R et al, 1997 ; Azarov V.I. and Churilov S.S , 1999]

Configuration Interactions

The atomic level structure more spread out with increasing ionic charge state → on average less mixing in the level composition

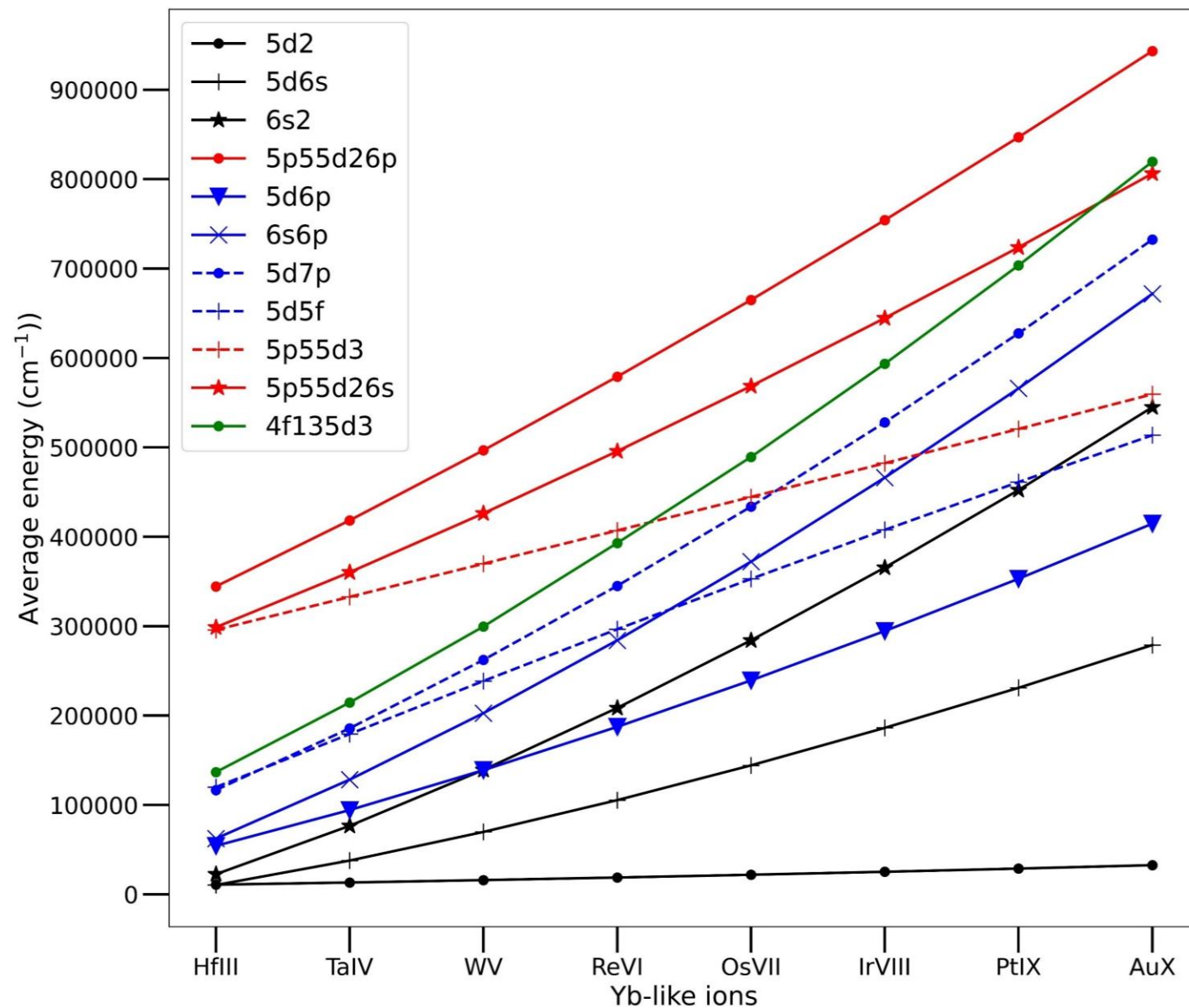


Core-valence correlations

$5p^5 5d^3$ closer to (and overlap) $5d7p$, $6s6p$ and $5d5f$

→ core-valence correlations with a pseudo potential no longer valid

→ need to introduce explicitly the configurations with an open $5p, 4f$ core orbitals in our model (through CI)



HFR(CV) Model

VV + CV interactions

Even parity

$5d^2$ $5p^5 5d^2 6p$
 $5d6s$ $5p^5 6s^2 6p$
 $6s^2$ $5p^5 5d6s6p$
 $5d7s$ $5p^5 5d^2 5f$
 $5d6d$ $5p^5 5d^2 7p$
 $5d7d$ $5s5p^6 5d^3$
 $6s7s$ $5s5p^6 5d^2 6s$
 $6s6d$ $5s5p^6 5d6s^2$
 $6s7d$ $4f^{13} 5p^6 5d^2 6p$
 $6p^2$ $4f^{13} 5p^6 5d6s6p$
 $6p7p$
 $6p5f$

Odd parity

$5d6p$ $5p^5 5d^3$
 $6s6p$ $5p^5 5d^2 6s$
 $5d7p$ $5p^5 5d6s^2$
 $5d5f$ $5p^5 5d6p^2$
 $5d6f$ $5p^5 6s6p^2$
 $5d7f$ $5s5p^6 5d^2 6p$
 $6s7p$ $5s5p^6 5d6s6p$
 $6s5f$ $4f^{13} 5p^6 5d^3$
 $6s6f$ $4f^{13} 5p^6 5d^2 6s$
 $6p6d$
 $6p7s$

	Even parity	
	$\sigma_{HFR+CPOL}$ (cm ⁻¹)	$\sigma_{HFR(CV)}$ (cm ⁻¹)
Ta IV	22	24
W V	26	31
Re VI	30	37
Os VII	31	40
Ir VIII	35	47
Pt IX	38	53
	Odd parity	
Ta IV	106	118
W V	123	141
Re VI	347	253
Os VII	779	139
Ir VIII	1216	571
Pt IX	3363	422

HFR(CV) Model

VV + CV interactions

→ σ of the even parity increases slightly due to more level mixing

Ex: the level $5d^2 \ ^3P_0$ observed at $11\ 166.5 \text{ cm}^{-1}$ in Ta IV (Z=73) and $18\ 617.0 \text{ cm}^{-1}$ in Pt IX (Z=78) is composed of the three most dominant spectroscopic terms $93.7\% \ 5d^2 \ ^3P + 5.5\% \ 5d^2 \ ^1S + 0.1\% \ 6s^2 \ ^1S$ in Ta IV and $87.2\% \ 5d^2 \ ^3P + 12.0\% \ 5d^2 \ ^1S + 0.2\% \ 5p^5 5d^2 6p \ ^3P$ in Pt IX

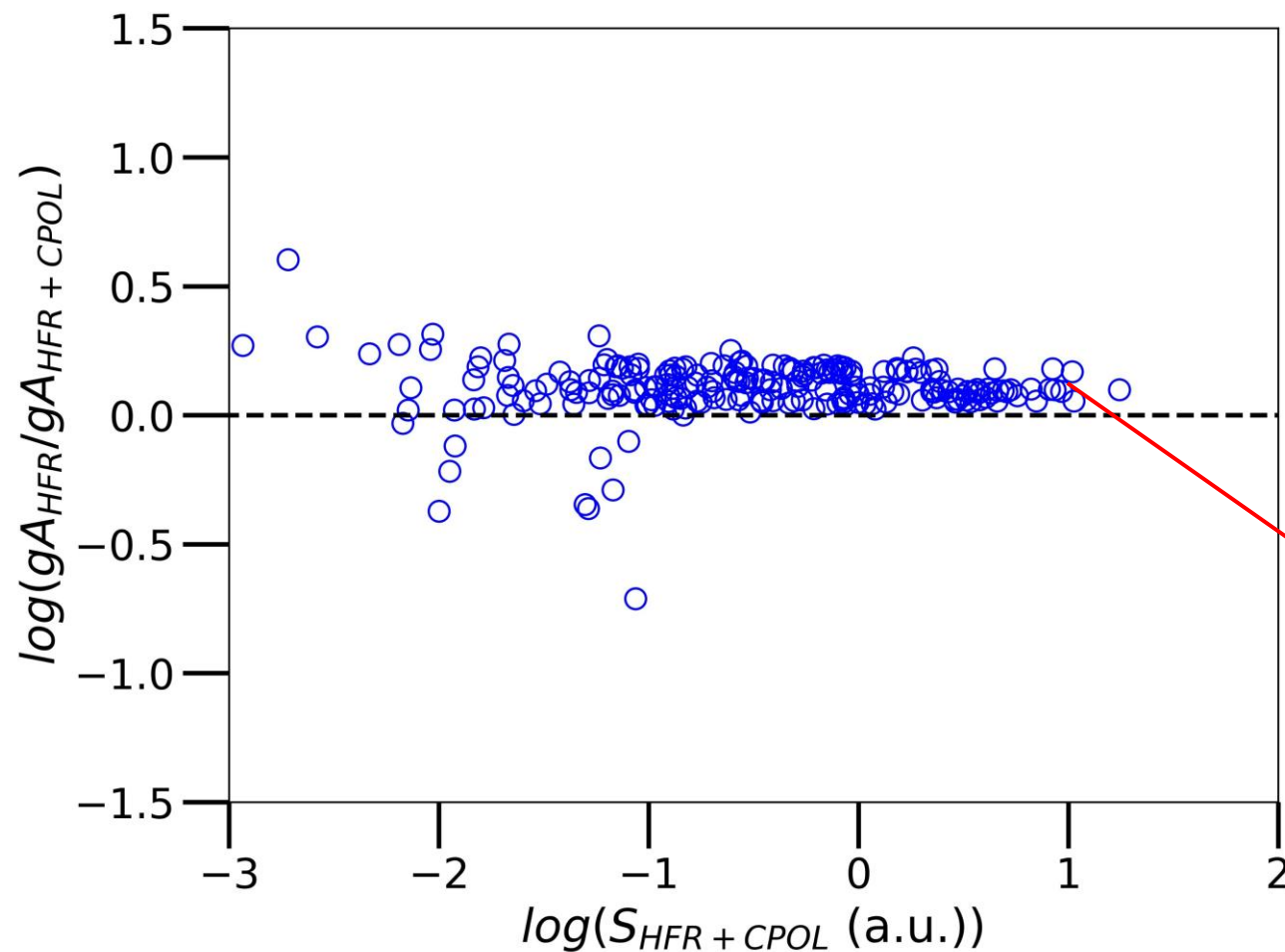
→ σ of the odd parity is significantly improved especially for ions from Re VI to Pt IX that enhance the accuracy of the computed gA's

	Even parity	
	$\sigma_{HFR+CPOL} \text{ (cm}^{-1}\text{)}$	$\sigma_{HFR(CV)} \text{ (cm}^{-1}\text{)}$
Ta IV	22	24
W V	26	31
Re VI	30	37
Os VII	31	40
Ir VIII	35	47
Pt IX	38	53
	Odd parity	
Ta IV	106	118
W V	123	141
Re VI	347	253
Os VII	779	139
Ir VIII	1216	571
Pt IX	3363	422

Radiative decay rates

Ta IV

[Churilov, S.S. et al, 1996 ; Meijer, F.G and Metsch, 1978 ; Kildiyarova, R.R et al, 1996]



229 observed electric dipole lines
between 551.422 – 3076.060 Å

221 observed lines with $\log(gf) > -4$

Mean ratio $gA_{HFR+CPOL}/gA_{HFR} = 0.82$

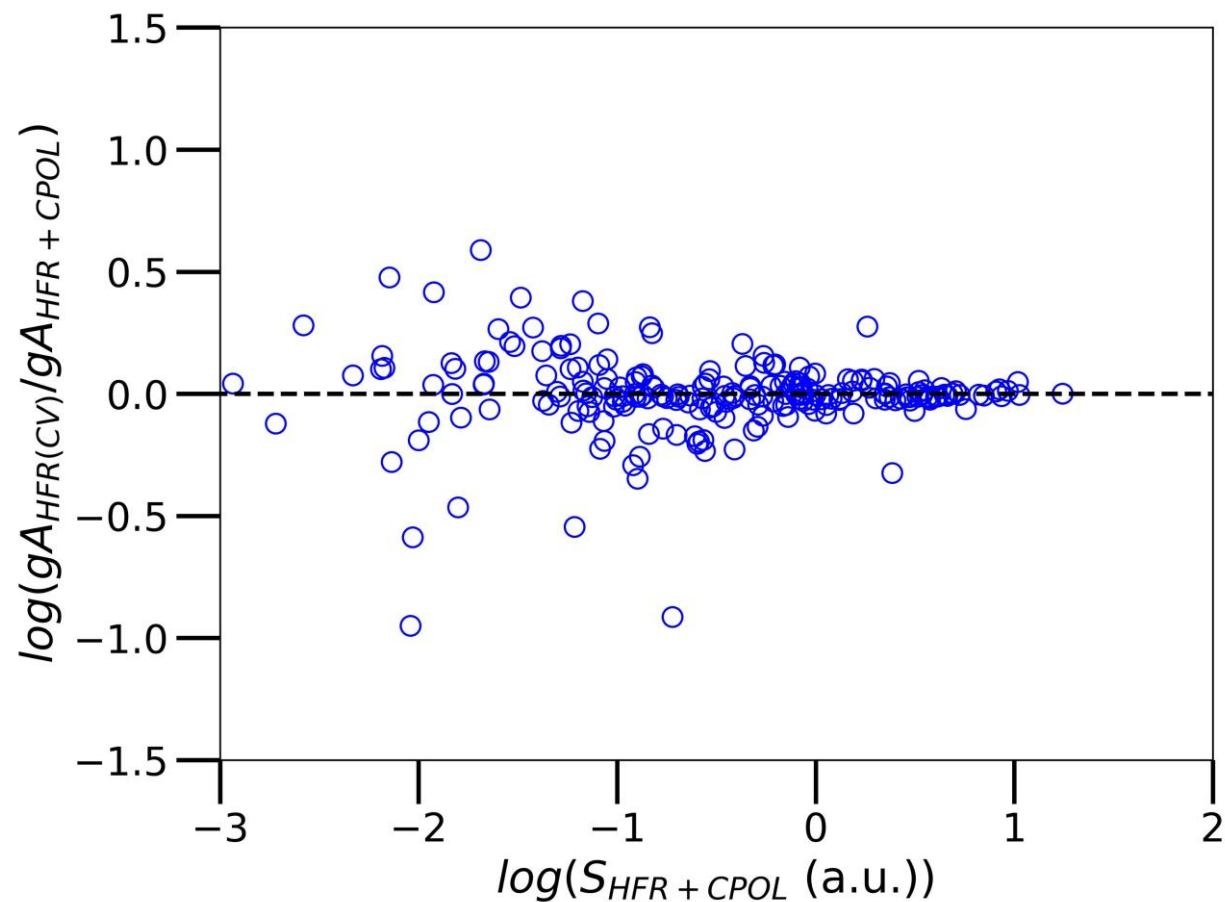
CPOL corrections reduce gA-values of
about 20%, as expected.

For $5d \rightarrow 5f, 7p$ ($5d^2 \rightarrow 5d5f, 5d7p$):
reduction is on average 30%

Radiative decay rates

Ta IV

[Churilov, S.S. et al, 1996 ; Meijer, F.G and Metsch, 1978 ; Kildiyarova, R.R et al, 1996]



229 observed electric dipole lines
between 551.422 – 3076.060 Å

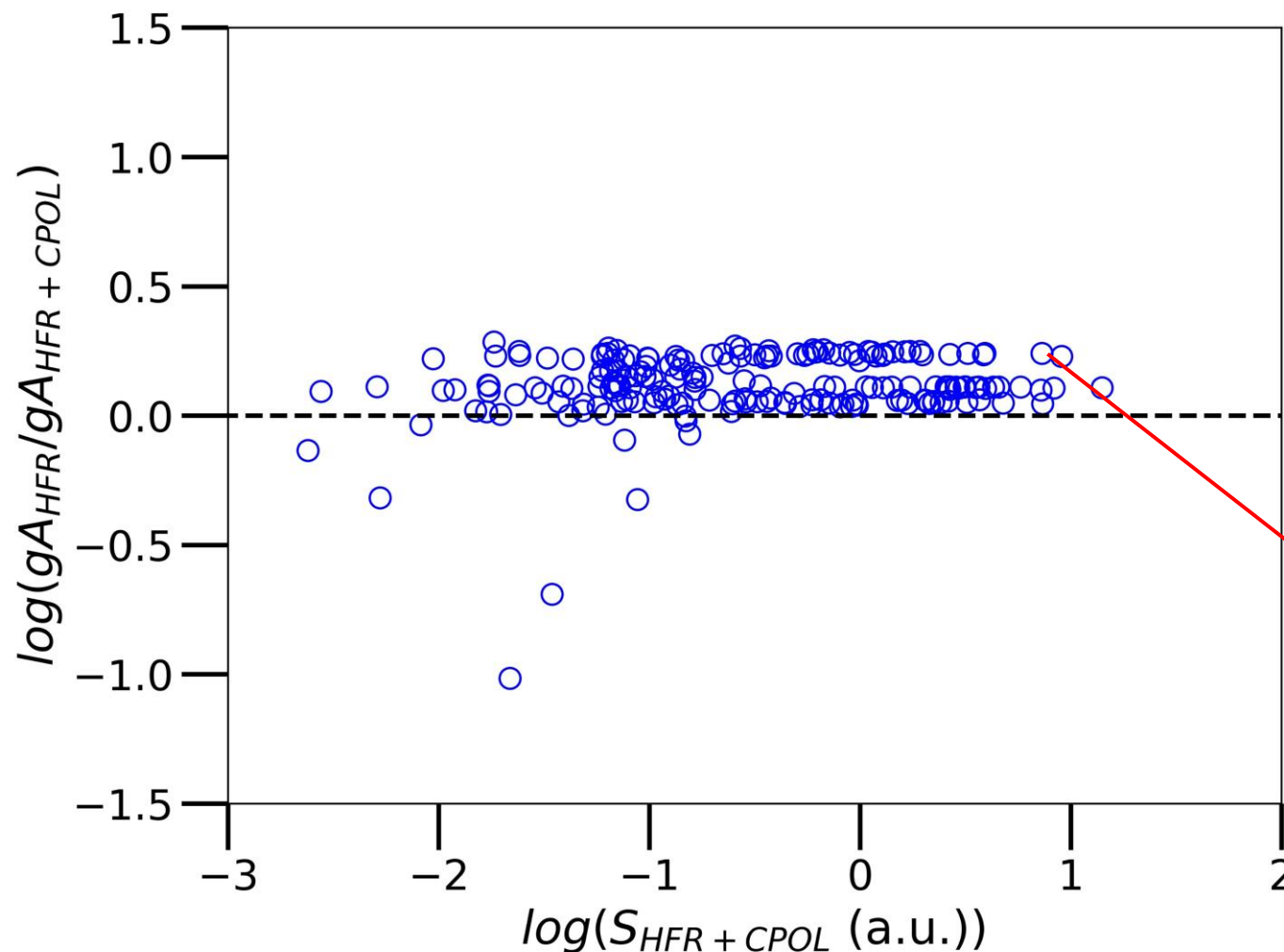
221 observed lines with $\log(gf) > -4$

Mean ratio $gA_{HFR(CV)}/gA_{HFR+CPOL} = 1.08 \pm 0.24$

Radiative decay rates

W V

[Nist, Kramida and Shirai, 2009]



193 observed electric dipole lines
between 391.566 – 2187.270 Å

Mean ratio $gA_{HFR+CPOL}/gA_{HFR}=0.79$

CPOL corrections reduce gA-values of
about 20%, as expected.

For 5d → 7p (5d² → 5d7p) : reduction
is on average 30%

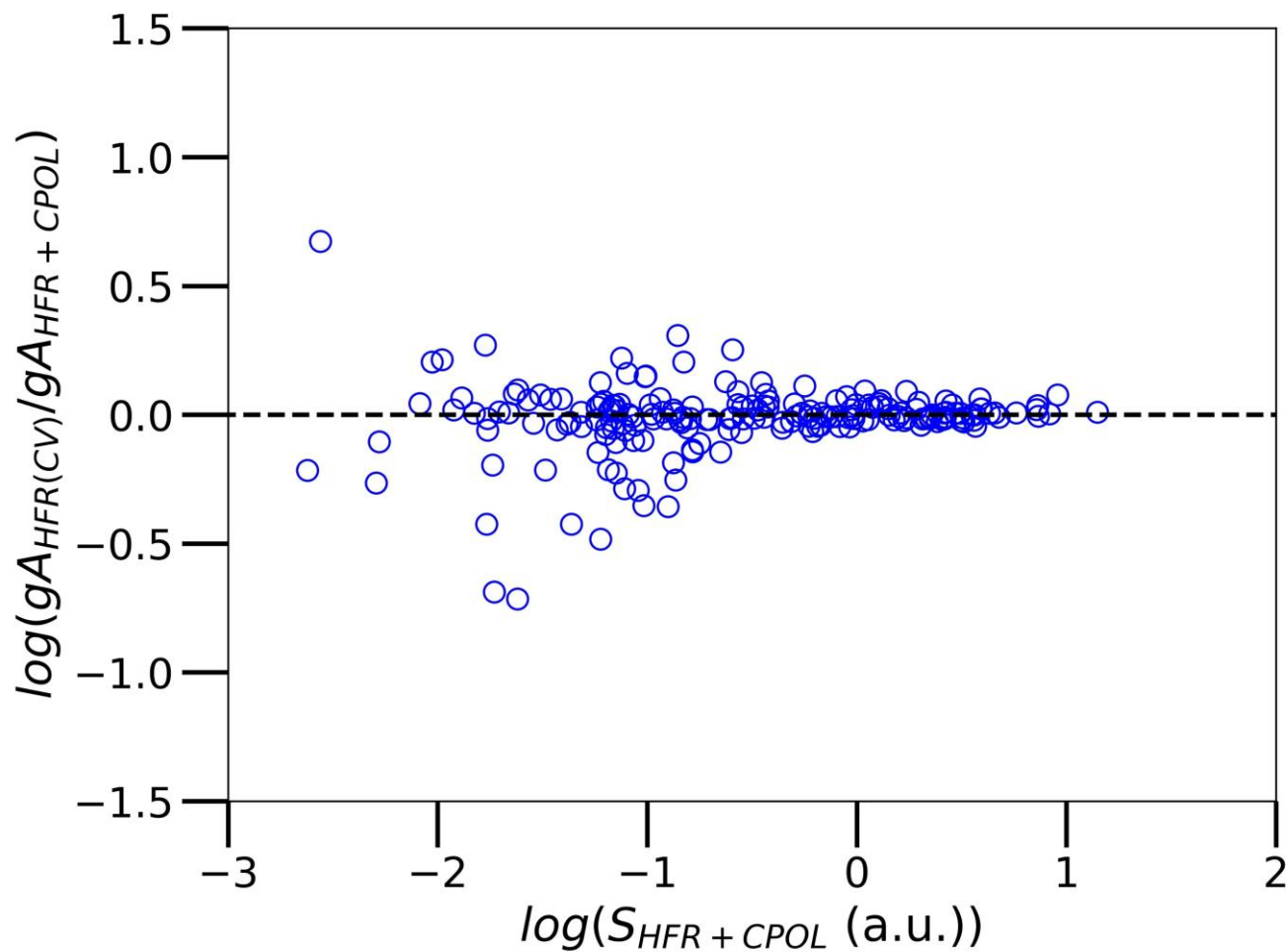
For 5d → 5f (5d² → 5d5f) : reduction
is on average 40%

Radiative decay rates

W V

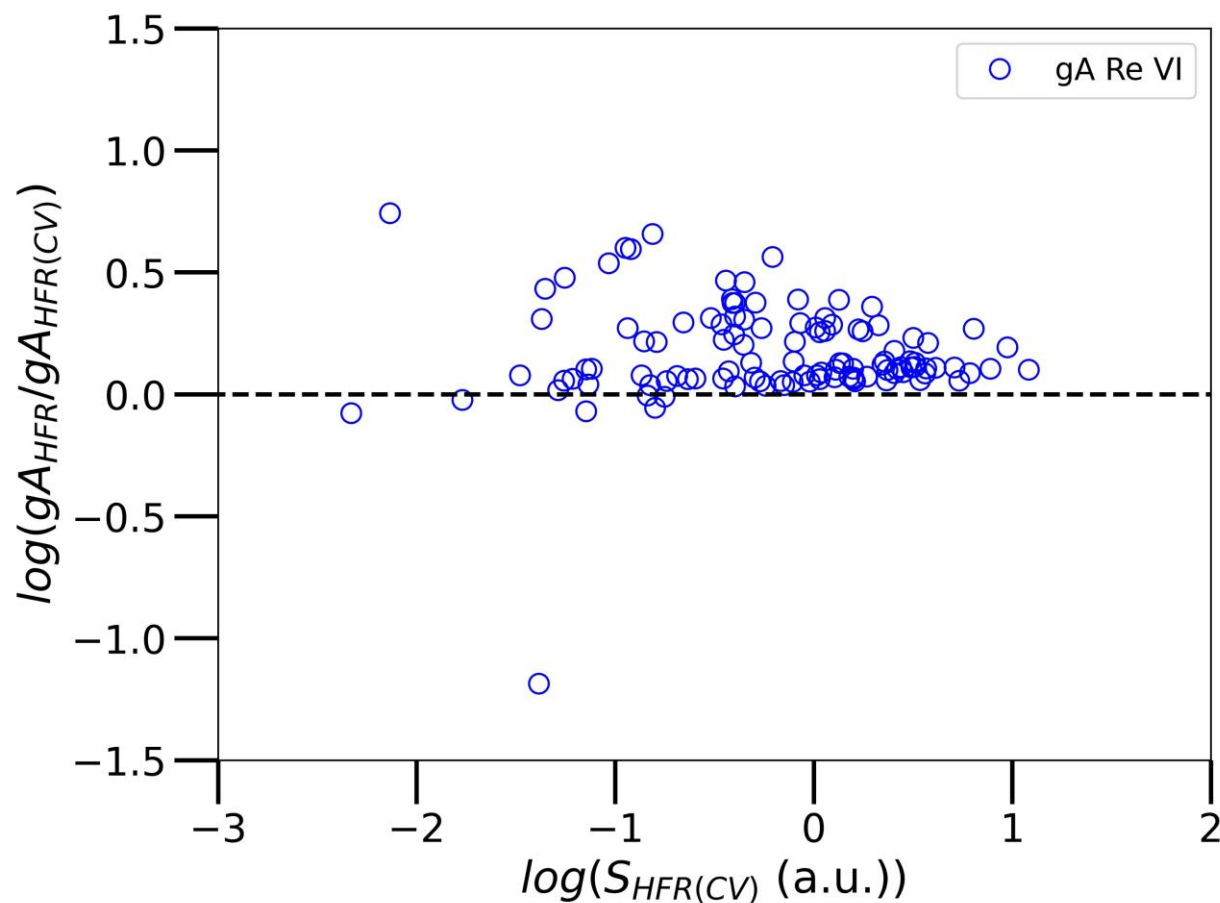
[Nist, Kramida and Shirai, 2009]

193 observed electric dipole lines
between 391.566 – 2187.270 Å



Mean ratio $gA_{HFR(CV)}/gA_{HFR+CPOL} = 1.02 \pm 0.36$

Re VI 112 observed electric dipole lines between 332.044 – 1513.957 Å [Sugar, J. et al, 1994]



Mean ratio $gA_{HFR(CV)}/gA_{HFR} = 0.70 \pm 0.18$

CV correlations reduce gA-values of about 30%

Os VII: 149 observed electric dipole lines between 288.274 – 1319.811 Å

Mean ratio $gA_{HFR(CV)}/gA_{HFR} = 0.74 \pm 0.28$

[van het Hof, G.J. et al, 1995 ; Kildiyarova, R.R et al, 1995]

Ir VIII: 129 observed electric dipole lines between 237.098 – 1172.084 Å

Mean ratio $gA_{HFR(CV)}/gA_{HFR} = 0.65 \pm 0.31$

[van het Hof, G.J. et al, 1995 ; Kildiyarova, R.R et al, 1995]

Pt IX: 131 observed electric dipole lines between 216.575 – 1055.171 Å

Mean ratio $gA_{HFR(CV)}/gA_{HFR} = 0.66 \pm 0.38$

[Kildiyarova, R.R et al, 1997 ; Azarov V.I. and Churilov S.S , 1999]

MCDHF results

MCDHF method

General procedure [Grant, I. P., 2007]

- $H_{DC} = \sum_{i=1}^N h_{D_i}$ with $h_{D_i} = c\vec{\alpha} \cdot \vec{p}_i + (\beta - 1)c^2 + V(r_i)$ ($\alpha^j = \gamma^0\gamma^j$ and $\beta = \gamma^0$)
- Each electron: $h_D\varphi = E\varphi \rightarrow \varphi(r, \theta, \phi) = \frac{1}{r} \begin{pmatrix} P_{n,\kappa}(r)\chi_{\kappa,m}(\theta, \phi) \\ iQ_{n,\kappa}(r)\chi_{\kappa,m}(\theta, \phi) \end{pmatrix}$ where $P_{n,\kappa}(r)$ and $Q_{n,\kappa}(r)$ are **large** and **small radial part**, respectively.
- $P_{n,\kappa}(r), Q_{n,\kappa}(r) ? \rightarrow$ solve MCDHF equations (Self-Consistent Field method)
- CI: (ASF) $\Psi(P, J, M) = \sum_{r=1}^{n_c} c_r \Phi(\gamma_r, P, J, M)$

MCDHF Models

- MCDHF method implemented in the GRASP18 packages [C. Froese Fischer et al, 2019]
- The Atomic State Functions (ASFs) are built with the Active Set approach ($n_{max}l, n'_{max}l', \dots$):
- Optimisation of all orbitals (5s,5p,5d,4f) on the $5d^2 \ ^3F_2$ ground state
- MR : (re)optimize valence orbitals on all levels
- VV1,2,3 : ONLY « new » correlation orbitals are optimized on all levels of the MR
- CV,CC : Relativistic Configuration Interaction (RCI) calculations

Even parity		Number of CSFs
MR (5d ² ,5d6s,6s ²)	(6s,5p,5d,4f)	14
VV1	SD(MR) → (7s,6p,6d,5f)	81
VV2	SD(MR) → (8s,7p,7d,6f)	225
VV3	SD(MR) → (9s,8p,8d,7f)	446
CV1 (RCI)	SrD (MR{4f}) → (9s,8p,8d,7f)	29 249
CV2 (RCI)	SrD (MR{4f,5p}) → (9s,8p,8d,7f)	47 273
CV3 (RCI)	SrD (MR{4f,5p,5s}) → (9s,8p,8d,7f)	53 778
CC1 (RCI)	SD (MR{4f(2)}) → (9s,8p,8d,7f)	274 515
CC2 (RCI)	SrD (MR{4f,5p}) → (9s,8p,8d,7f)	367 215
CC3 (RCI)	SrD(MR{4f,5p}) + SrD (MR{5s}) → (9s,8p,8d,7f)	373 720
Odd parity		Number of CSFs
MR (5d6p,6s6p,5d5f,5d7p)	(6s,7p,5d,5f)	47
VV1	SD(SR) → (7s,8p,6d,6f)	188
VV2	SD(SR) → (8s,9p,7d,7f)	399
VV3	SD(SR) → (9s,10p,8d,8f)	688
CV1 (RCI)	SrD (MR{4f}) → (9s,10p,8d,8f)	115 980
CV2 (RCI)	SrD (MR{4f,5p}) → (9s,10p,8d,8f)	184 664
CV3 (RCI)	SrD (MR{4f,5p,5s}) → (9s,10p,8d,8f)	208 892
CC1 (RCI)	SD (MR{4f(2)}) → (9s,10p,8d,8f)	1 980 405
CC2 (RCI)	SrD(MR{4f,5p}) → (9s,10p,8d,8f)	2 574 277
CC3 (RCI)	SrD(MR{4f,5p}) + SrD (MR{5s}) → (9s,10p,8d,8f)	2 602 097

Convergence of the models

Ta IV

	Even parity		Odd parity	
	$\Delta E/E_{obs}$	$\Delta E/E_{prev}$	$\Delta E/E_{obs}$	$\Delta E/E_{prev}$
MR	9.99%		1.53%	
VV1	4.12%	5.91%	1.52%	0.35%
VV2	3.75%	0.39%	1.56%	0.05%
VV3	3.69%	0.06%	1.57%	0.01%
CV1	5.25%	1.86%	0.71%	1.44%
CV2	7.71%	3.35%	2.11%	2.08%
CV3	6.40%	1.31%	2.33%	0.21%
CC1	6.59%	1.60%	10.60%	9.48%
CC2	6.90%	0.86%	5.10%	2.83%
CC3	5.65%	0.88%	5.23%	2.74%

303 transitions over 317 have a ratio $gA_{HFR+CPOL}/gA_{MCDHF} < 10$ with a mean ratio 1.39

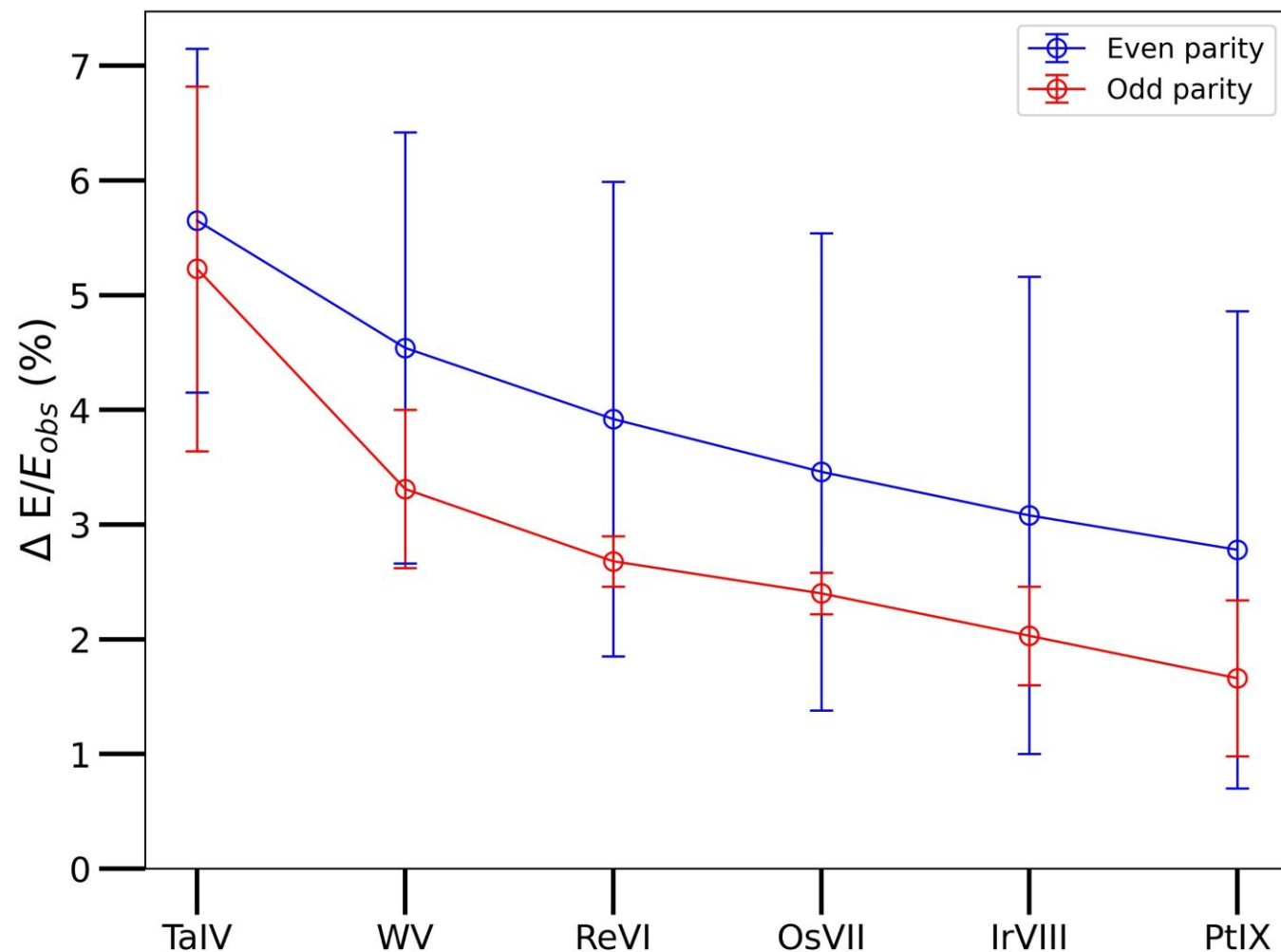
299 transitions over 317 have a ratio $gA_{HFR+CPOL}/gA_{MCDHF} < 10$ with a mean ratio 1.26

Even parity		Number of CSFs
MR (5d ² ,5d6s,6s ²)	(6s,5p,5d,4f)	14
VV1	SD(MR) → (7s,6p,6d,5f)	81
VV2	SD(MR) → (8s,7p,7d,6f)	225
VV3	SD(MR) → (9s,8p,8d,7f)	446
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CC1 (RCI)	SrD (MR{4f(2)}) → (9s,8p,8d,7f)	274 515
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CC3 (RCI)	SrD(MR{4f,5p}) + SrD (MR{5s}) → (9s,8p,8d,7f)	373 720
Odd parity		Number of CSFs
MR (5d6p,6s6p,5d5f,5d7p)	(6s,7p,5d,5f)	47
VV1	SD(SR) → (7s,8p,6d,6f)	188
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CC2 (RCI)	SrD(MR{4f,5p}) → (9s,10p,8d,8f)	2 574 277
CC3 (RCI)	SrD(MR{4f,5p}) + SrD (MR{5s}) → (9s,10p,8d,8f)	2 602 097

Even parity (CC3) : SD (MR {4f,5p}) + SrD (MR {5s}) \rightarrow (9s,8p,8d,7f)

Odd parity (CC3) : SD (MR {4f,5p}) + SrD (MR {5s}) \rightarrow (9s,10p,8d,8f)

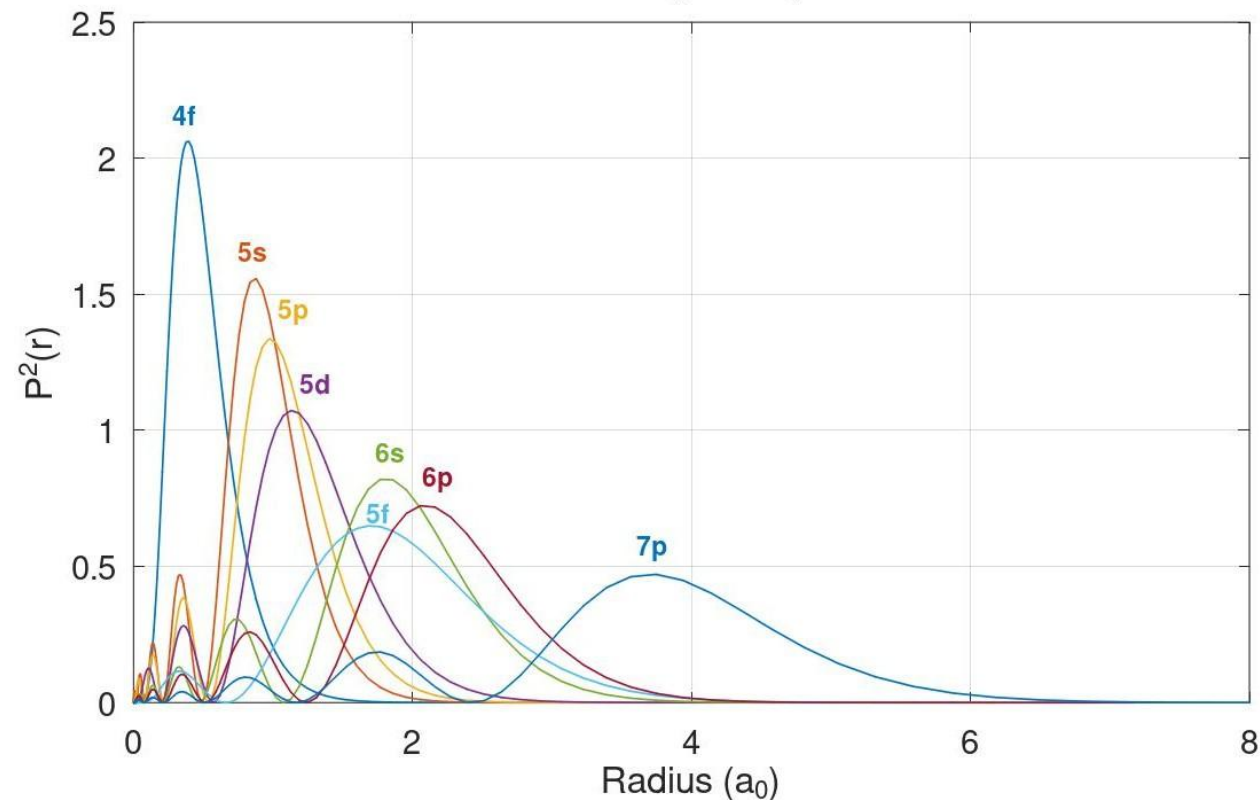
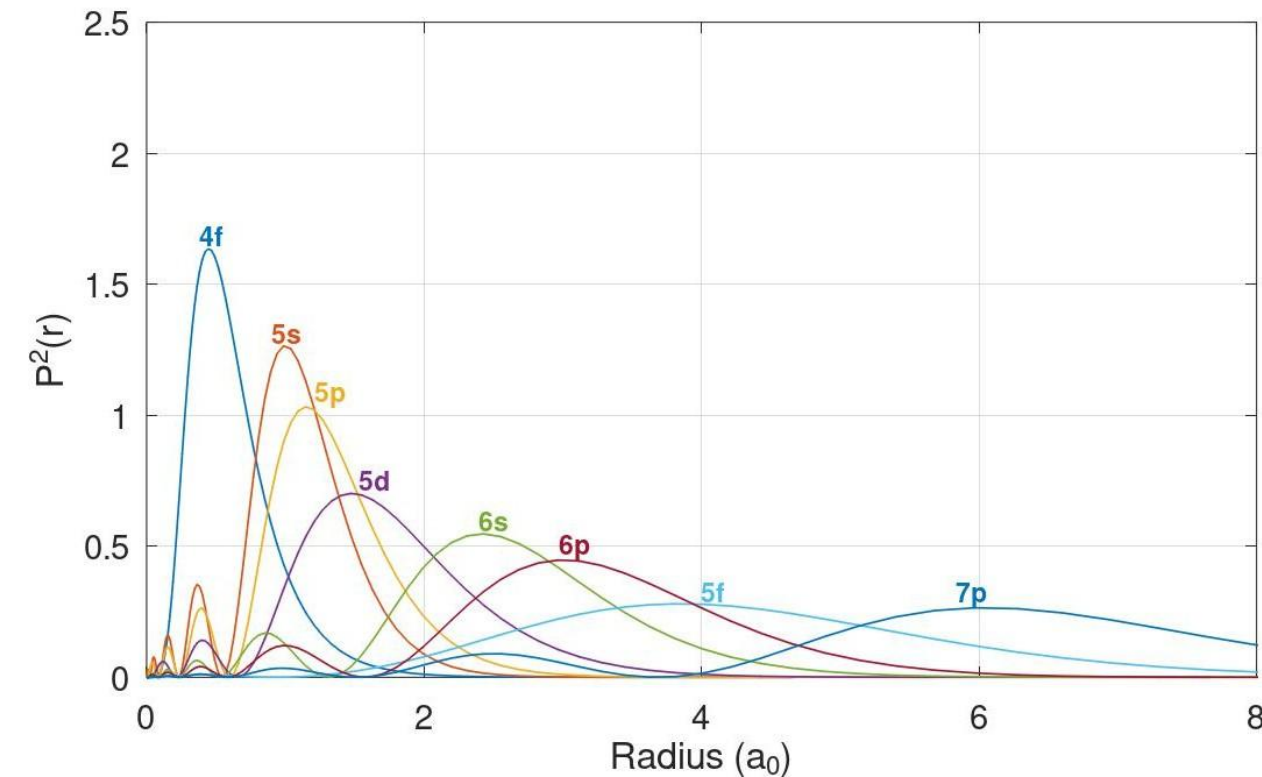
	$\Delta E/E_{obs}$	
	Even parity	Odd parity
TaIV	5.65%	5.23%
WV	4.54%	3.31%
ReVI	3.92%	2.68%
OsVII	3.46%	2.40%
IrVIII	3.08%	2.03%
PtIX	2.78%	1.80%



Large radial part squared computed with the MCDHF method for the 4f, 5s, 5p core orbitals and 5d, 6s, 6p, 5f, 7p valence orbitals after the optimization of the radial part → 5f orbitals moves deeper into the core than the other valence orbitals

Ta IV (Z = 73)

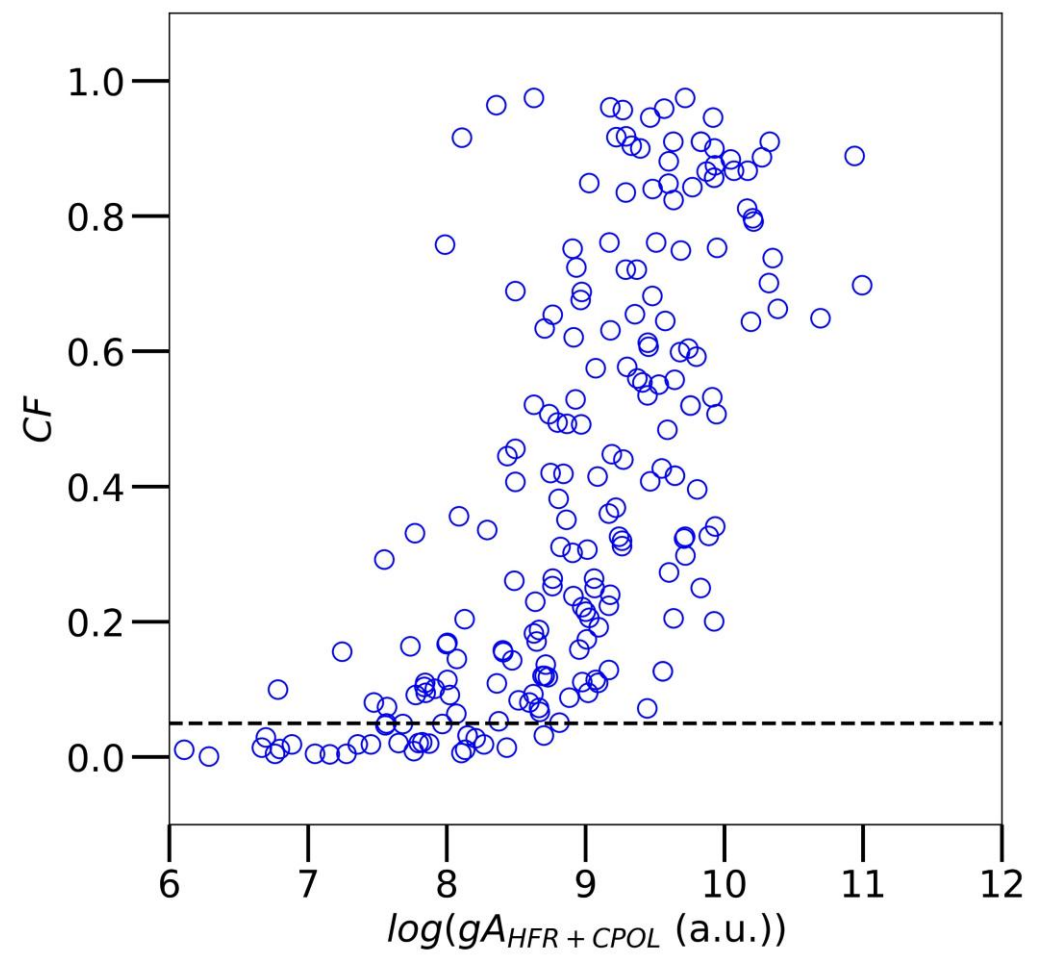
Pt IX (Z = 78)



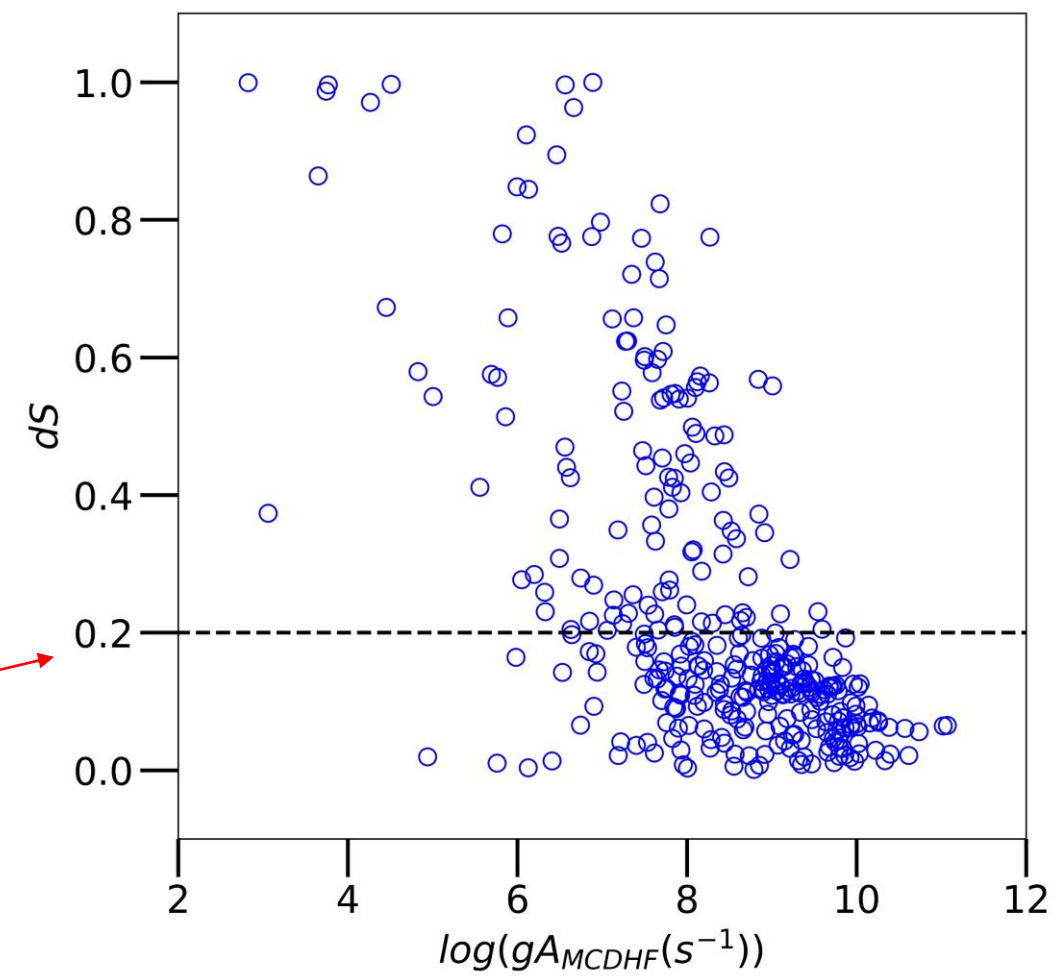
Comparisons between HFR+CPOL and MCDHF gA's Ta IV

Cancellation Factor $CF_{ij} = \left(\frac{|\sum_b \sum_c y_j^b y_i^c \langle \psi_c | \mathbf{P}^{(1)} | \psi_b \rangle|}{\sum_b \sum_c |y_j^b y_i^c \langle \psi_c | \mathbf{P}^{(1)} | \psi_b \rangle|} \right)^2$ [Cowan, R. D., 1981]

 Uncertainty of MCDHF transition rates : $dS = \frac{|S_B - S_C|}{\max(S_B, S_C)}$ [Froese Fisher, C., 2009]



0.05
[Cowan, R. D., 1981]



Comparisons between HFR+CPOL and MCDHF gA's

Ta IV

- It remains 170 transitions (among 221) with $CF > 0.05$ and $dS < 0.2$
- 150 transitions have an uncertainty lower than 50%
- The uncertainty on the HFR+CPOL and MCDHF results estimated at 20% on average

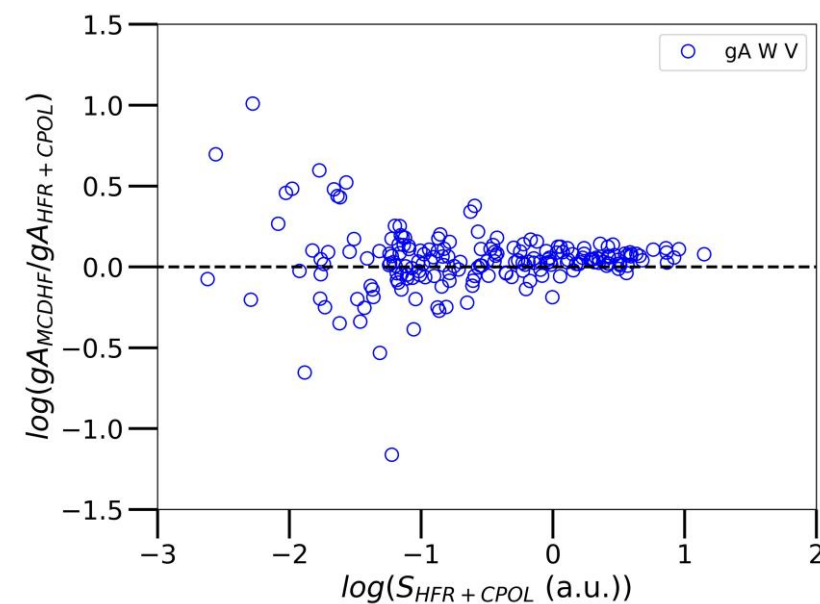
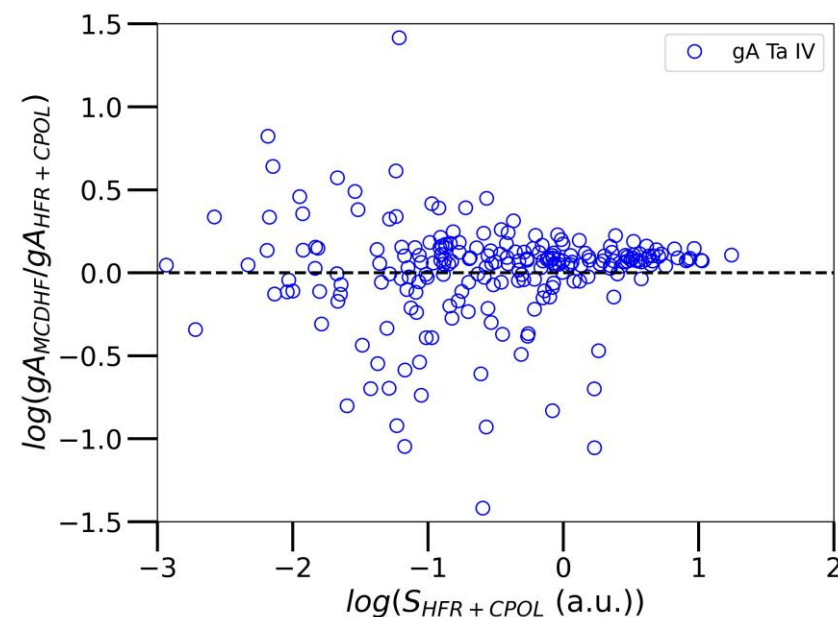
$$\hookrightarrow \frac{\Delta gA}{\max} \text{ where } \Delta gA = |gA_{HFR+CPOL} - gA_{MCDHF}|$$

$$\text{and } \max = \max(gA_{HFR+CPOL}; gA_{MCDHF})$$

- Mean ratio $gA_{HFR+CPOL}/gA_{MCDHF} = 1.18 \pm 0.25$

W V

- It remains 158 transitions (among 193) with $CF > 0.05$ and $dS < 0.2$
- 155 transitions have an uncertainty lower than 50%
- The uncertainty estimated at 16% on average with a mean ratio 1.08 ± 0.23



Comparisons between HFR(CV) and MCDHF gA's

Re VI

- It remains 90 transitions (among 112) with $CF > 0.05$ and $dS < 0.2$
- 87 transitions have an uncertainty lower than 50%
- The uncertainty estimated at 10% on average with a mean ratio 1.07 ± 0.13

Os VII

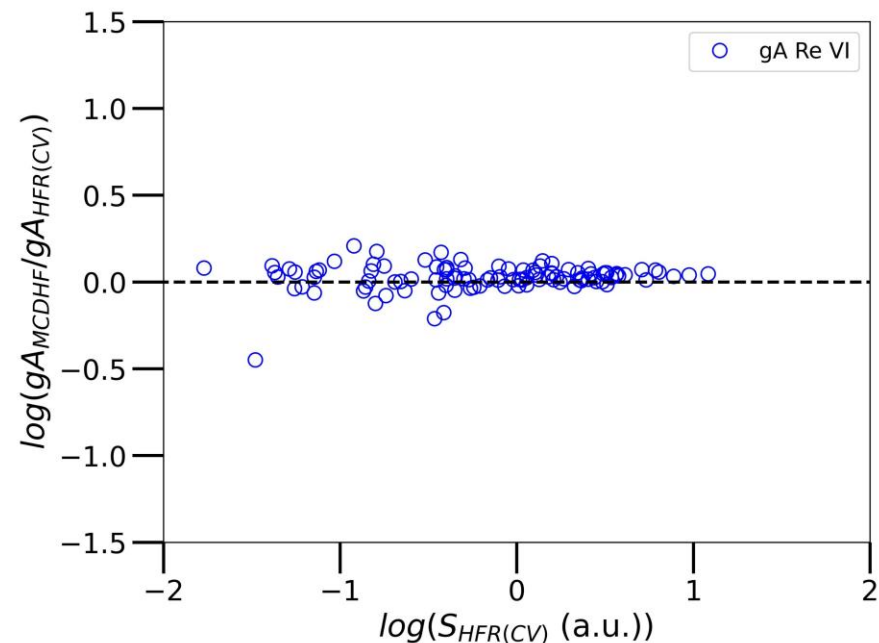
- The uncertainty of 90 transitions (among 149) estimated at 13% on average with a mean ratio 1.06 ± 0.18

Ir VIII

- The uncertainty of 75 transitions (among 129) estimated at 8% on average with a mean ratio 1.01 ± 0.13

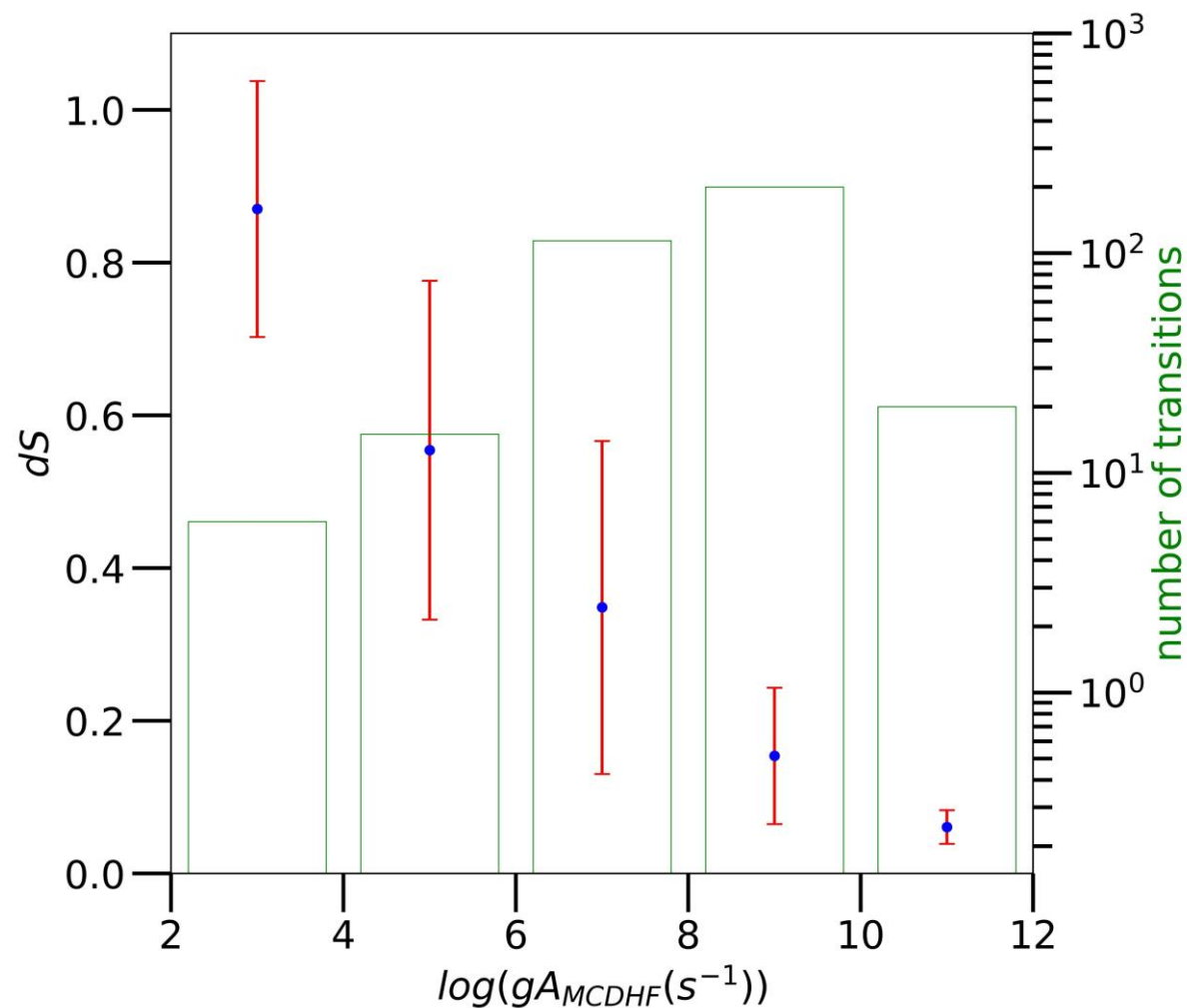
Pt IX

- The uncertainty of 60 transitions (among 131) estimated at 7% on average with a mean ratio 1.02 ± 0.09



Ta IV

- All 355 transitions computed in the MCDHF method
- ⇒ 251 transitions have $dS < 0.25$
- ⇒ The more intense the transitions, the lower the dS value



- Origin of Tantalum up to Platinum in the fusion plasma (tungsten transmutation)
- Compute radiative parameters with HFR+CPOL method + least squares adjustment
- Increasing the ionic charge, configurations with an open 4f,5p core orbitals begin to overlap the valence configurations of interest → Introduce explicitly these configurations for Re VI → Pt IX
- Good agreement between HFR+CPOL and MCDHF method and comparisons allow to estimate uncertainty of a selected set of new transition probabilities (TaIV:20%; WV:16%; ReVI:10%; OsVII:13%; IrVIII:8%; PtIX:7%)
 - set of new accurate atomic data for TaIV → PtIX for plasma diagnostics
- Same procedure for higher ionic charge state of tungsten transmutation products (Ta, Re, Os, Ir, Pt)
- However, few atomic data published

THANK YOU !



- Biémont, E., Garnir, H. P., Palmeri, P., Quinet, P., Li, Z. S., Zhang, Z. G., & Svanberg, S. (2001). Core-polarization effects and radiative lifetime measurements in PrIII. *Physical Review A*, 64, 022503.
- Churilov, S. S., Kildiyarova, R. R., and Joshi, Y. N. Analyses of the 5d²–5d7p transitions in the Ta IV and W V spectra. *Canadian Journal of Physics* 74, 3-4 (1996), 145–149.
- Cowan, R.D. *The Theory of Atomic Structure and Spectra*; University of California Press: Berkeley, CA, USA, 1981.
- Froese Fischer, C., Gaigalas, G., Jönsson, P. and Bieroń, J. GRASP2018—A Fortran95 version of the General Relativistic Atomic Structure Package. *Computer Physics Communications*, 237:184–187, 2019.
- Froese Fischer, C. Evaluating the accuracy of theoretical transition data *Physica Scripta* 2009, 2009 (T134), 014019.
- Fraga, S., Karwowski, J., & Saxena, K. M. S. (1976). *Handbook of atomic data*. Elsevier, Amsterdam.
- Gilbert, N.R.; Sublet, J.C. Neutron-induced transmutation effects in W and W-alloys in a fusion environment. *Nucl. Fusion* 2011, 51, 043005.
- Grant, I.P. *Relativistic Quantum Theory of Atoms and Molecules*; Springer: New York, NY, USA, 2007.
- Kildiyarova, R. R., Churilov, S. S., Joshi, Y. N., & Ryabtsev, A. N. (1996). Analysis of the 5d5f configuration of trebly ionized tantalum and quadruply ionized tungsten: Ta IV and W V. *Physica Scripta*, 53 (4), 454.
- Kramida A., Ralchenko Yu., Reader J., and NIST ASD Team. *Atomic Spectra Database*. National Institute of Standards and Technology, Gaithersburg, 2024. URL. <https://www.nist.gov/pml/atomic-spectra-database>
- Kunze, H.-J. (2009). *Introduction to Plasma Spectroscopy (Vol. 56)*. Springer
- Meijer, F. G., and Metsch, B. C. The analysis of the fourth spectrum of tantalum, Ta IV. *Physica B+C* 94, 2 (1978), 259–269

- Kildiyarova, R.R., Joshi, Y.N. et Sugar, J. (1996). Analysis of the 5d5f configuration of Os VII and Ir VIII , *Physica Scripta*, 53(5), p. 560.
- Van het Hof, G.J. et al. (1995). Analysis of the (5d²+5d6s)–5d6p Transition Arrays of Os VII and Ir VIII, and the 6s 2S–6p 2P Transitions of Ir IX , *Journal of Research of the National Institute of Standards and Technology*, 100(6), p. 687-697.
- Quinet, P., Palmeri, P., Biémont, E., Li, Z. S., Zhang, Z. G., & Svanberg, S. (2002). Radiative lifetime measurements and transition probability calculations in lanthanide ions. *Journal of Alloys and Compounds*, 344 (1), 255–259
- Quinet, P., Palmeri, P., Biémont, E., McCurdy, M. M., Rieger, G., Pinnington, E. H., Wickliffe, M. E., & Lawler, J. E. (1999). Experimental and theoretical radiative lifetimes, branching fractions and oscillator strengths in Lu ii. *Monthly Notices of the Royal Astronomical Society*, 307 (4), 934–940.
- Sugar, J., Wyart, J.-F., Hof, G. J. v. h., & Joshi, Y. N. (1994). Spectrum and energy levels of five-times-ionized rhenium. *JOSA B*, 11 (12), 2327–2332.
- Yoca, S. E., Quinet, P., Palmeri, P., and Biémont, Comparative semi-empirical and ab initio atomic structure calculations in Yb-like tungsten W4 +. *Journal of Physics B: Atomic, Molecular and Optical Physics* 45, 6 (2012), 065001
- Azarov, V.I. et Churilov, S.S. (2000). Assignment of the 5d6s-5d6p transitions in the PtIX ion: Comparison of two calculations of the 5d², 5d6s, and 5d6p configurations in the ion , *Optics and Spectroscopy*, 88(1), p. 11-16.
- Kildiyarova, R.R. et al. (1997). A study of the 5d², 5d6p and 5d5f configurations of Pt IX, *Physica Scripta*, 55(4), p. 438.