HIGH RESOLUTION VACUUM ULTRA-VIOLET EMISSION SPECTRA OF ATOMIC IONS

W.-Ü Lydia Tchang-Brillet

[a] LERMA, Observatoire de Paris-Meudon, PSL Research University

[b]Sorbonne Université, UPMC Univ. Paris 6, CNRS, UMR8112, F-92195 Meudon, France

l'Observatoire de Paris | LERMA

Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

PSL RESEARCH UNIVERSITY PARIS

UPMC SORBONNE UNIVERSITÉS

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Outline

- Introduction
- Experimental and theoretical methods
- Examples of results
- Summary

Laboratory works carried on in the Meudon Observatory

Jean-François Wyart, Lab. Aimé Cotton, Orsay, associated to the Paris-Meudon Observatory

Collaborations

- Ali Meftah (ass. Observatory), Djamel Deghiche and colleagues, PhD students, University Mouloud Mammeri in Tizi-Ouzou, Algeria

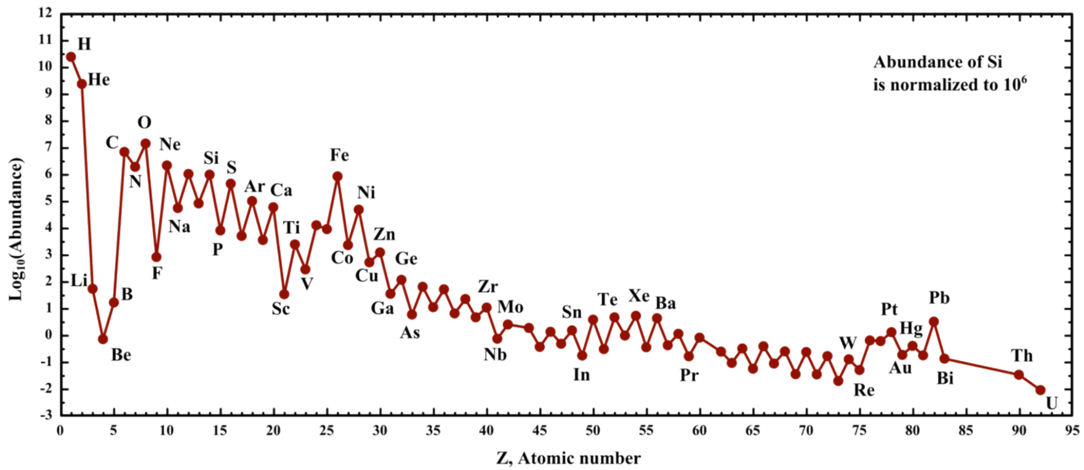
Nd IV, Nd V, Tm IV (Phys. Scr. 2007-2008)
Recently Yb V (PS 2013), Nd V (core-excited config.) (PS 2015) and Er IV (JPB 2016).

- Alexander Ryabtsev and colleagues Institute of Spectroscopy Troitsk, Moscow, Russia (IAEA-CRP 2010-2014)

W VIII (2013) and isoelectronic ions of Hf VI (2013), TaVII (2014), Re IX(2015), W IX (ATOMS 2015)

Technical support in the Meudon Observatory

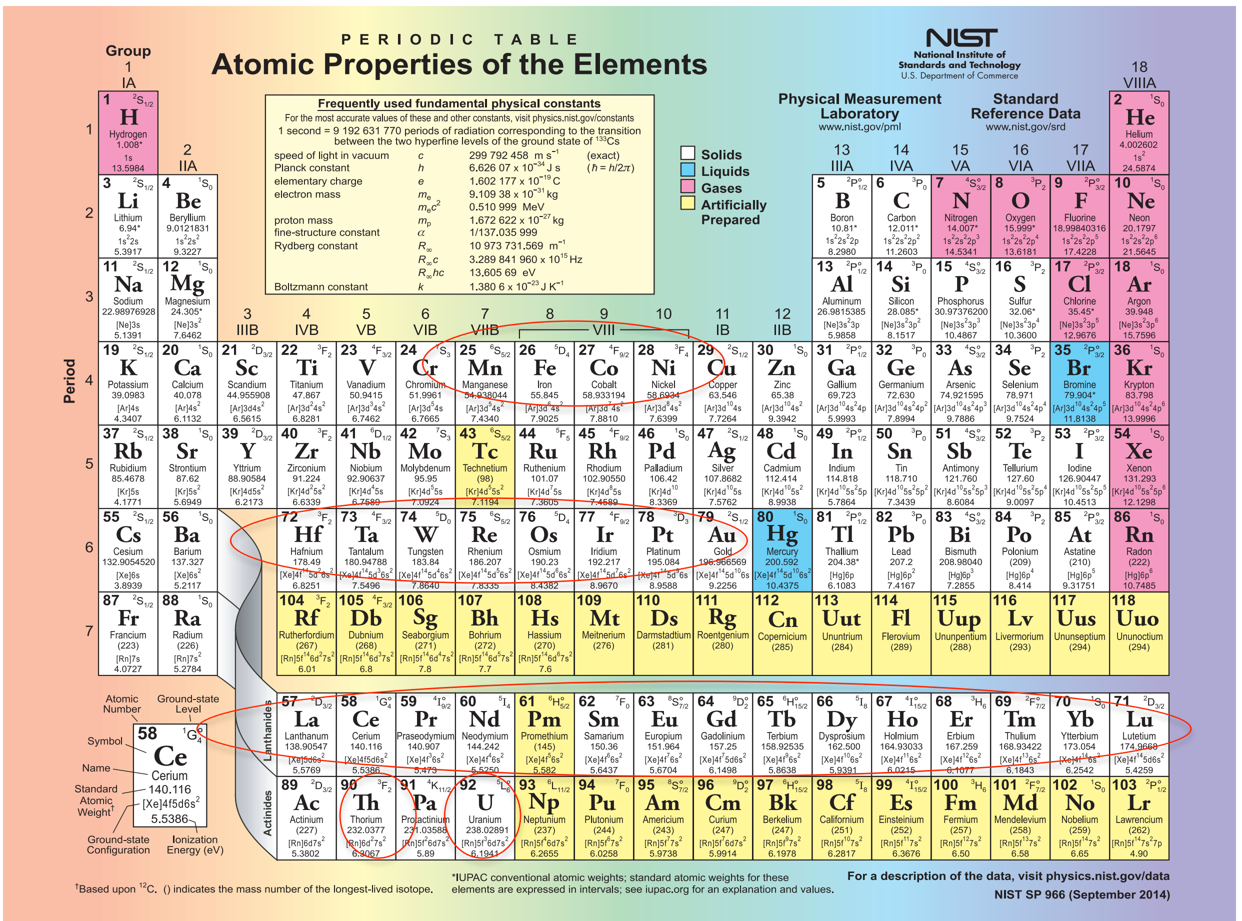
- Norbert Champion, Christophe Blaess



Transition metals and other heavy elements : Lanthanides, actinides

Complex spectra

d^N, $d^{N-1}nl$, f^N, $f^{N-1}nl$



Motivations

Useful data for interpretation of NLET line formation :
λ, gA, energy levels, SHF, IS, Landé factors, collision rates
⟹ **Collisional-radiatif model of plasmas**

Astrophysical plasmas
Interpretation of observed VUV spectra :
HST, FUSE, SOHO. Futures missions : WSO, ARAGO, LUVOIR
Chemically perculiar stars : elemental abundances
White Dwarfs : variation of fundamental constants (Berengut, Flambaum, Webb)

Large contribution to opacities
Ex : Lanthanides and actinides ions predicted to be present in emission of neutron stars mergers (Kasen, Badnell & Barnes)

Solar Physics
Magnetic-field-induced transitions (MIT) for diagnostic of magnetic field

Laboratory plasmas
Fusion applications : Tungsten ions

Triply charged Lanthanides:
Solid state laser material, lighting industry, films etc

Spectra of moderately charged ions

Production of high resolution laboratory spectra
(fine or hyperfine structures)

+

Analysis of complex spectra based on :
- Ritz combination principle $\sigma = E_{sup} - E_{inf}$
- Theoretical and semi-empirical calculations of level structure

$\Downarrow$

Linelist with λ, relative intensities and identifications

+

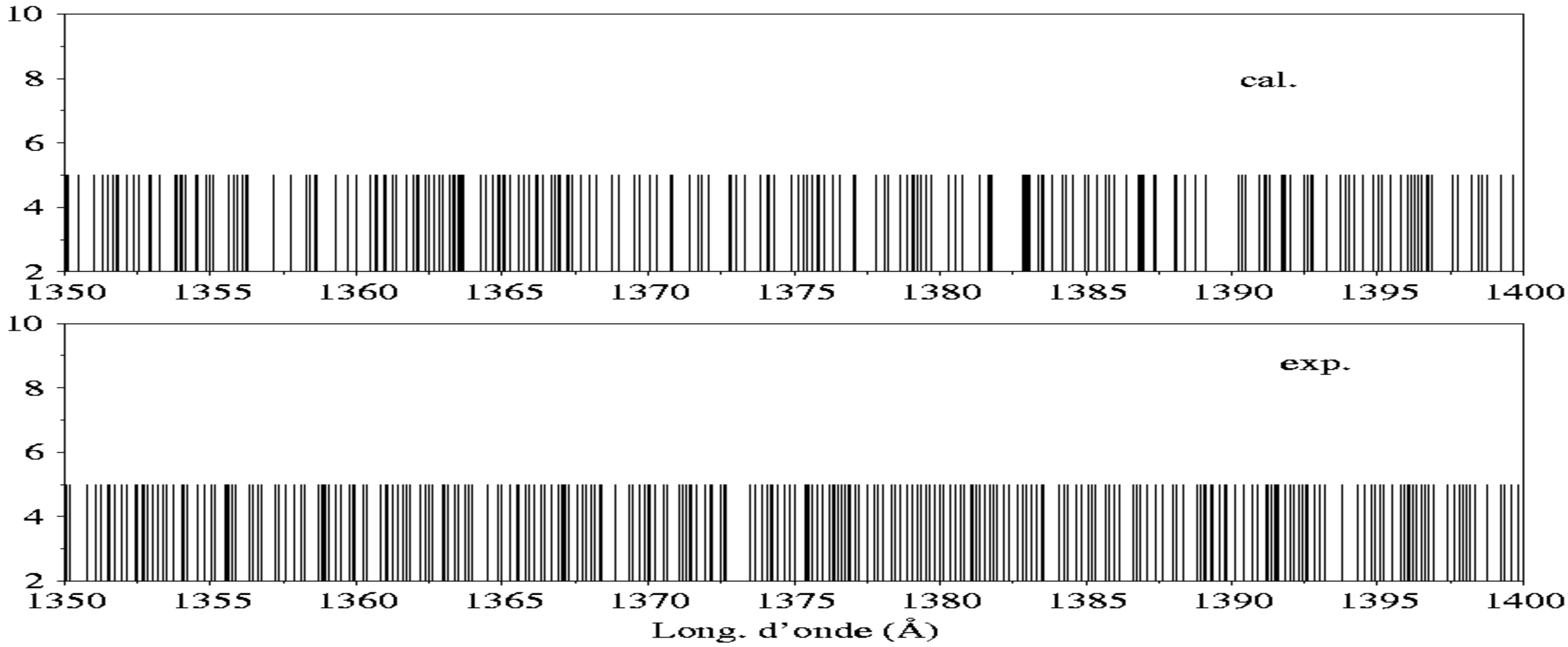
Level energies and wavefunctions in intermediate coupling scheme

+

gA, lifetimes, branching ratios, Landé factors

The Nd IV spectrum

Direct identification between λ_{cal} and λ_{exp} : impossible



10 m high resolution VUV spectrograph
Meudon Observatory

- Concave holographic grating 3600 lines/mm dispersion = 0.25 Å /mm first order.

- Resolution ~ 150 000 (8mÅ, slit 30μm)

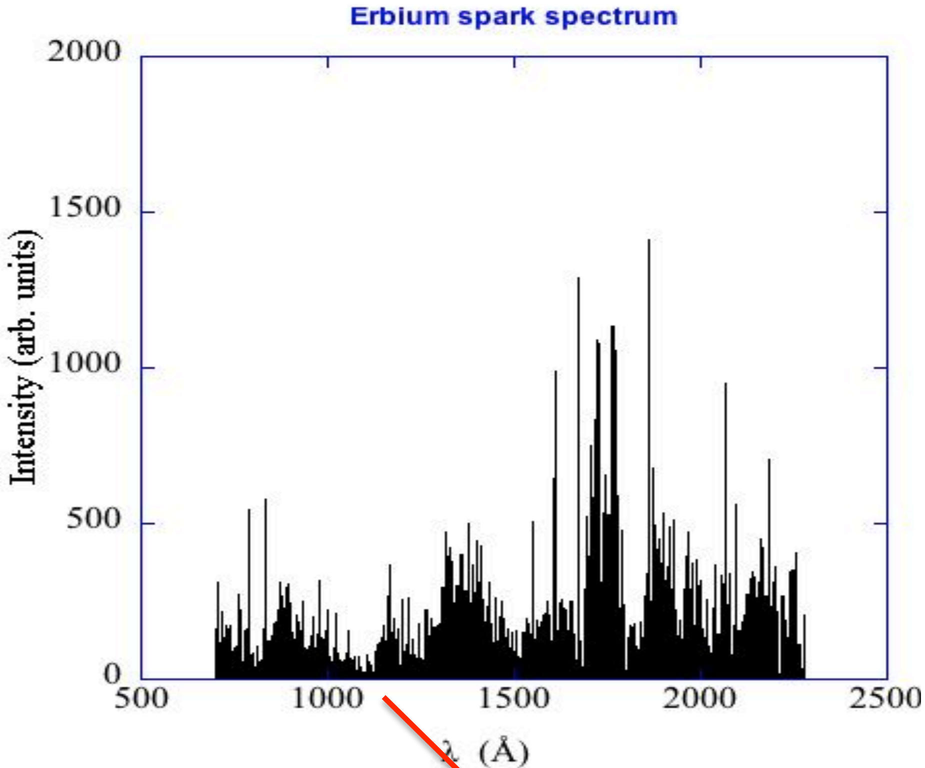
- Wavelength range : 200-3000 Å

- One single exposure : ~ 2 x 120Å on two photographic plates or image plates

Light sources : high voltage vacuum sparks and hollow cathode for atomic ion spectra with fine (or HF) structures ;

Penning discharge in molecular gas for electronic transitions of molécules with rotational resolution

Emission light sources : vaccum spark source



Photographic plate

Calibration with references : $\Delta\lambda = \pm$ 0.001-0.005Å

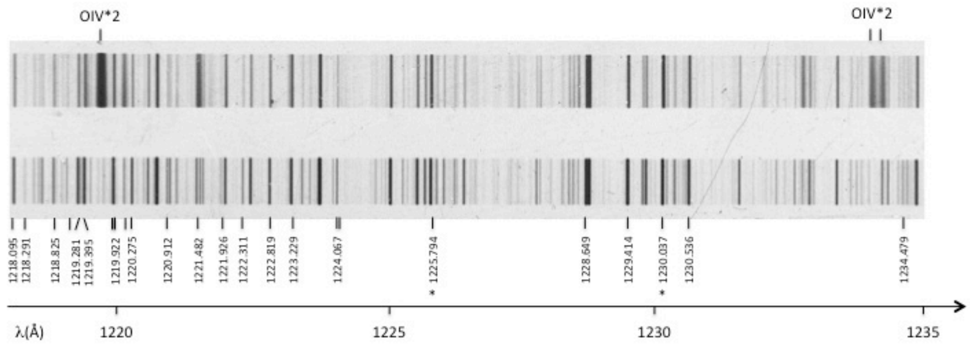
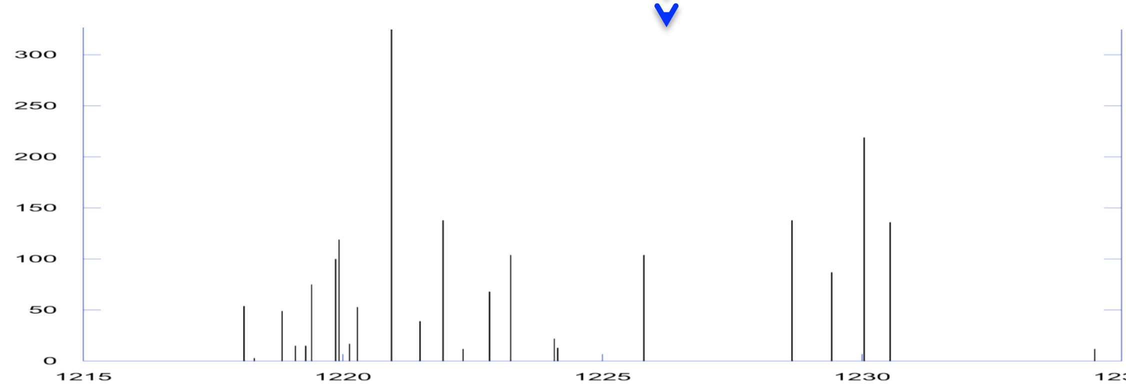


Image plate

linear intensity response over 5 orders of magnitude



1215Å

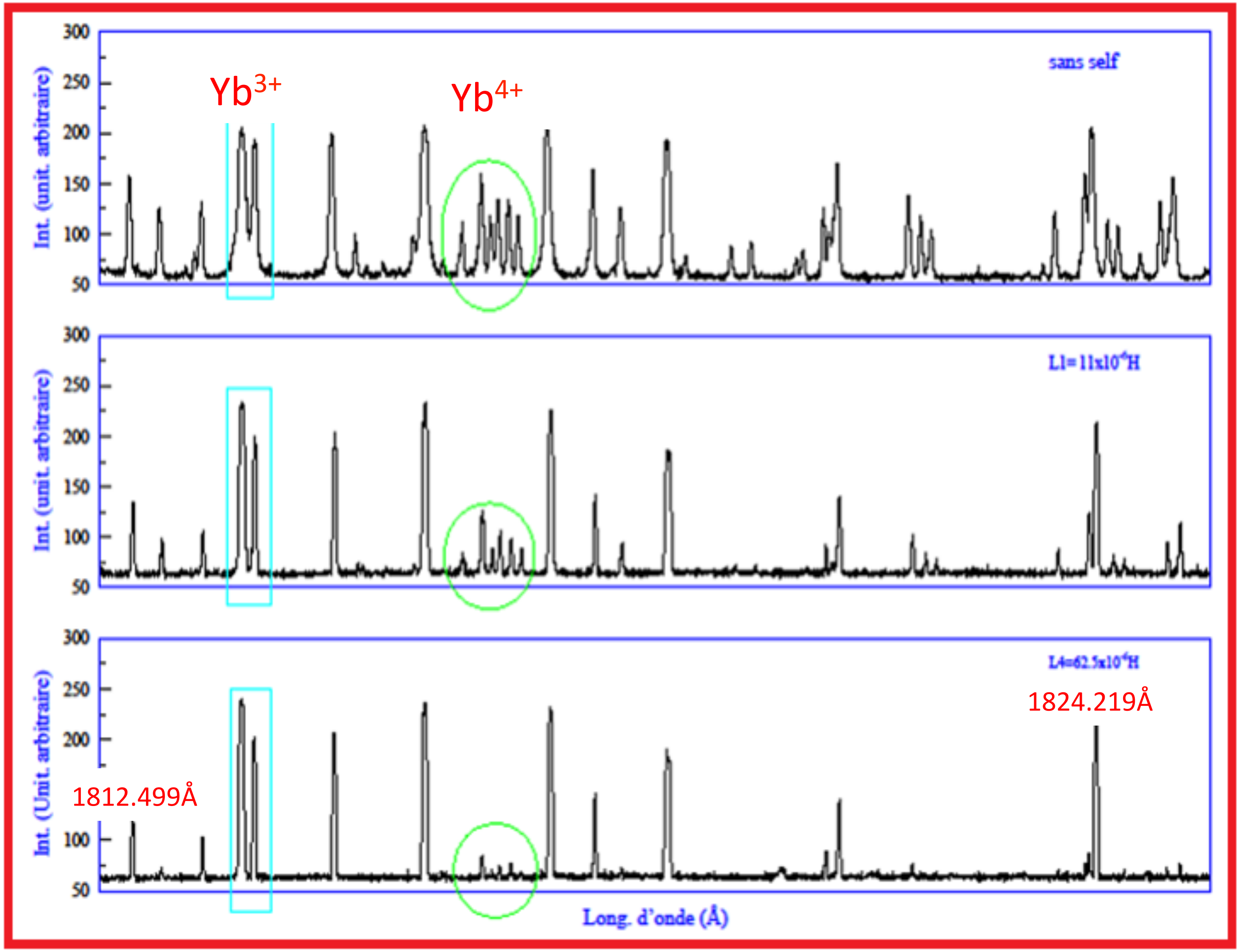
1235Å

20Å

Differentiation of ionization stages

Ytterbium vacuum spark spectrum

Inductance

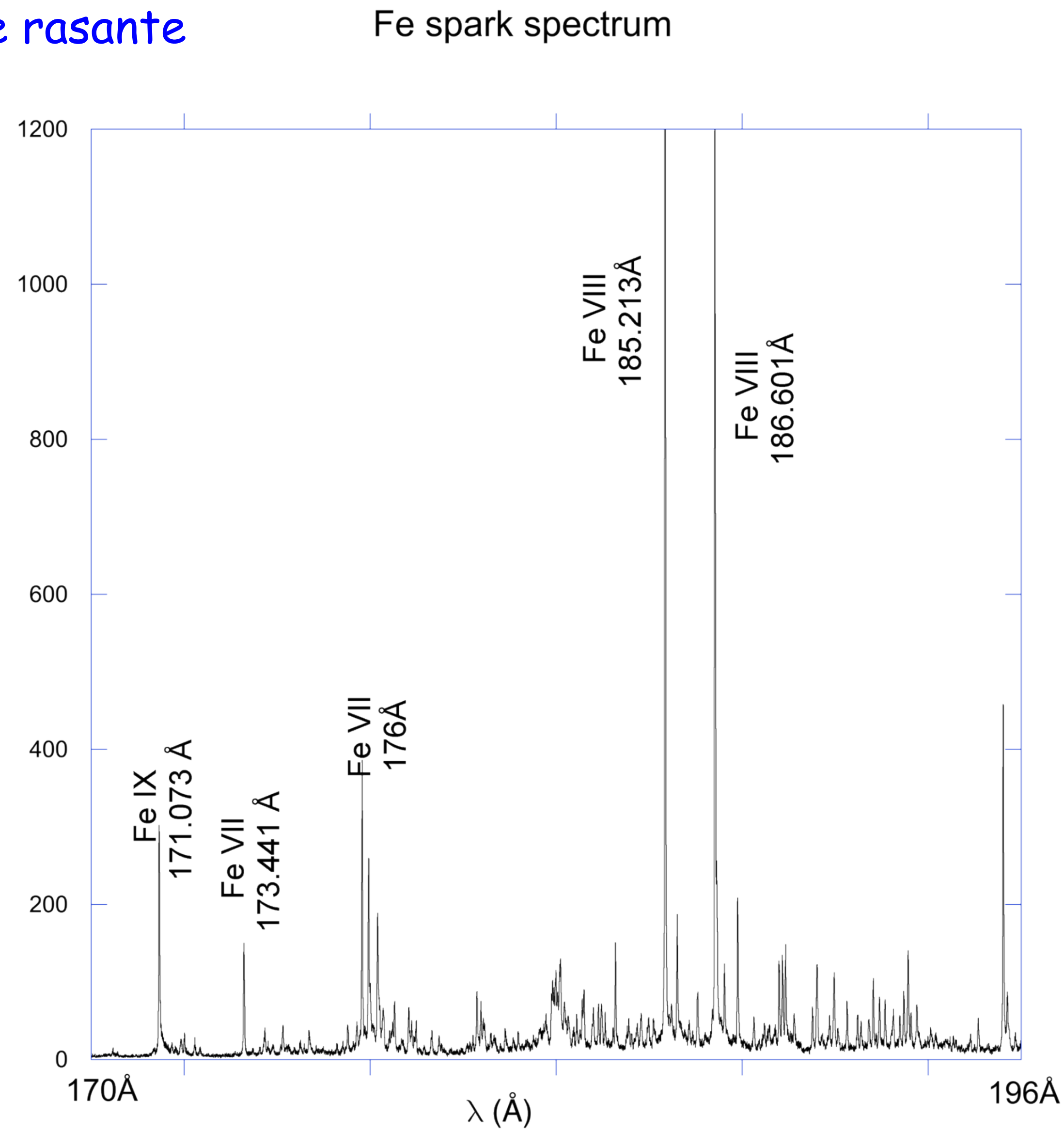


L=0

L=11 μH

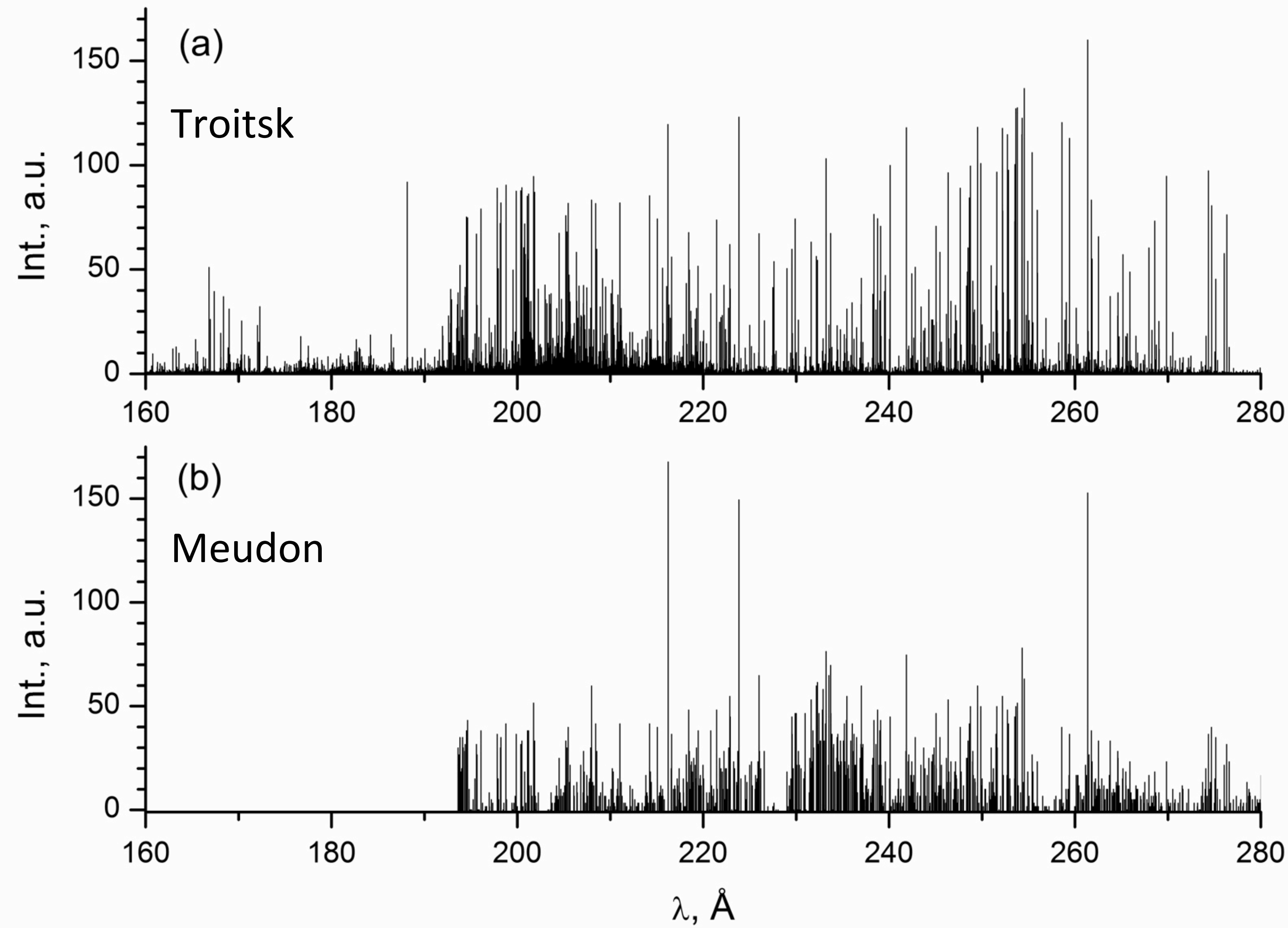
L=62 μH

Extension vers les courtes λ (~165Å)
Recouvrement avec incidence rasante



Short λ overlap

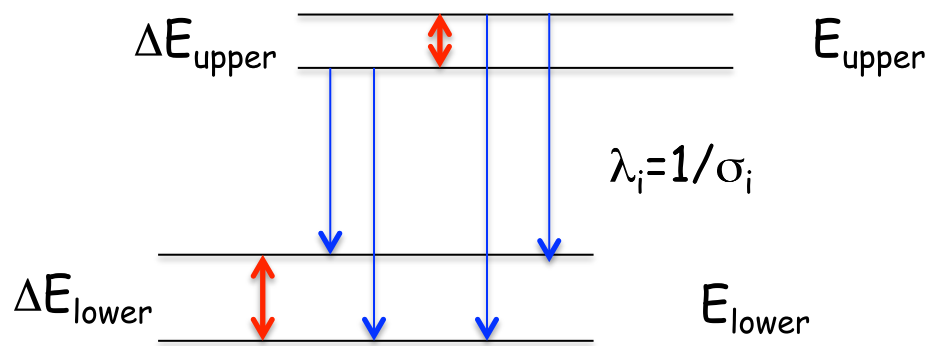
(a) Troitsk grazing incidence spectrograph ; (b) Meudon normal incidence spectrograph



Ionized W spectra : Vacuum spark source

Analysis: to build the energy level scheme from lines

Ritz combination principle :
$\sigma = (\lambda)^{-1} = E_{upper} - E_{lower}$ (cm^{-1})
+
Selection rules



!! Line intensities ←→ calculated transition probabilities *gA*

A long trial and error procedure sped up by the IDEN code (Azarov 1991 & 1993)
⇒ E_{exp}, identification of $\lambda_{measured}$

Optimization of all E_{exp} values from all $\lambda_{measured}$ of identified transitions (LOPT code, Kramida 2011)

⇒ Precise Ritz λ for allowed and forbidden lines $\lambda_{Ritz} = (E_u^{opt} - E_l^{opt})^{-1}$

Theoretical Method (Racah-Slater)
RCN/RCG/RCE codes by R.D. Cowan

HFR

$$H = H_0 + H_1$$

H_0 : central field hamiltonian $\Longrightarrow$
Hartree-Fock solution for orbitals and $E_{average}$ for configurations

$H_1 = Q + \Lambda$ = electrostatic interactions + relativistic corrections (spin-orbit)

- Diagonalization : basis of one or several configurations (CI)

$\Rightarrow$ Predicted energies and wavefunctions

$\Rightarrow$ Calculation of transition integrals : gA ←→ predicted intensitie

Semi-empirical approach (RCE)

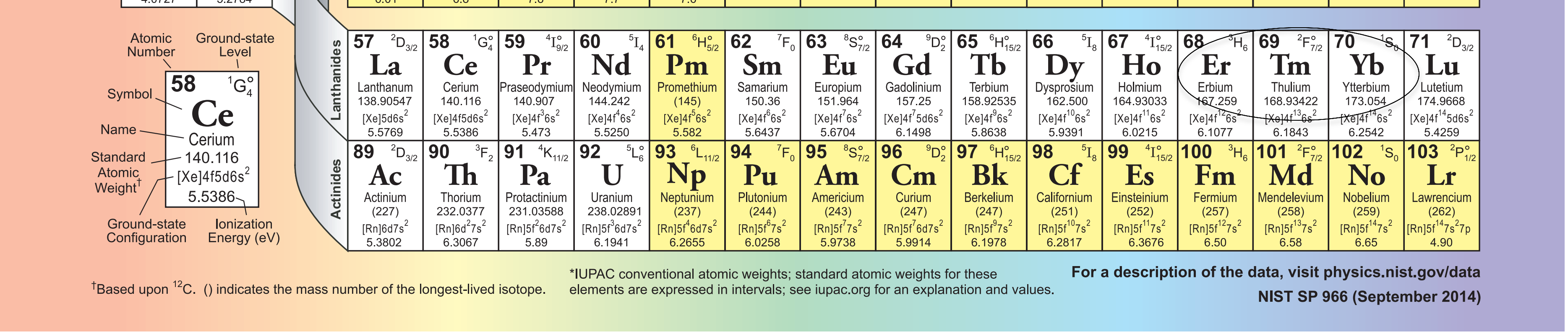
matrix element : $H_{1ij} = \sum_{\alpha} c_{ij}^{\alpha} P_{\alpha}$

c_{ij}^{α} : angular part → Racah algebra

P_{α} : radial integral → ajustable energy parameters

- iterative least squares fits of P_α to minimize $\Delta E = \sqrt{\sum_i (E_i^{exp} - E_i^{cal.})^2 / (N_l - N_p)}$

Initial values of P_α : HFR values or multiplied by a scaling factor



Er IV

ground configuration $5p^6 4f^{11}$

excited $5p^6 4f^{10}$ 5d, 6s, 6p…

core excited $5p^5 4f^{11}$5d, 6s, 6p…

isoionic ↑

Previous analysis by Carter (thesis 1966) needs complete revision

MCDHF calculations by Radžiutė et al (2015)

Tm IV

Meftah et al.
Phys. Scr. 2008

→ isoelectronic

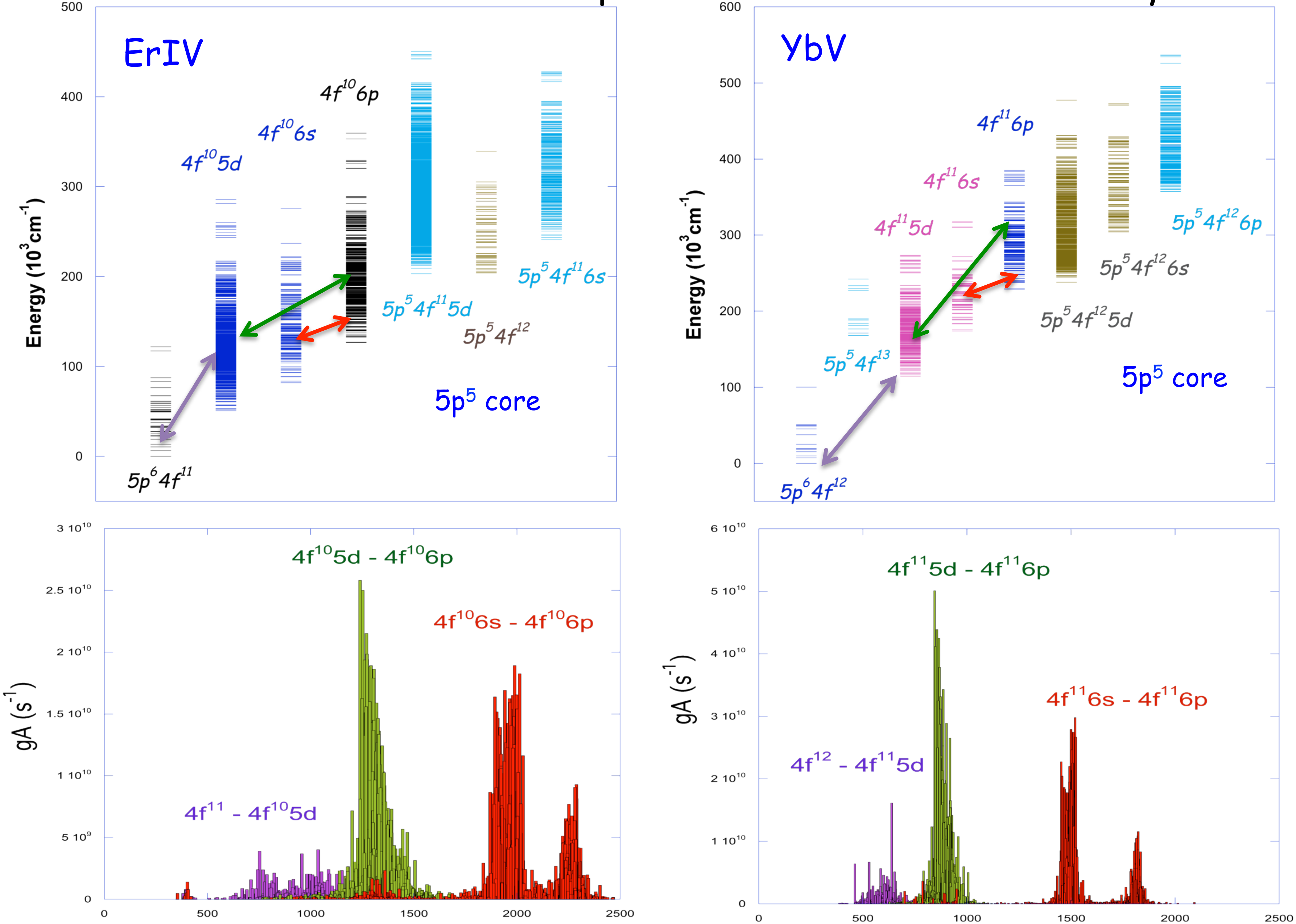
Yb V previously unknown

ground configuration $5p^6 4f^{12}$,

excited $5p^6 4f^{11}$ 5d, 6s, 6p…

core excited $5p^5 4f^{12}$5d, 6s, 6p…

Relativistic Hartree-Fock predictions for transition arrays



Consistency of scaling factor (SF) values $SF=P_{fit}/P_{HFR}$ and effective CI parameters

Parameters	Nd IV	Nd V	Tm IV	Er II	Yb V	Er IV
	$4f^3$+... $4f^2$5d+...	$4f^2$+4f6p 4f5d+....	$4f^{12}+4f^{11}6p$ $4f^{11}$5d+...	$4f^{12}$6p $4f^{12}$5d....	$4f^{12}+4f^{11}6p$ $4f^{11}$5d+...	$4f^{11}+4f^{10}6p$ $4f^{10}$5d+...
F^2(4f,4f)	0.768	0.761	0.785	0.763	0.800	0.779
F^4(4f,4f)	0.839	0.852	0.868	0.844	0.898	0.880
F^6(4f,4f)	0.797	0.766	0.855	0.930	0.864	0.877
ζ_{4f}	0.932	0.927	0.982	0.981	0.982	0.991
F^2(4f,5d)	0.758	0.763	0.806	0.816	0.807	0.804
F^4(4f,5d)	1.082	1.100	1.132	1.174	1.129	1.152
G^1(4f,5d)	0.846	0.860	0.751	0.683	0.774	0.693
G^3(4f,5d)	0.954	0.983	0.974	1.013	0.960	0.966
G^5(4f,5d)	0.839	0.868	0.830	0.753	0.843	0.822
F^2(4f,6p)	0.797	0.815	0.867	0.820	0.844	0.803
ζ_{6p}	1.207	1.168	1.17	1.320	1.143	1.173
Effective CI parameter						
F^1(4f,5d)	**758±57**	**839±147**	**866±106**	**902±62**	**819±81**	**1066±109**

Fitted Energy Parameters Yb V Even parity

$4f^{12}$, $4f^{11}6p$
$5p^54f^{13}$, $5p^54f^{12}6p$

56 Eexp
N_p=21
RMS=55 cm^{-1}

$SF=P_{fit}/P_{HFR}$

	$4f^{12}$				$4f^{11}6p$			
Param.	*Fitted*	*St.dev.*	*HFR*	*SF*	*Fitted*	*St.dev.*	*HFR*	*SF*
E_{av}	20531	17			300546	35	264316	
$F^2(4f4f)$ r	114180	175	142711	0.800	119139	183	148907	0.800
$F^4(4f4f)$ r	80688	377	89854	0.898	84488	395	94085	0.898
$F^6(4f4f)$ r	55929	267	64733	0.864	58646	280	67877	0.864
α	17.9	2			21.7	3		
β r	-738	86			-738	86		
γ r	1757	104			1757	104		
ζ_{4f} r	3066	6	3121	0.982	3228	6	3287	0.982
ζ_{6p}					7739	16	6777	1.143
$F^1(4f6p)$					270	85		
$F^2(4f6p)$					9625	283	11403	0.844
$G^2(4f6p)$					2939	88	2919	1.007
$G^4(4f6p)$					2560	233	2677	0.956

	$5p^54f^{13}$				$5p^54f^{12}6p$			
Param.	*Fitted*	*St.dev.*	*HFR*	*SF*	*Fitted*	*St.dev.*	*HFR*	*SF*
E_{av}	192408	f	172089		412123	f	391804	
$F^2(4f4f)$					113153	f	144145	
$F^4(4f4f)$					79482	f	90836	
$F^6(4f4f)$					56625	f	65463	
α					17	f		
β					-653	f		
γ					1712	f		
ζ_{4f}	2932	f	2986	0.982	3090	f	3147	0.982
ζ_{5p}	35833	f	35833	1.000	39067	f	39067	1.000
ζ_{6p}					7881	f	6736	1.169
$F^1(5p4f)$	1000	f				f		
$F^2(5p4f)$	46397	f	57796	0.800	47896	f	59871	0.800
$F^1(4f6p)$		f			100	f		
$F^2(4f6p)$		f			10120	f	11627	0.870
$F^1(5p6p)$		f				f		
$F^2(5p6p)$		f			17729	f	22162	0.800
$G^2(5p4f)$	22571	f	28213	0.800	22176	f	27721	0.960
$G^4(5p4f)$	17677		22096	0.800	17688	f	22110	0.800
$G^2(4f6p)$					3054	f	3054	1.000
$G^4(4f6p)$					2509	f	2788	0.900
$G^0(5p6p)$					3332	f	4165	0.800
$G^2(5p6p)$					4689	f	5862	0.800
C.I.Parameter	*Fitted*	*St.dev.*	*HFR*	*SF*				
$5p^64f^{12}-5p^54f^{13}$								
$R^2(4f5p,4f4f)$	-10022	f	-15745	(0.700)				
$R^4(4f4f,4f5p)$	-4279	f	-6113	(0.700)				
$R^2(5p5p,4f5p)$	-28260	f	-40371	(0.700)				
$5p^64f^{12}-5p^64f^{11}6p$								
$R^2(4f4f,4f6p)$	-2278	f	-3254	(0.700)				
$R^4(4f4f,4f6p)$	-1092	f	-1560	(0.700)				
$5p^64f^{12}-5p^54f^{12}6p$								
$R^2(4f5p,4f6p)$	11025	f	15750	(0.700)				
$R^2(4f5p,6p4f)$	5692	f	8132	(0.700)				
$R^4(4f5p,6p4f)$	4903	f	7004	(0.700)				
$R^2(5p5p,5p6p)$	7380	f	10543	(0.700)				

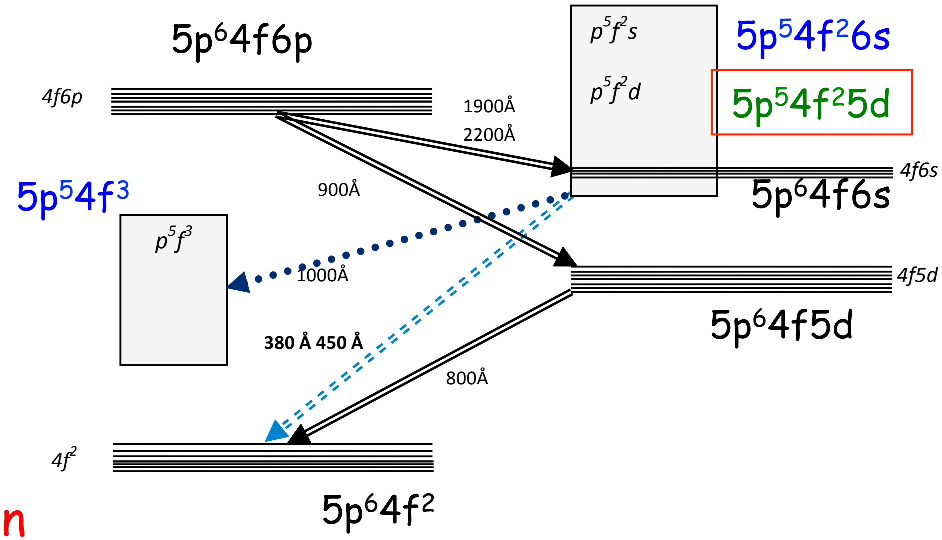
CI parameters →

r : all the parameters of the same name are linked by a constant ratio
f : fixed parameter

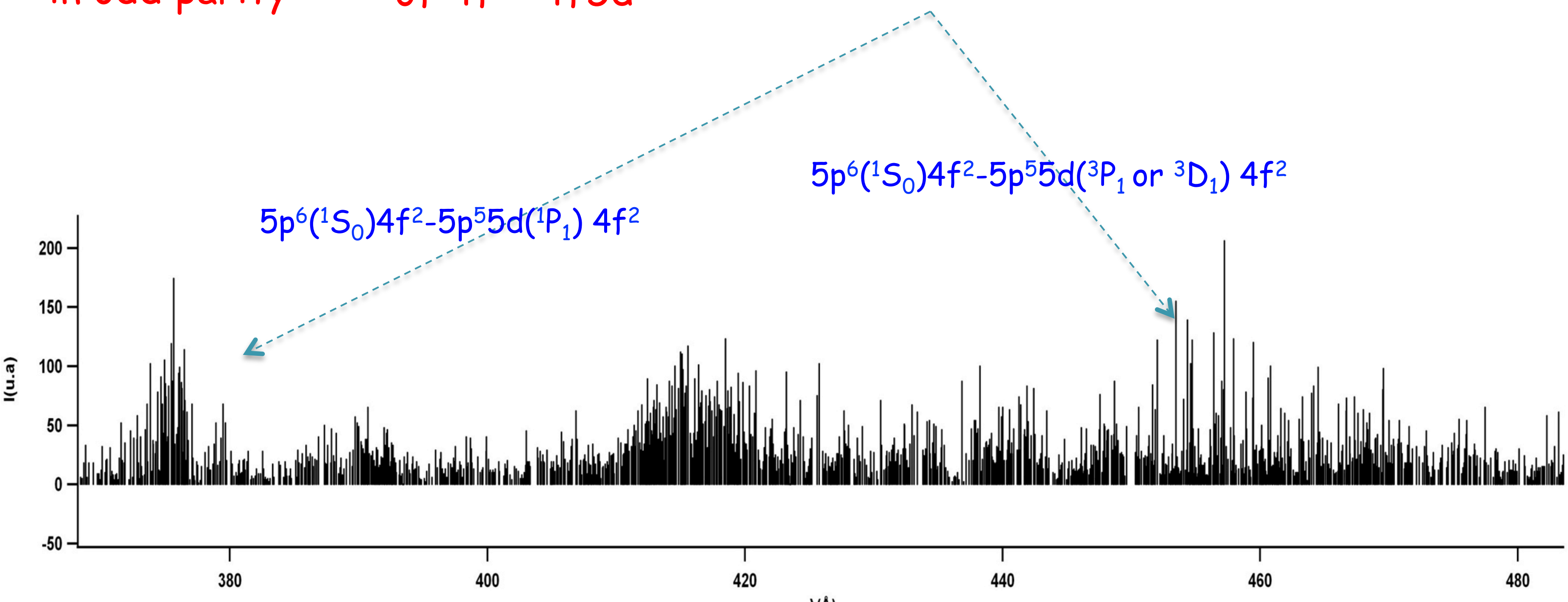
Mean error of the fit = 55 cm^{-1}

Nd V core-excited configuration
$5p^54f^25d$
(Deghiche et al 2015)

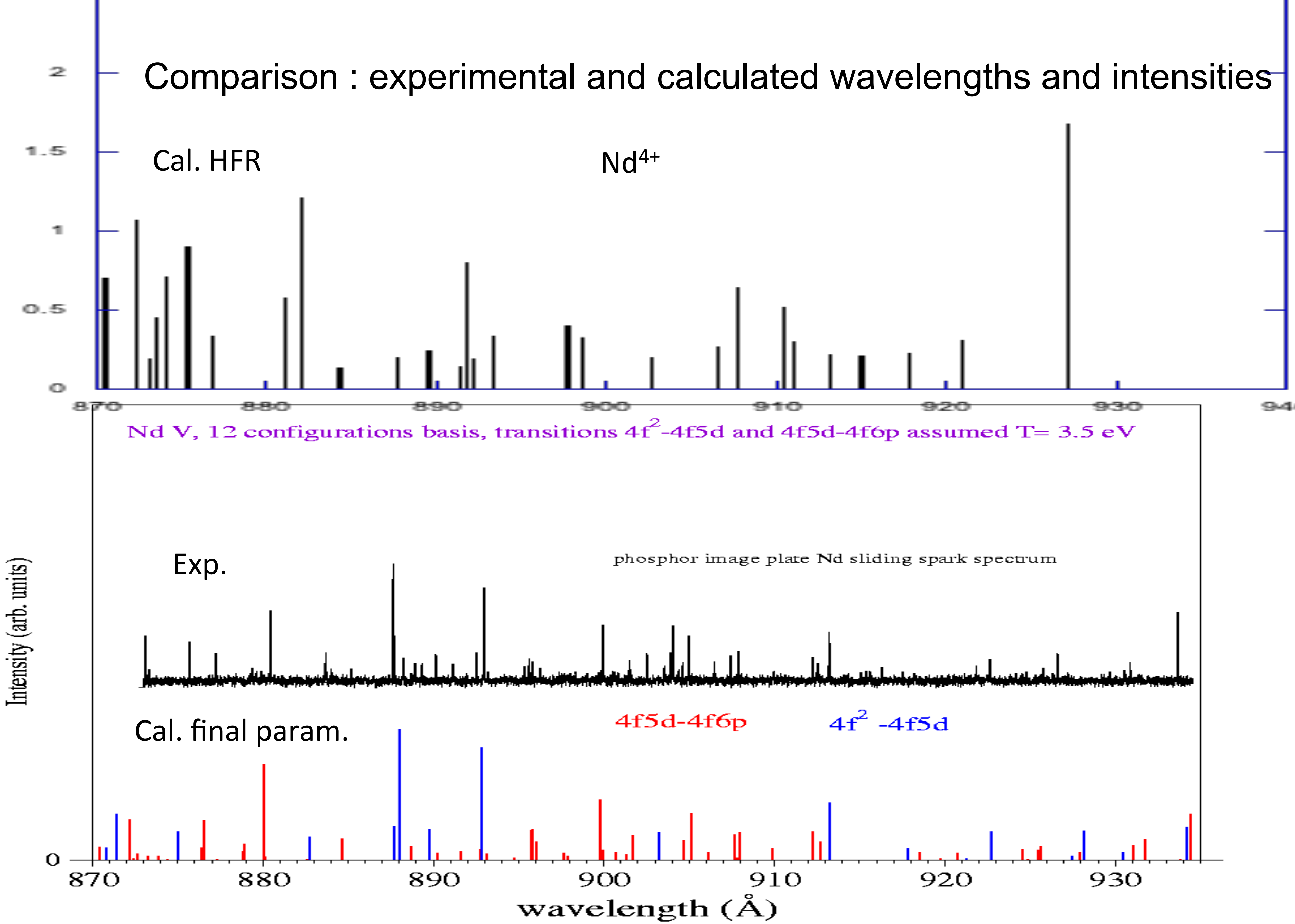
305 lines
λ (350 -550Å)
104 energy levels



Strong CI in odd parity → Intensity reduction of $4f^2$- 4f5d



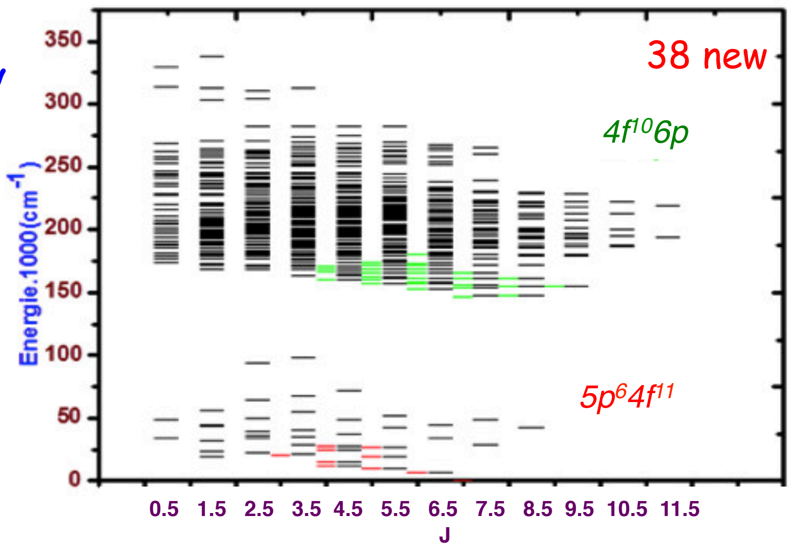
Comparison : experimental and calculated wavelengths and intensities



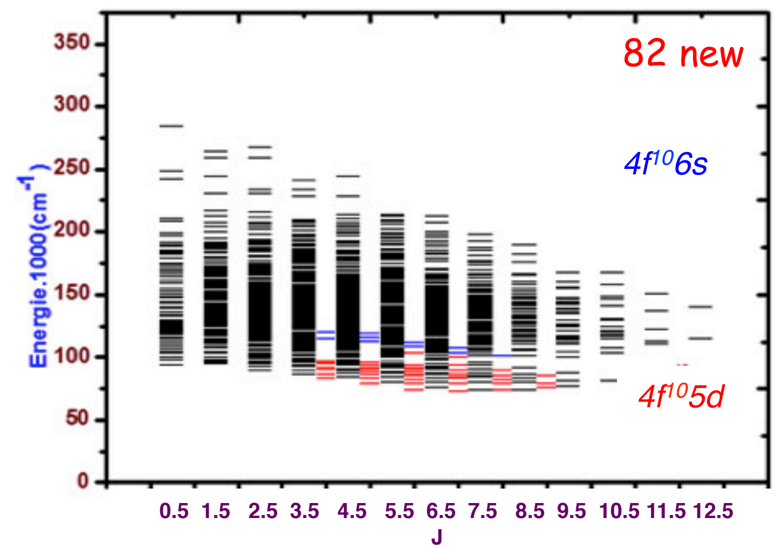
Results on energy levels calc. (black) and exp. (color)

ErIV

odd



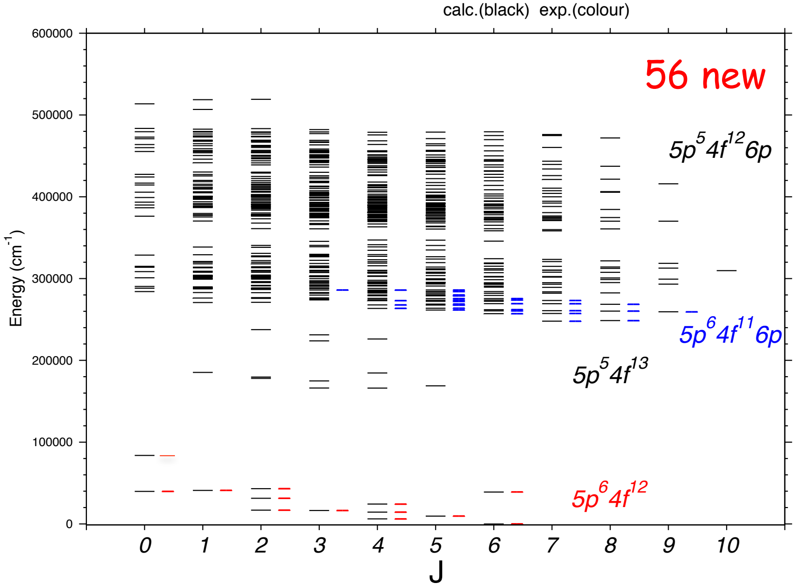
even



YbV

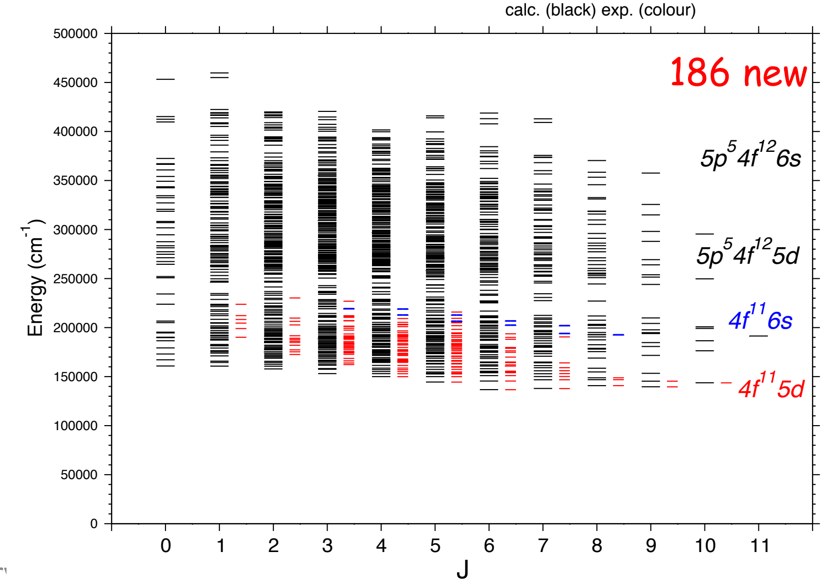
Yb V even parity levels

calc.(black) exp.(colour)



Yb V odd parity levels

calc. (black) exp. (colour)

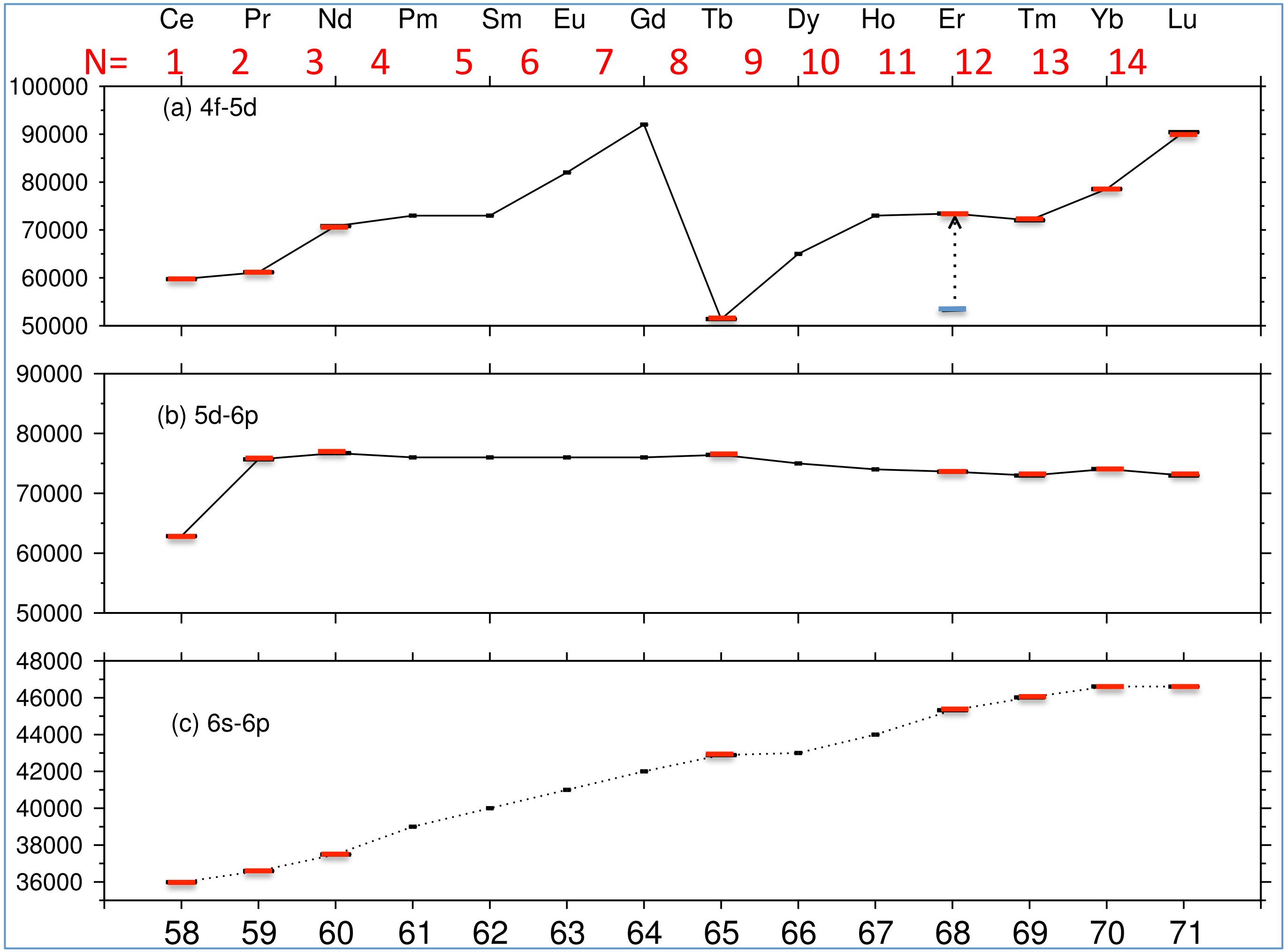


Energy interval between the lowest levels of the main configurations in all triply ionized lanthanides Ln^{3+}

$4f^N$ - $4f^{N-1}$ 5d

$4f^{N-1}$ 5d – 6p

$4f^{N-1}$ 6s – 6p



– Experimentally known

Energy ranges of even configurations in the Dy I isoelectronic sequence → W IX

5p→4f excitation ε ↘ ⇒ $5p^6 4f^N$ - $5p^5 4f^{N+1}$ cores overlap

Energy (cm^{-1})

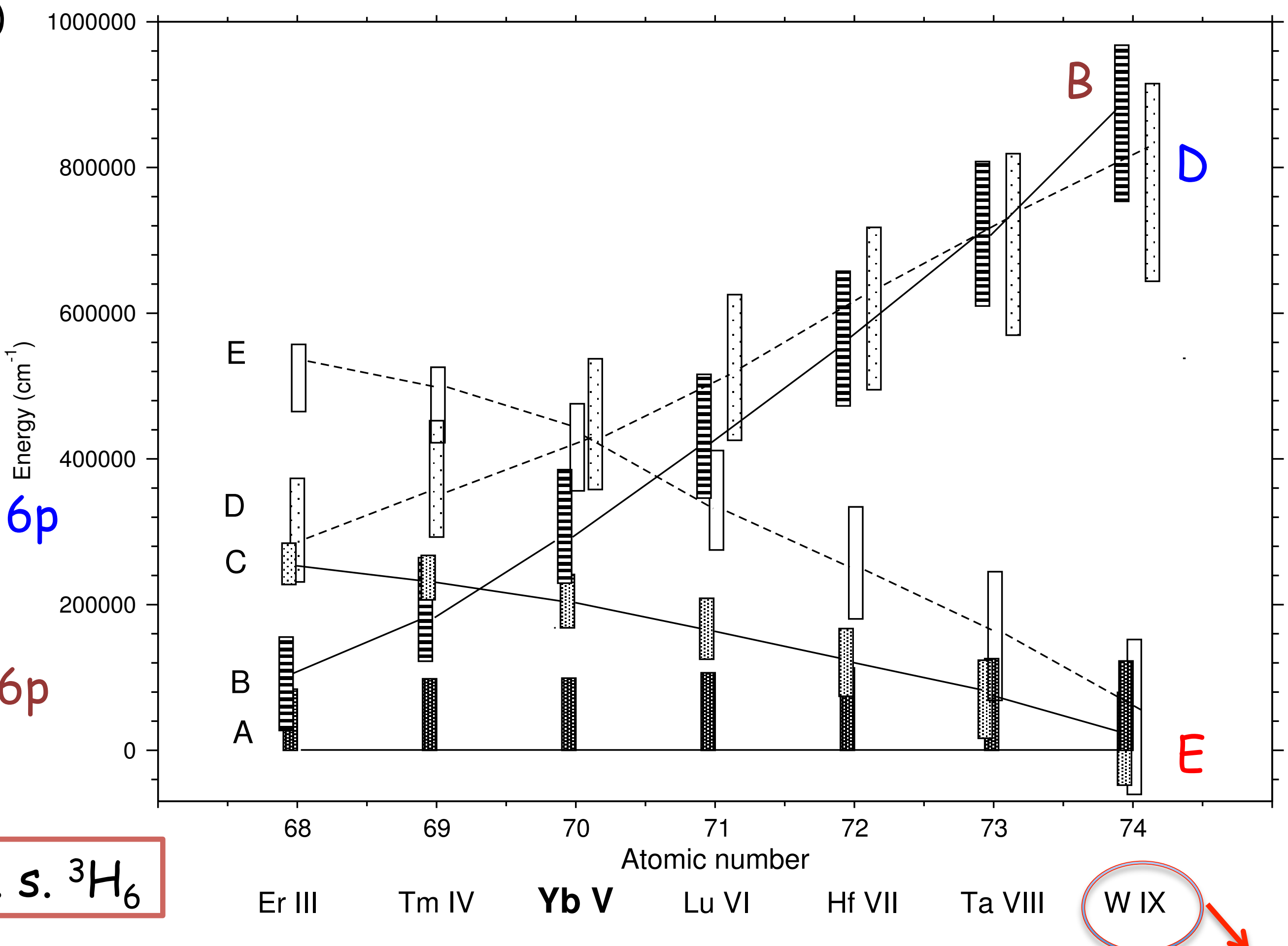
E $5p^4\ 4f^{14}$

D $5p^5\ 4f^{12}\ 6p$

C $5p^5\ 4f^{13}$

B $5p^6\ 4f^{11}\ 6p$

A $5p^6\ 4f^{12}$



4f→6p excitation

g. s. $^3H_6$

g. s. $5p^4\ 4f^{14}\ ^3P_2$

U II : Results of the Least Squares Fits (RCE)

Odd parity 253 experimental E, 24 free parameters, 62 constrained ones

Root Mean Square 60 cm^{-1}

Even parity 125 experimental E, 22 free parameters 39 constrained ones

Root Mean Square 84 cm^{-1}

Partition function for a typical stellar temperature

$$Q(T) = \sum_i (2J+1)\exp\left(-\frac{E_i}{k_B T}\right)$$

k_B: Boltzmann Constant

T= 4825 K ⟺ k_BT= 3353.541 cm^{-1}

Taking into account all E_i < 50 000 cm^{-1}

Odd + even levels

Experimental energies : Q = 109.67 + 13.32 = 122.99

Calculated energies after LSF :

Q = 107.84 + 13.15 = 120.99 Δ ~ 2%

Ab initio HFR calculations :

Q = 87.13 + 2.06 = 89.19 Δ ~ 28%

Table 3: Energy levels of U II, odd parity. Comparison of experimental energies and Landé factors with values calculated from the parameter set of Table 1. The configuration percentage is reported in the last five columns.

J	E^{exp}	E^{th}	ΔE	g_L^{th}	g_L^{exp}	%	$1^{st}conf.$	Comp.	f^3ds	f^3d^2	f^3s^2	f^4p	f^5	Note
4.5	0.000	-66.3	66	0.757	0.765	76	f3.s2	(4I)4I	3.39	4.88	91.71	0.01	0.01	
5.5	289.041	218.3	70	0.656	0.655	77	f3.ds	(4I)6L	99.85	0.14	0	0	0	
4.5	914.765	923.6	-8	0.604	0.605	71	f3.ds	(4I)6K	96.26	0.85	2.58	0.31	0	
6.5	1749.123	1717.8	31	0.864	0.865	45	f3.ds	(4I)6L	93.82	6.15	0.03	0	0	
5.5	2294.696	2317.5	-22	0.868	0.865	47	f3.ds	(4I)6K	97.49	1.82	0.40	0.20	0	
5.5	4420.871	4410.9	9	0.971	0.97	89	f3.s2	(4I)4I	1.43	4.99	93.56	0	0.01	
6.5	4585.434	4585.0	0	0.793	0.785	28	f3.d2	(4I)6M	48.11	51.84	0.05	0	0	
2.5	4706.273	4649.5	56	0.478	0.480	32	f3.ds	(4I)6H	96.78	1.69	1.16	0.37	0.01	
7.5	5259.653	5247.5	12	1.007	1.015	68	f3.ds	(4I)6L	97.57	2.42	0.01	0	0	
3.5	5401.503	5344.6	56	0.801	0.690	20	f3.ds	(4I)6I	98.10	1.07	0.06	0.77	0	
6.5	5526.750	5552.3	-25	1.019	1.020	70	f3.ds	(4I)6K	98.28	1.32	0.12	0.28	0	
3.5	5667.331	5700.7	-33	0.623	0.735	57	f3.ds	(4I)6I	96.89	1.41	0.12	1.58	0	
5.5	5790.641	5832.7	-42	0.852	0.860	39	f3.ds	(4I)6K	95.52	4.06	0.06	0.36	0	
6.5	6283.431	6395.7	-112	0.786	0.790	38	f3.d2	(4I)6M	54.49	45.37	0.13	0.01	0	
4.5	6445.035	6487.7	-42	0.832	0.840	43	f3.ds	(4I)6I	97.65	0.63	0.15	1.58	0	
0.5		6933.0		2.394		20	f3.ds	(4F)4Pa	97.75	2.19	0.02	0.04	0	
1.5	7017.172	7087.3	-70	0.611	0.620	59	f3.s2	(4F)4F	3.88	5.27	90.81	0.03	0.02	
4.5	7166.632	7255.5	-88	0.951	0.940	20	f3.ds	(4I)6H	95.20	4.14	0.10	0.56	0	
3.5	7547.374	7614.9	-67	0.802	0.790	21	f3.ds	(4I)4Ha	84.63	14.61	0.15	0.61	0	
5.5	7598.353	7615.6	-17	0.971	0.980	18	f3.ds	(4I)4Ia	98.01	1.48	0.02	0.49	0	
6.5	8276.733	8259.7	17	1.093	1.090	84	f3.s2	(4I)4I	4.92	5.13	89.93	0.01	0.01	
4.5	8379.697	8357.6	22	0.838	0.840	14	f3.ds	(4I)6I	75.96	21.67	1.74	0.62	0.01	
1.5	8400.125	8432.2	-32	0.086	0.150	68	f3.ds	(4I)6G	97.66	0.96	0.51	0.87	0	
2.5	8430.185	8438.3	-8	0.719	0.720	38	f3.ds	(4I)6G	94.18	1.86	3.22	0.72	0.02	
7.5	8394.362	8444.8	-50	1.057	0.960	56	f3.ds	(4I)6K	74.24	25.52	0.04	0.21	0	
5.5	8510.866	8467.4	43	0.855	0.860	11	f3.ds	(4I)4Kb	78.67	21.18	0.02	0.13	0	
7.5	8521.922	8542.0	-20	0.963	1.060	42	f3.d2	(4I)6M	42.79	57.13	0.01	0	0	
6.5	8755.640	8764.1	-8	1.043	1.040	14	f3.ds	(4I)4Lb	92.23	4.90	2.66	0.21	0	
8.5	8853.748	8820.3	33	1.105	1.105	83	f3.ds	(4I)6L	98.62	1.38	0	0	0	
3.5	9075.732	9010.2	66	0.873	0.870	15	f3.ds	(4I)6H	68.32	30.46	0.83	0.39	0.01	
2.5	9344.625	9245.1	99	0.754	0.79	25	f3.s2	(4G)4G	42.57	8.68	48.15	0.35	0.26	
4.5	9241.971	9249.9	-7	1.028	1.015	12	f3.ds	(4I)6H	76.03	5.71	17.65	0.60	0.01	
5.5	9553.187	9609.9	-56	1.052	1.060	56	f3.ds	(4I)6I	96.38	1.95	0.02	1.65	0	

"Complete" linelist of Eu III

http://molat.obsp

Wyart, Tchang-Brillet, Churilov ar

Description:

This table contains 23827 transitions of the Eu III spectrum, involving experimentally determined or calculated energy levels. The calculations were carried out by using Cowan's codes, as explained in the paper : "Extended analysis of the Eu III spectrum ", by J.-F. Wyart, W.-‹ L. Tchang-Brillet, S. S. Churilov and A.N. Ryabtsev, Astron. & Astrophys. 483, 339-359 (2008).

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Range 1:  2000.000-  3360.000: Max. gA = 5.1E+09 sec-1, Min gA = 1.0E+05 sec-1
Range 2:  3360.000-  6010.000: Max. gA = 2.5E+07 sec-1, Min gA = 1.0E+04 sec-1
Range 3:  6010.000-  9999.000: Max. gA = 5.1E+06 sec-1, Min gA = 1.0E+04 sec-1
Column
  1 -  8  Wavelength calculated from level energies (Ritz values)
 10 - 18  Weighted transition probability (s-1), gu - statistic weight of the upper level
 20 - 25  Logarithm of weighted oscillator strengths, gl - statistic weight of the lower level
 28 - 33  Cancellation factor (see R.D.Cowan. Theory of atomic structure and spectra, p.432)
 35 - 42  Energy of the lower level (cm-1)
 43       Status of the lower level: * - experimentally measured, otherwise - calculated
 44 - 46  Parity: e - even, o - odd
 48 - 53  g - factor Lande
 55 - 66  Level designation by first component of LS - composition
 69 - 71  J
 75 - 82  Energy of the upper level (cm-1)
 83       Status of the upper level: * - experimentally measured, otherwise - calculated
 84 - 86  Parity: e - even, o - odd
 88 - 93  g - factor Lande
 95 -107  Level designation by first component of LS - composition
110 -112  J
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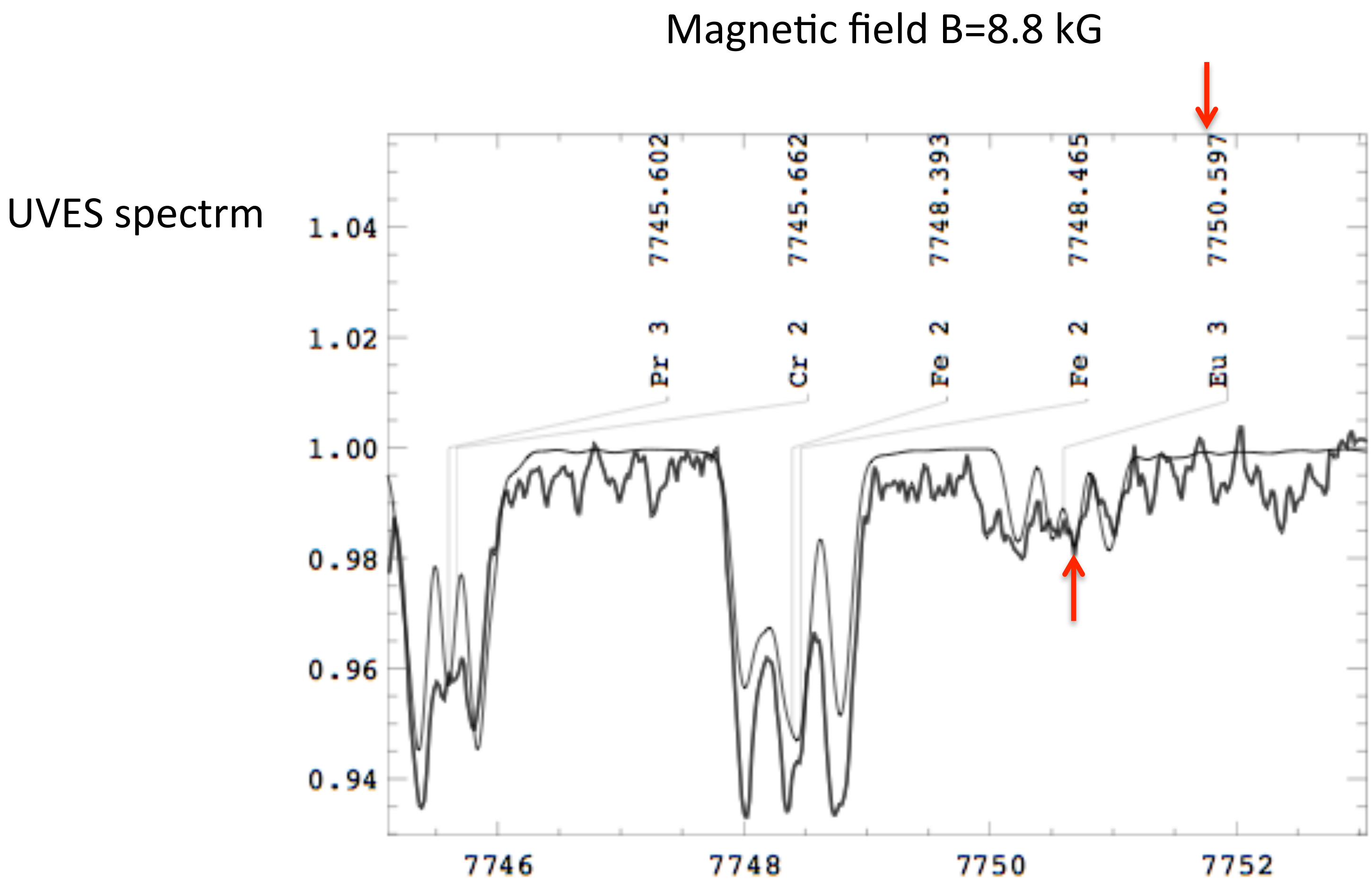
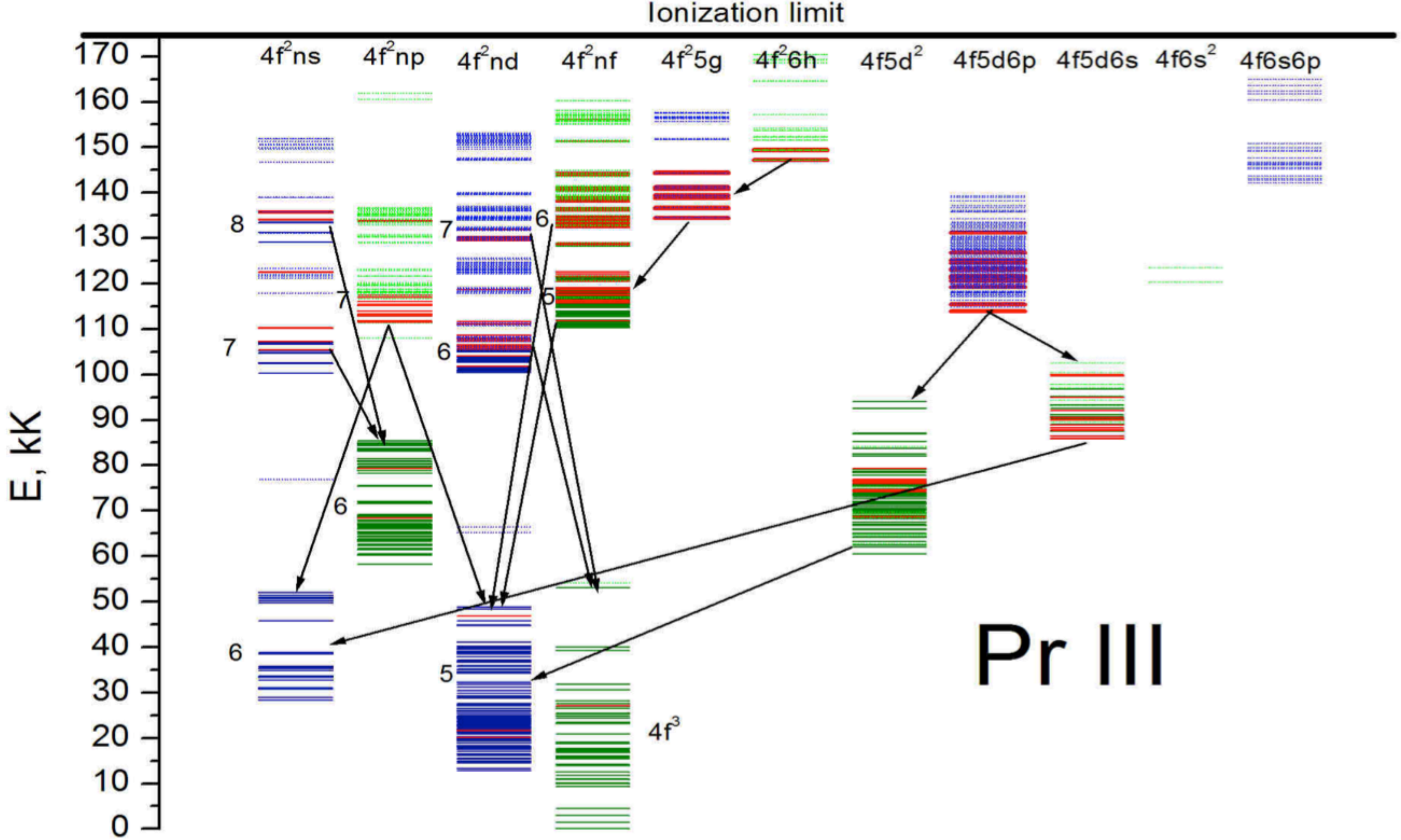
Lambda,A	guA	log(glf)	CF	Lower level E,cm^(-1)	g	Name	J		Upper level E,cm^(-1)	g	Name	J
2000.032	2.811E+05	-3.773	-0.020	35262.00 (o)	3.318	4f7 6D	0.5	-	85245.00 (e)	1.182	4f65d (5D2)4S	1.5
2000.232	2.081E+05	-3.903	0.010	35480.00 (o)	1.667	4f7 6D	2.5	-	85458.00 (e)	1.033	4f65d (5P)4F	2.5
2000.312	4.092E+05	-3.610	-0.010	35480.00 (o)	1.667	4f7 6D	2.5	-	85456.00 (e)	0.978	4f65d (3K5)4H	3.5
2000.753	2.045E+05	-3.911	-0.070	28848.00 (o)	2.369	4f7 6P	1.5	-	78813.01 (e)	0.197	4f65d (5G2)4D	0.5
2000.795	1.928E+06	-2.936	-0.050	28200.06*(o)	1.691	4f7 6P	3.5	-	78164.00 (e)	1.015	4f65d (5K)6I	4.5
2000.965	3.308E+05	-3.700	-0.020	32073.30*(o)	1.292	4f7 6I	8.5	-	82033.00 (e)	1.129	4f65d (5K)4L	9.5
2000.993	2.295E+07	-1.861	0.290	28848.00 (o)	2.369	4f7 6P	1.5	-	78807.00 (e)	1.375	4f65d (5D2)6P	2.5
2001.084	2.185E+06	-2.879	-0.220	0.00*(o)	1.997	4f7 8S	3.5	-	49956.73*(e)	1.491	4f65d (7F)6D	4.5
2001.354	1.192E+05	-4.145	-0.010	35338.00 (o)	1.589	4f7 6D	3.5	-	85288.00 (e)	1.057	4f65d (3F8)2D	2.5
2001.366	4.125E+06	-2.604	0.090	32073.30*(o)	1.292	4f7 6I	8.5	-	82023.00 (e)	1.185	4f66s (5I2)6I	7.5
2001.526	2.086E+06	-2.902	0.150	36962.29*(e)	1.298	4f65d(7F)8H	5.5	-	86908.00 (o)	0.971	4f7 2H9	4.5
2001.859	2.434E+07	-1.834	-0.040	38229.07*(e)	1.790	4f65d(7F)8D	3.5	-	88166.46*(o)	1.524	4f66p (7F)6D	4.5

Results used for identification of Eu III lines in Ap star HD 144897 and determination of Eu abundance



Comparison between the observed spectrum of HD 144897 in the region of Eu III λ7750.59 Å line (double line) and synthesized spectrum with the atomic parameters derived in the present work (full line).



Experimental data :7300 lines (821 - 10717 Å)

New analysis : ~ 4900 classified = from high lying levels of 4f^{2}7p, 4f^{2}7d, 4f^{2}6f, 4f^{2}5g, 4f^{2}6h and 4f5d6p configurations

Determination of 403 odd levels (prev. 234) and 235 even levels (167).

Parametric studies : odd 4f^3+ 4f^{2}6p+ 4f^{2}7p+ 4f^{5}5d^2+ 4f5d6s+ 4f6s^2+ 4f^{2}5f+f^{2}6f+5p^{5}7f+5p^{5}4f^{3}6p

even 4f^{2}5d+4f^{2}6d+ 4f^{2}6s+ 4f^{2}7s+ 4f^{2}8s+ 4f5d6p+ 4f6s6p+ 4f5d5f+ 5p^{5}4f^{3}5d+5p^{5}4f^{3}6s

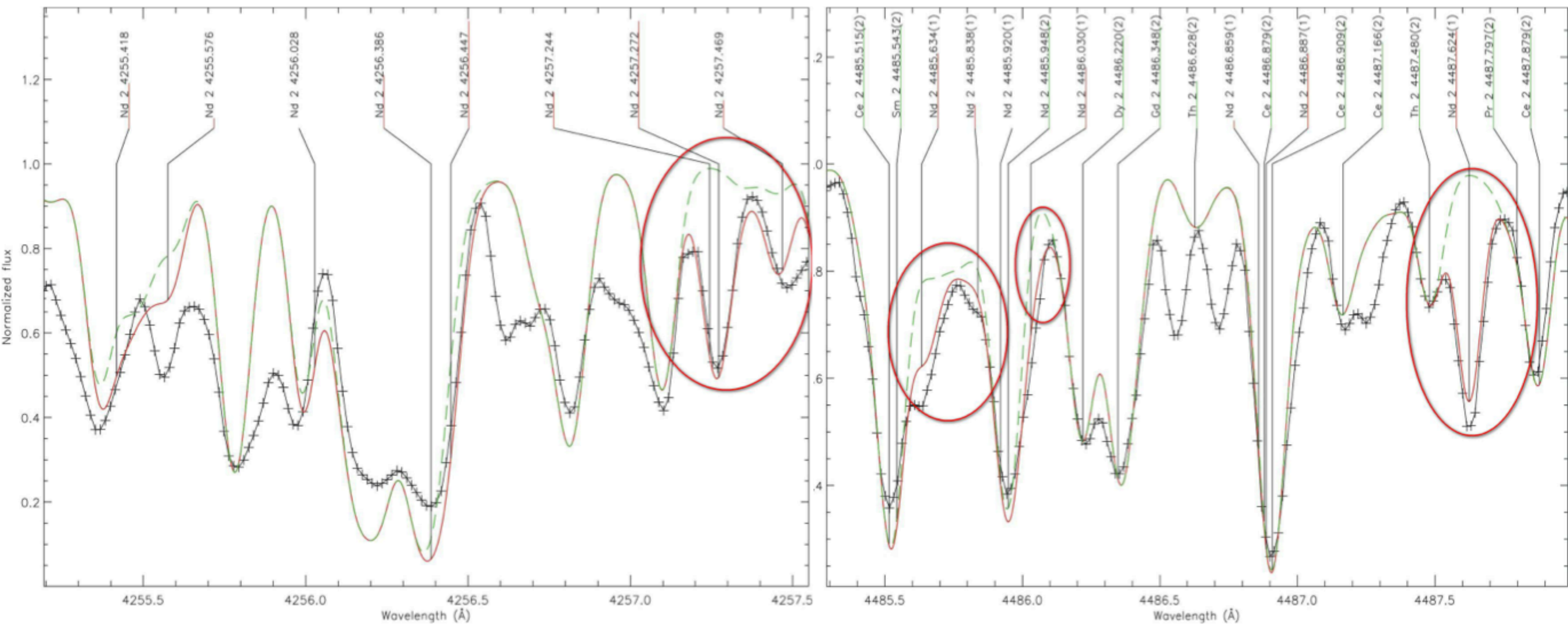
Std= 59 and 56 cm^{-1}.

Application to to the analysis of Pr abundance in the atmosphere of Am star 32 Aqr (Ryabchikova et al)

New analysis of Nd II spectrum for search of Nd II lines in the spectrum of Przybylski' star (HD 101065)

597 levels of the odd $4f^35d6s$+ $4f^35d^2$+ $4f^36s^2$+ $4f^46p$+ $5p^64f^5$ configurations and 233 levels of the even $4f^46s$+ 4f45d+ $4f^36s6p$ +$4f^35d6p$ configurations interpreted with a STD of respectively 87 and 57 cm^{-1}

In VALD 1287 lines ➔ 5700 lines



Summary

Work in progress :

- Compilation of systematic trends by isoelectronic or isoionic sequences in singly and doubly ionized lanthanides (Ln II, Ln III)

$\Longrightarrow$ estimation of scaling factors and energy intervals

- Analyses of Eu IV and of iron group elements Mn (IV, V), Fe VI, Ni (VII) , W V
- Precision measurements (±0.001-0.002Å) of Fe IV, V and Ni V wavelengths for variation of fundamental constants
- Improvements in U II, Th II

- MIT in Fe X

- VUV spectrum of HD

- Data on line on molat.obspm.fr

Fe X :   magnetic field induced transition (MIT)

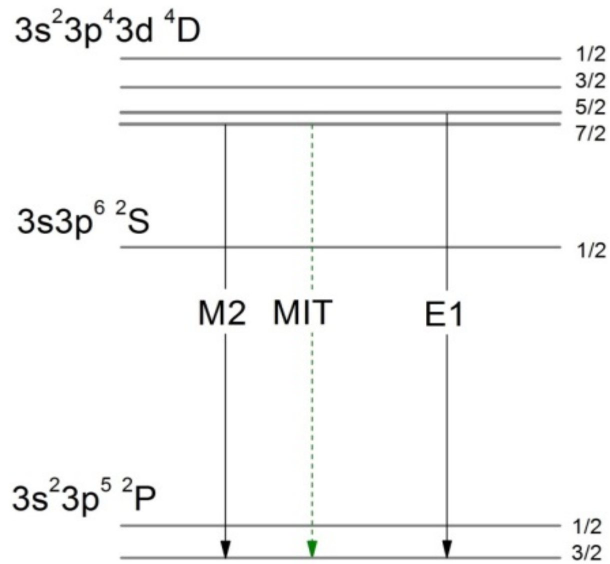


Figure 1: Schematic energy-level diagram for Chlorine-like ions with Z < 26 and zero nuclear spin, where $^4D_{7/2}$ is the lowest level in the configuration $3s^2 3p^4 3d$. For ions with Z > 26, a level crossing has occurred and $^4D_{5/2}$ is lower than $^4D_{7/2}$. Under the influence of an external magnetic field, an E1 transition opens up from the $^4D_{7/2}$ to the ground state through mixing with the $^4D_{5/2}$.

Newly identified lines and new experimental levels molat.obspm.fr

(2007-2008)

- Tm IV
  - 760 lines, 209 energy levels
- Nd IV
  - 1426 lines, 232 levels
- Eu III
  - 90 new lines, 30 new levels
  - (1150 Ritz wavelengths)

Nd V

- 160 lines 48 levels

- More recent
- Yb V (2013)
  - 1080 lines, 242 energy levels
- Nd V (2015) for core-excited configurations
  - 304 lines, 104 energy levels

Er IV (2016)

- 591 lines, 120 energy levels

Thank you for your attention !