DYNAMICAL
AND
PARTIAL DYNAMICAL
SYMMETRIES
IN NUCLEI AND THEIR BREAKING

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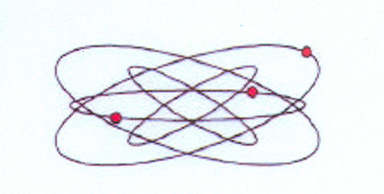
Themes and challenges of Modern Science

•Complexity out of simplicity -- Microscopic

How the world, with all its apparent complexity and diversity can be constructed out of a few elementary building blocks and their interactions

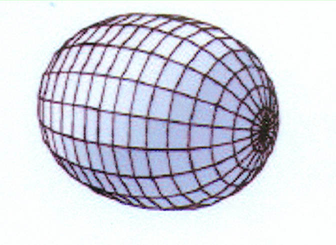
What is the force that binds nuclei?
Why do nuclei do what they do?



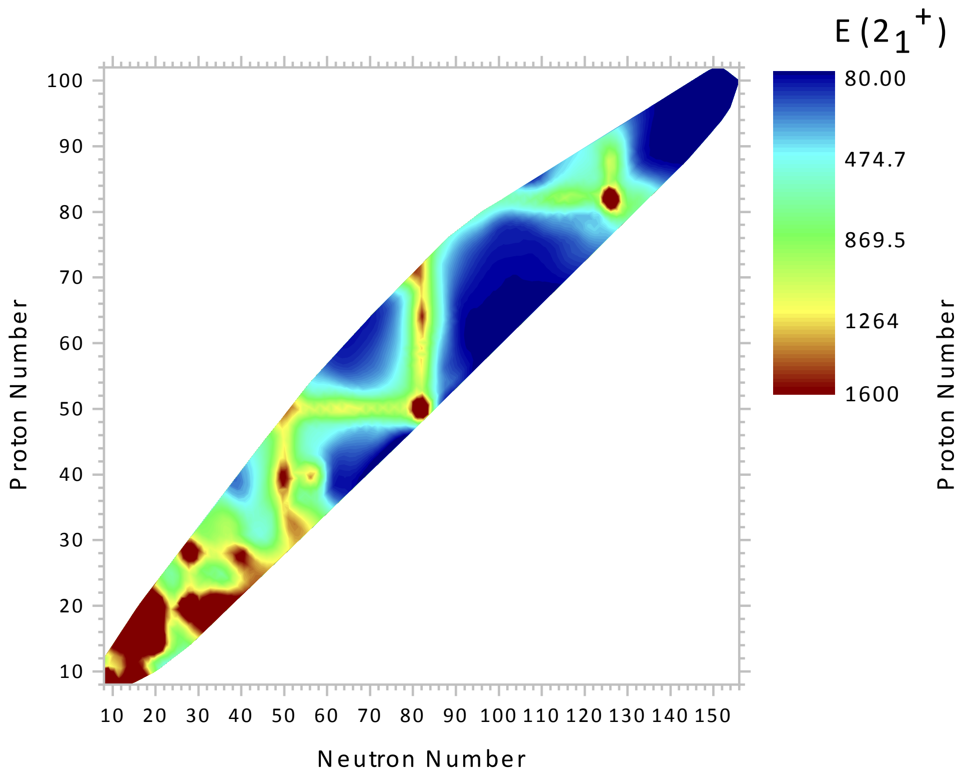
•Simplicity out of complexity – Macroscopic

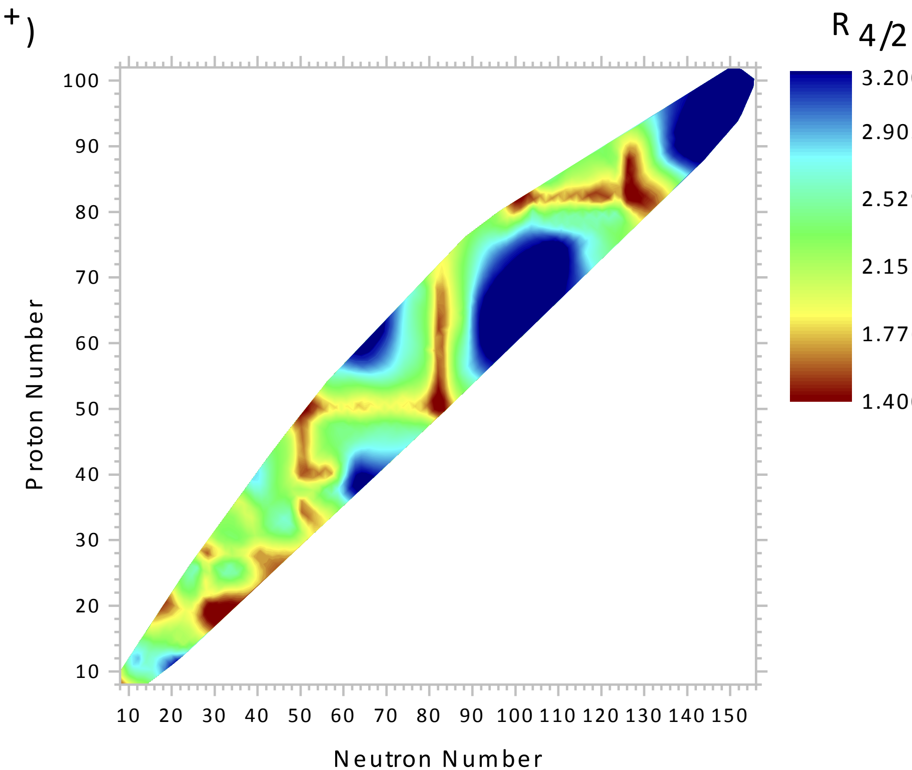
How the world of complex systems can display such remarkable regularity and simplicity

What are the simple patterns that nuclei display and what is their origin ?



Broad perspective on structural evolution Z=50-82, N=82-126





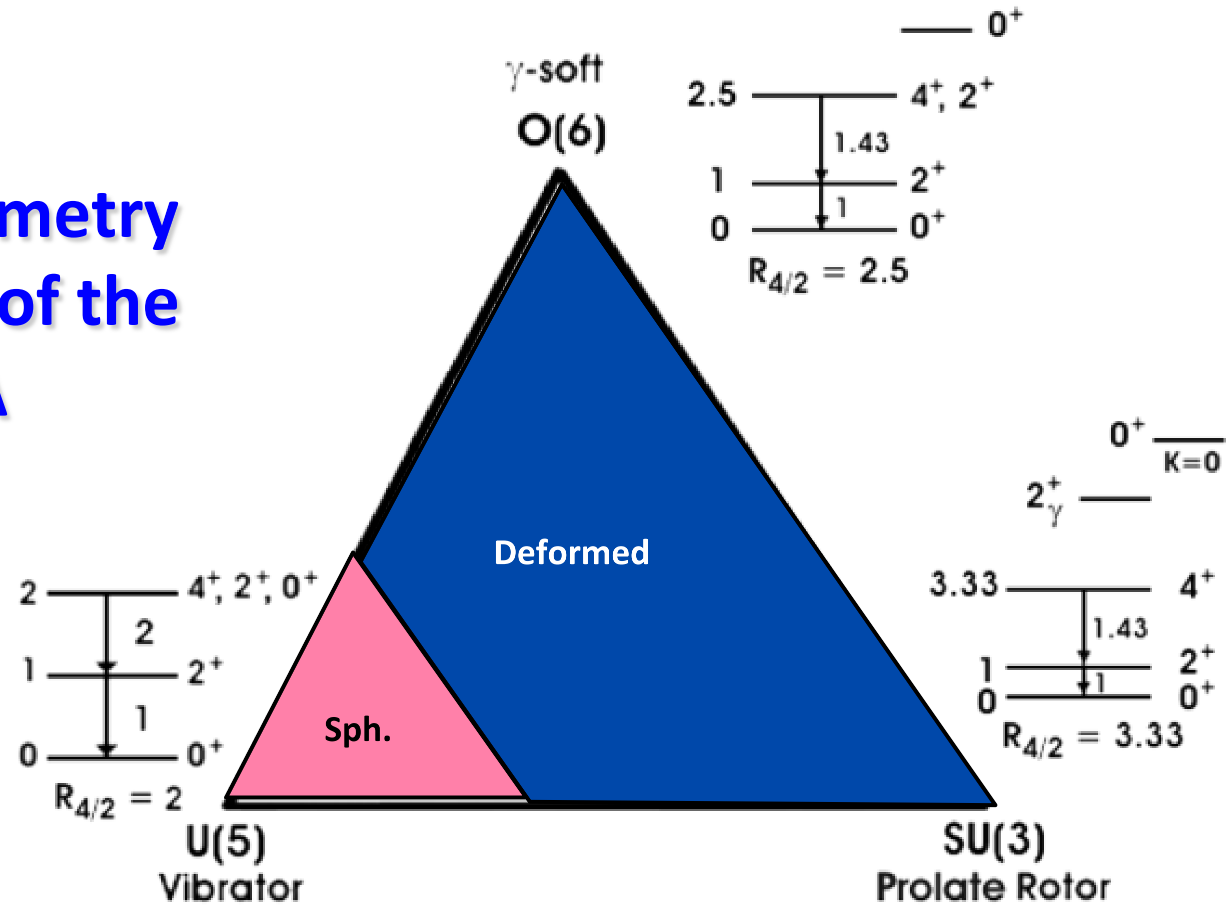
The remarkable regularity of these patterns is one of the beauties of nuclear systematics and one of the challenges to nuclear theory.
Whether they persist far off stability is one of the fascinating questions for the future

Cakirli

Structural (dynamical) Symmetries

Unique insights into complex many-body systems: shape, quantum numbers, selection rules, analytic formulas (often parameter free)

The Symmetry Triangle of the IBA



Doubly magic plus 2 nucleons

$$R_{4/2} < 2.0$$

Vibrator (H.O.)

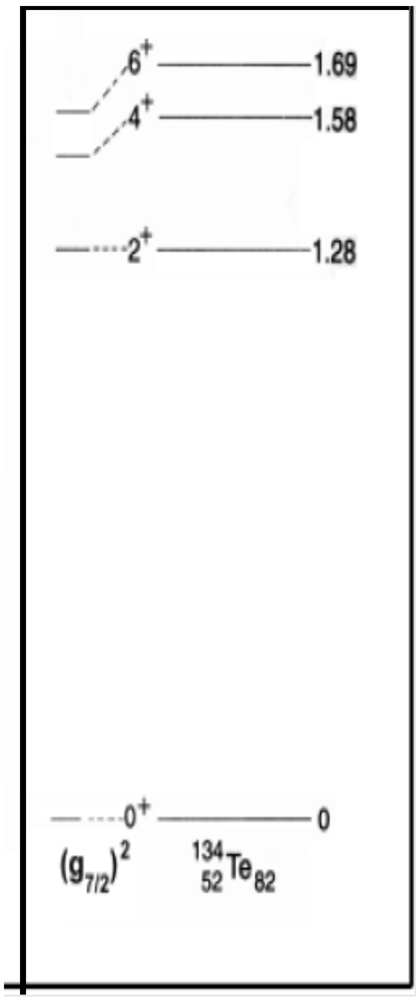
$$E(J) = n\,(\hbar\,\omega_0)$$

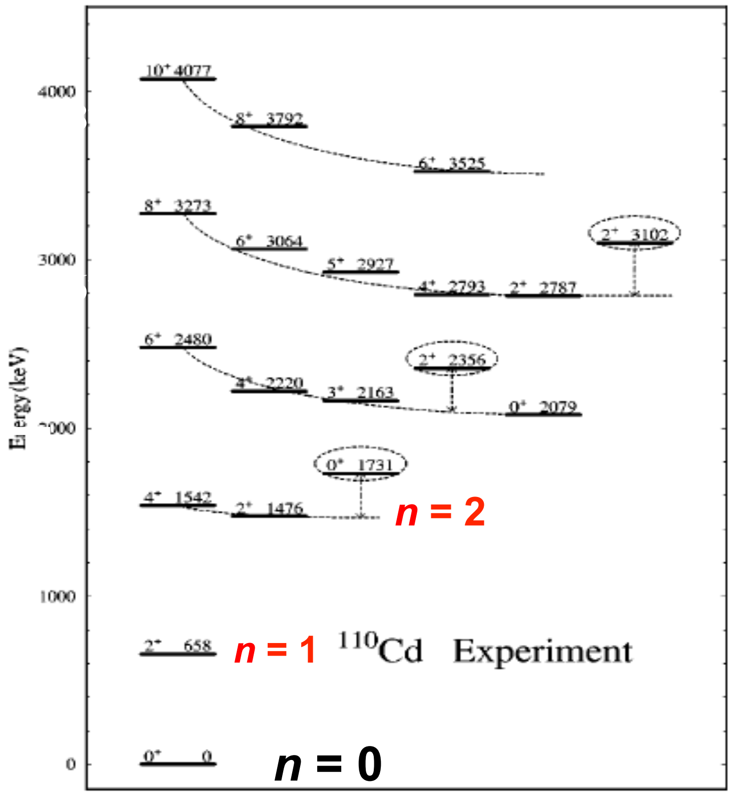
$$R_{4/2} = 2.0$$

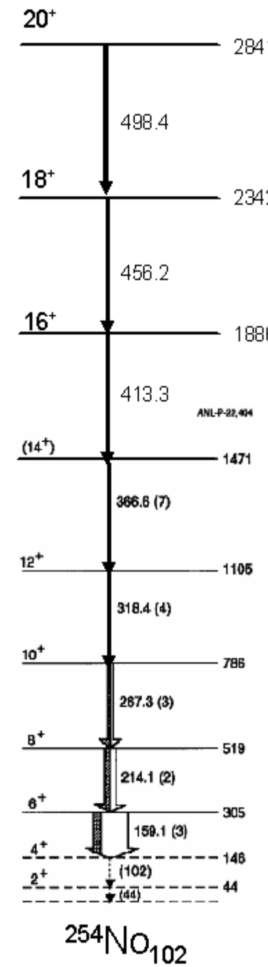
Rotor

$$E(J) \propto (\hbar^2/2I)\,J(J+1)$$

$$R_{4/2} = 3.33$$

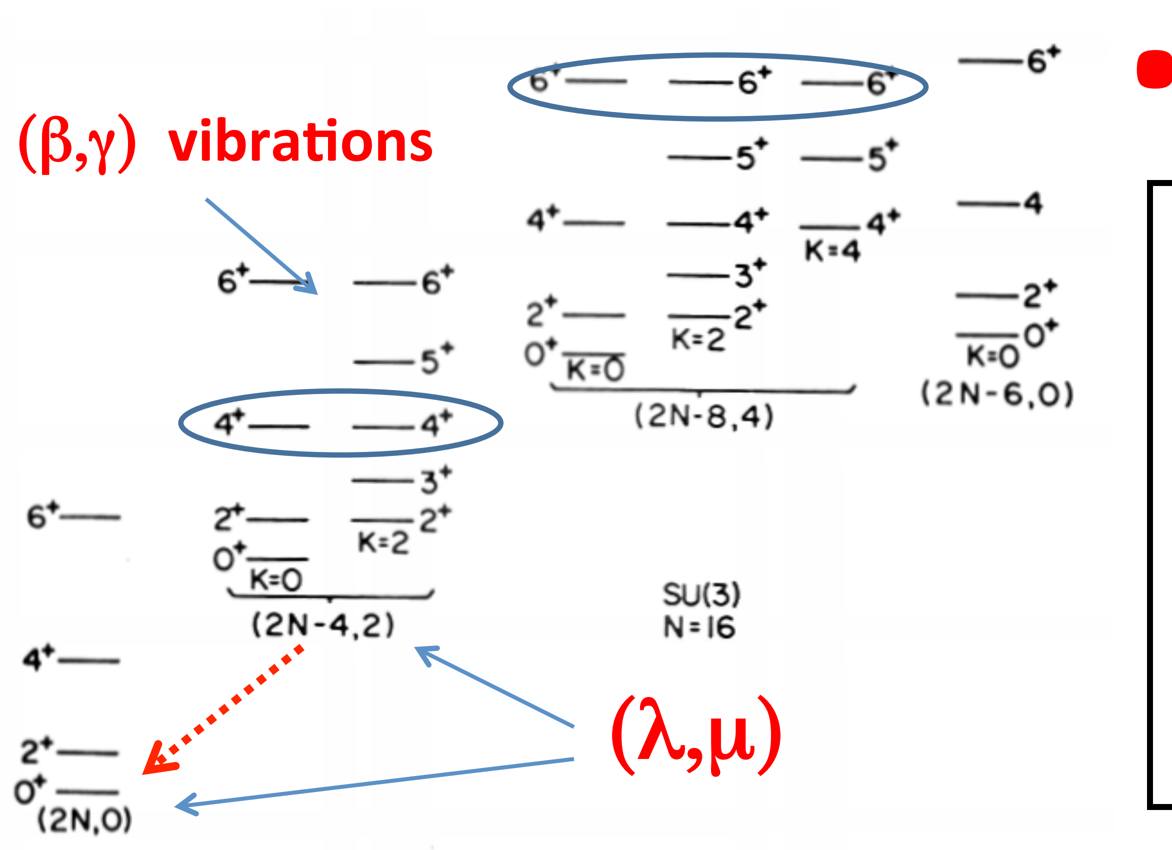






Typical SU(3) Scheme

(for N valence nucleons)



Characteristic signatures:

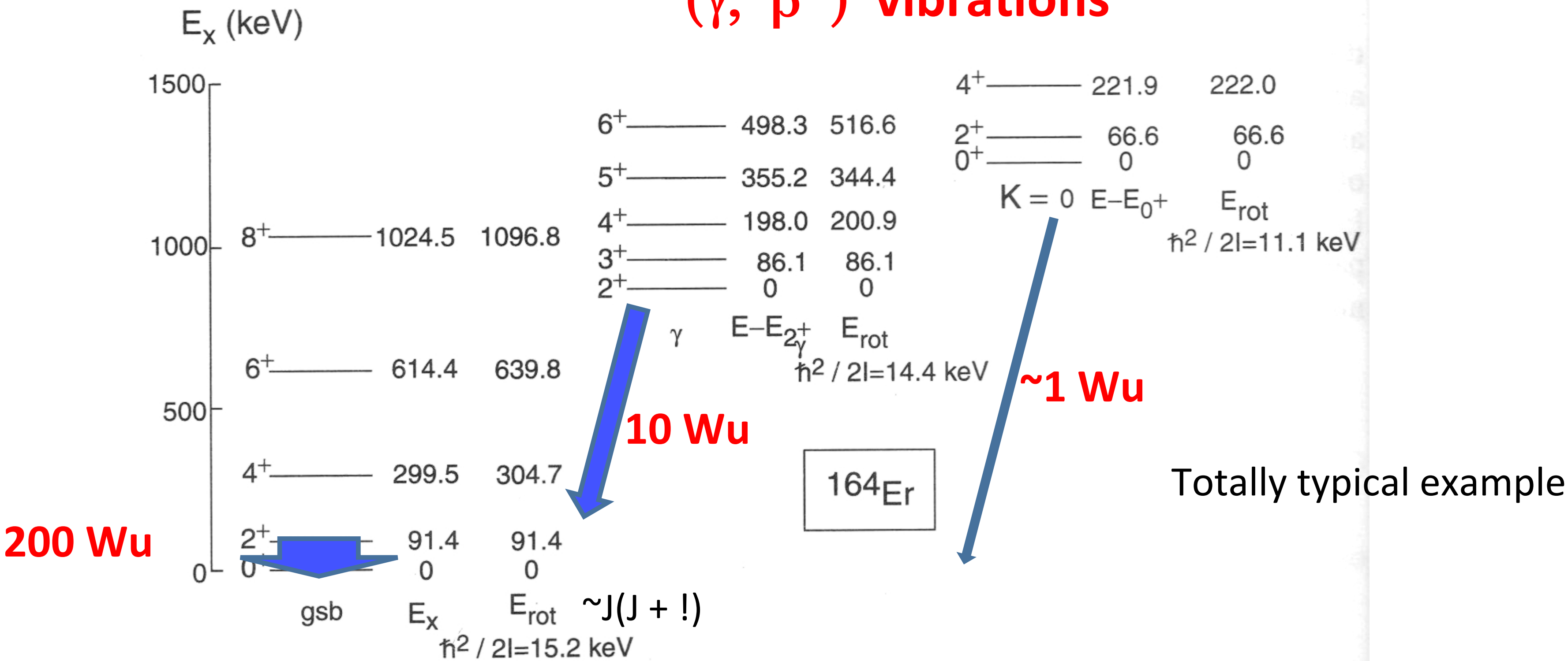
- **Degenerate bands within a group**
- **Vanishing B(E2) values between groups (cancelation in E2 operator)**

$$E(\lambda,\mu,J) = A[\lambda^2 + \mu^2 + \lambda\mu + 3(\lambda+\mu)] + BJ(J+1)$$

SU(3) O(3)

What do real nuclei look like – what are the data??

(γ,“β”) vibrations



Similar to SU(3). **But β,γ vibrations not degenerate and collective B(E2) values from γ to ground band. Most deformed rotors are not SU(3).**

Unfortunately, very few nuclei manifest an idealized structural symmetry exactly, limiting their direct role to that of benchmarks

Approach: parameterized collective Hamiltonians - break symmetries. (Since β band is not so collective, most exp focus has been on γ band.)

BUT (???) Partial Symmetries (to the rescue???)

However, something new is on the market with a proliferation of new "partial" and "quasi" dynamical symmetries (PDS, QDS)

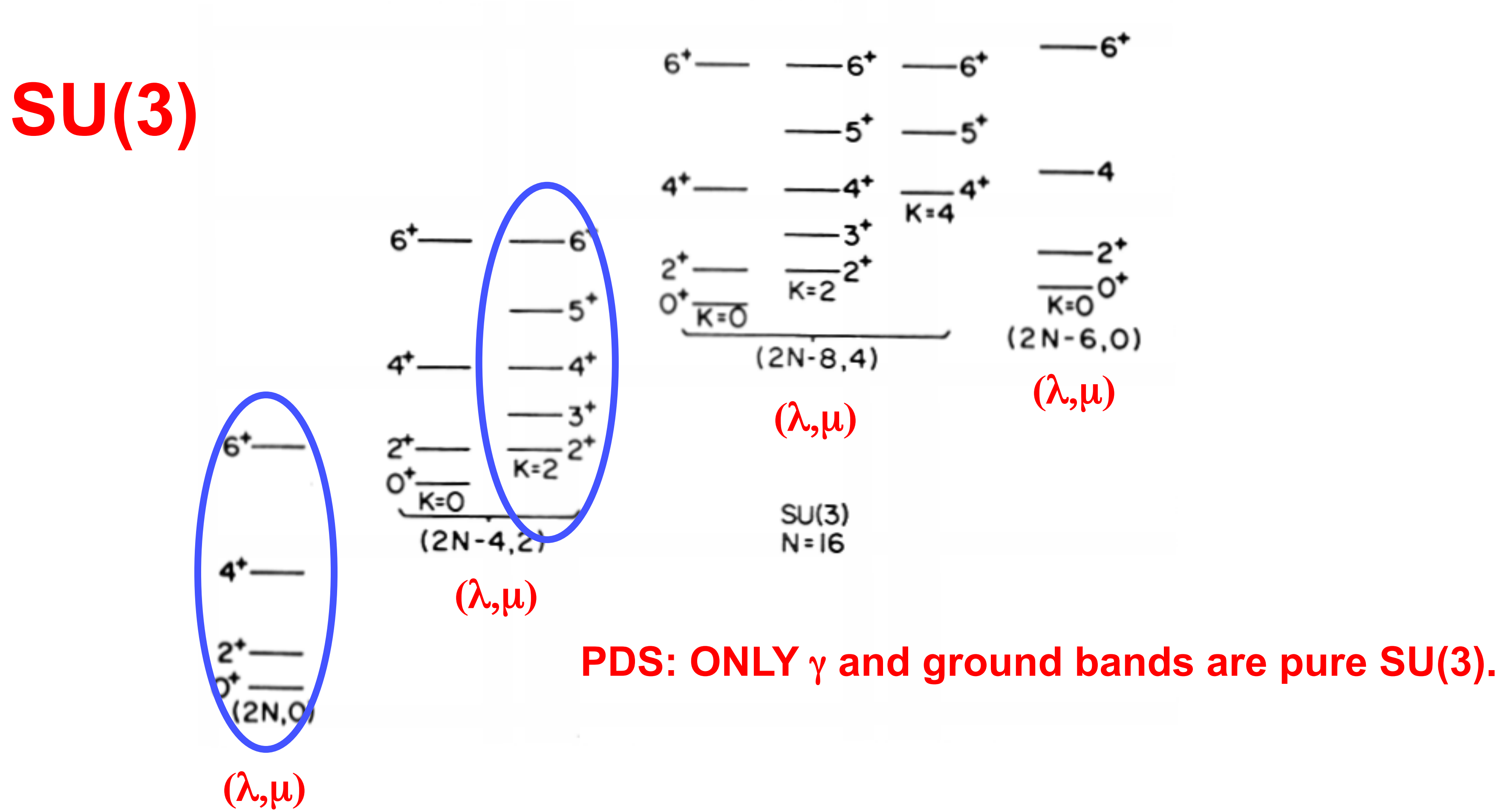
Possibility of a considerably expanded role of symmetry descriptions for nuclei

PDS: some features of a Dyn.Sym. persist even though there is considerable symmetry breaking.

Why do we need such a strange thing? We have excellent fits to data with parameterized numerical IBA and geometric collective model calculations that break SU(3).

[QDS: Some degeneracies characteristic of a symmetry persist and some of the wave function correlations persist.]

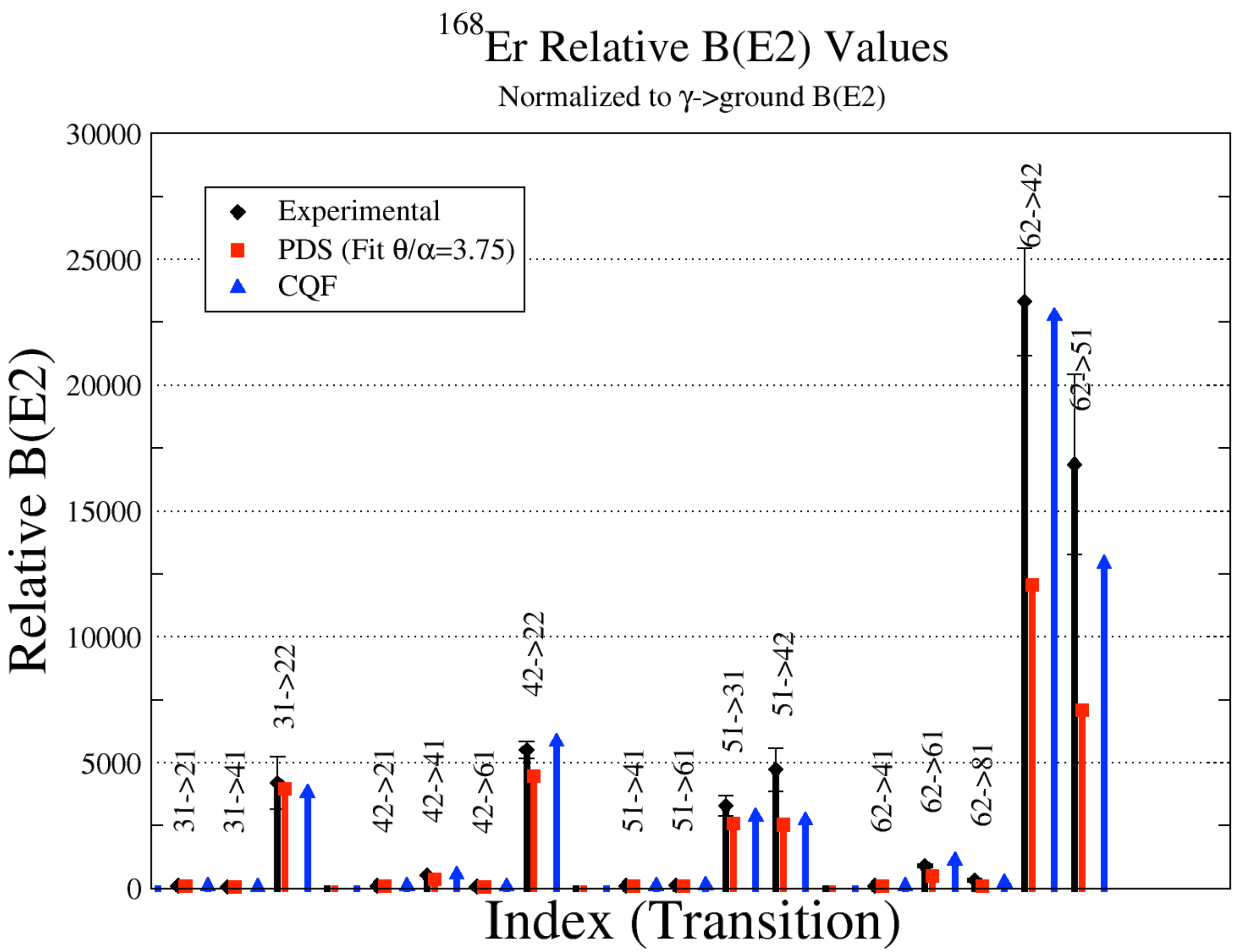
Partial Dynamical Symmetry (PDS)



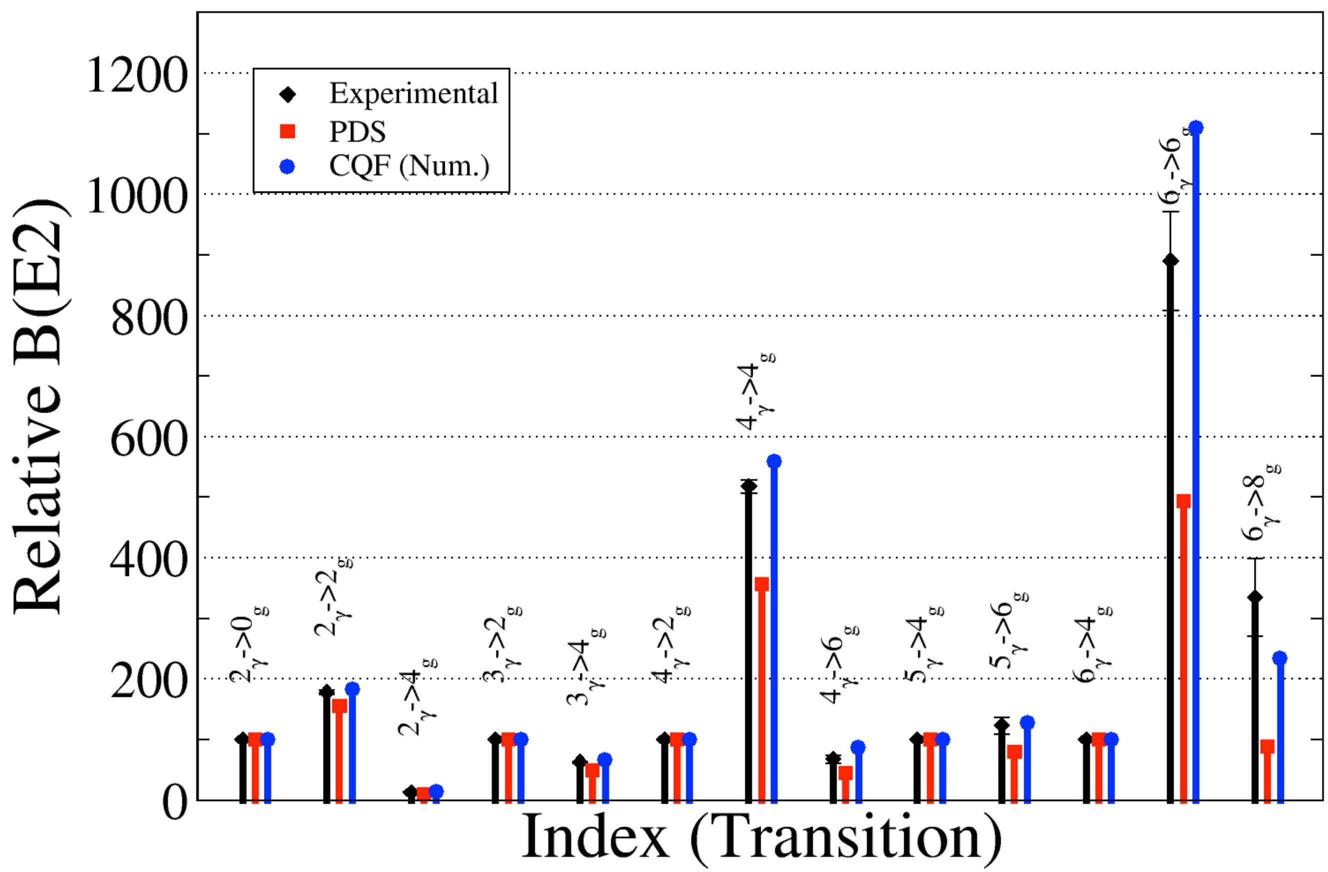
So, expect PDS to predict vanishing B(E2) values between these bands as in SU(3). But we saw that empirically these B(E2) values are collective! However, γ to ground B(E2)s are finite in the PDS by using the general E2 operator. Introduces a new parameter. BUT, branching ratios are PARAMETER FREE

Testing the PDS

Extensive test (60 nuclei) in rare earth, actinide, and A ~ 100 regions



^{168}Er Interband Relative B(E2) Values
Parameter free

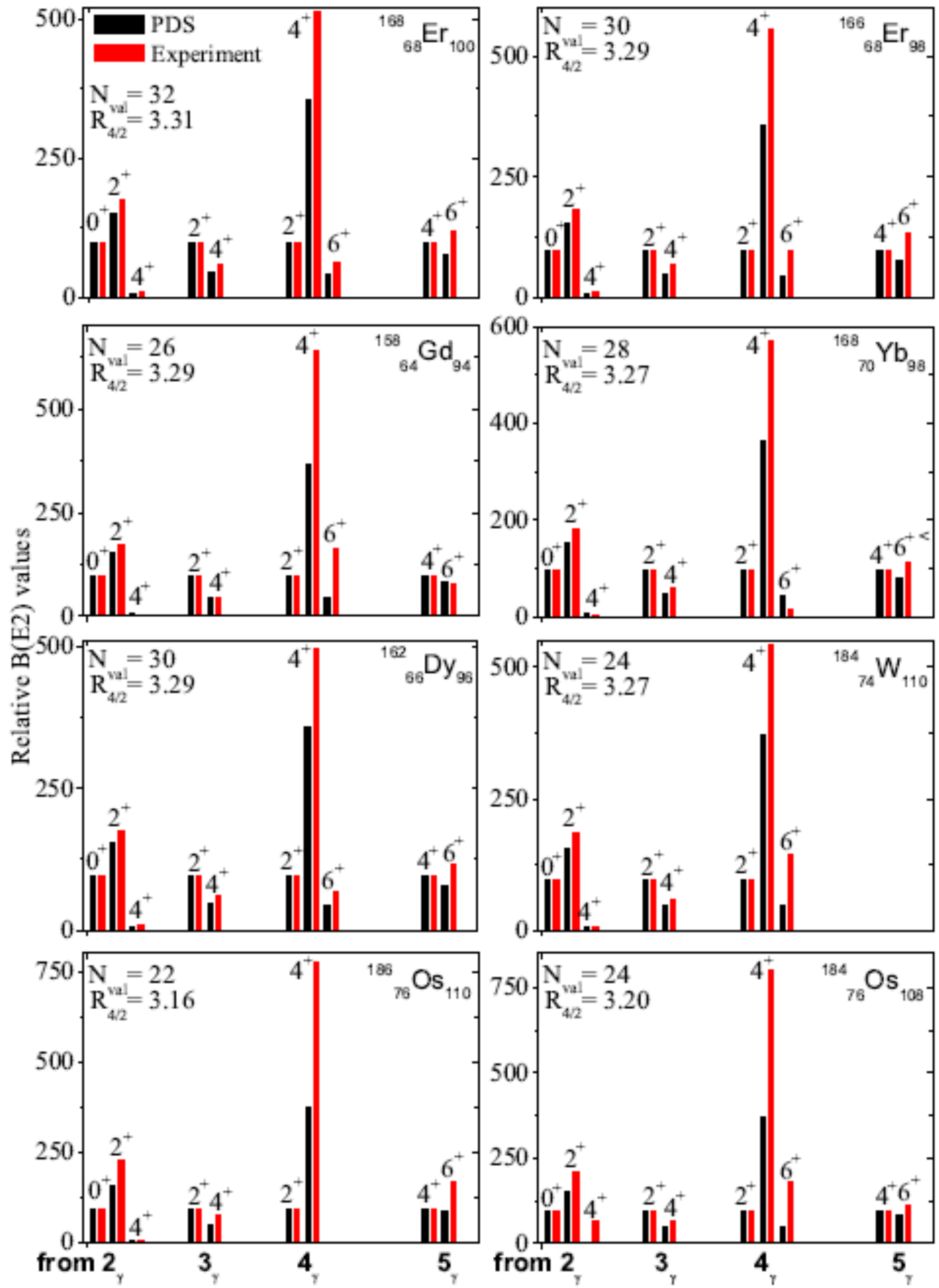


INTERBAND
γ –– ground

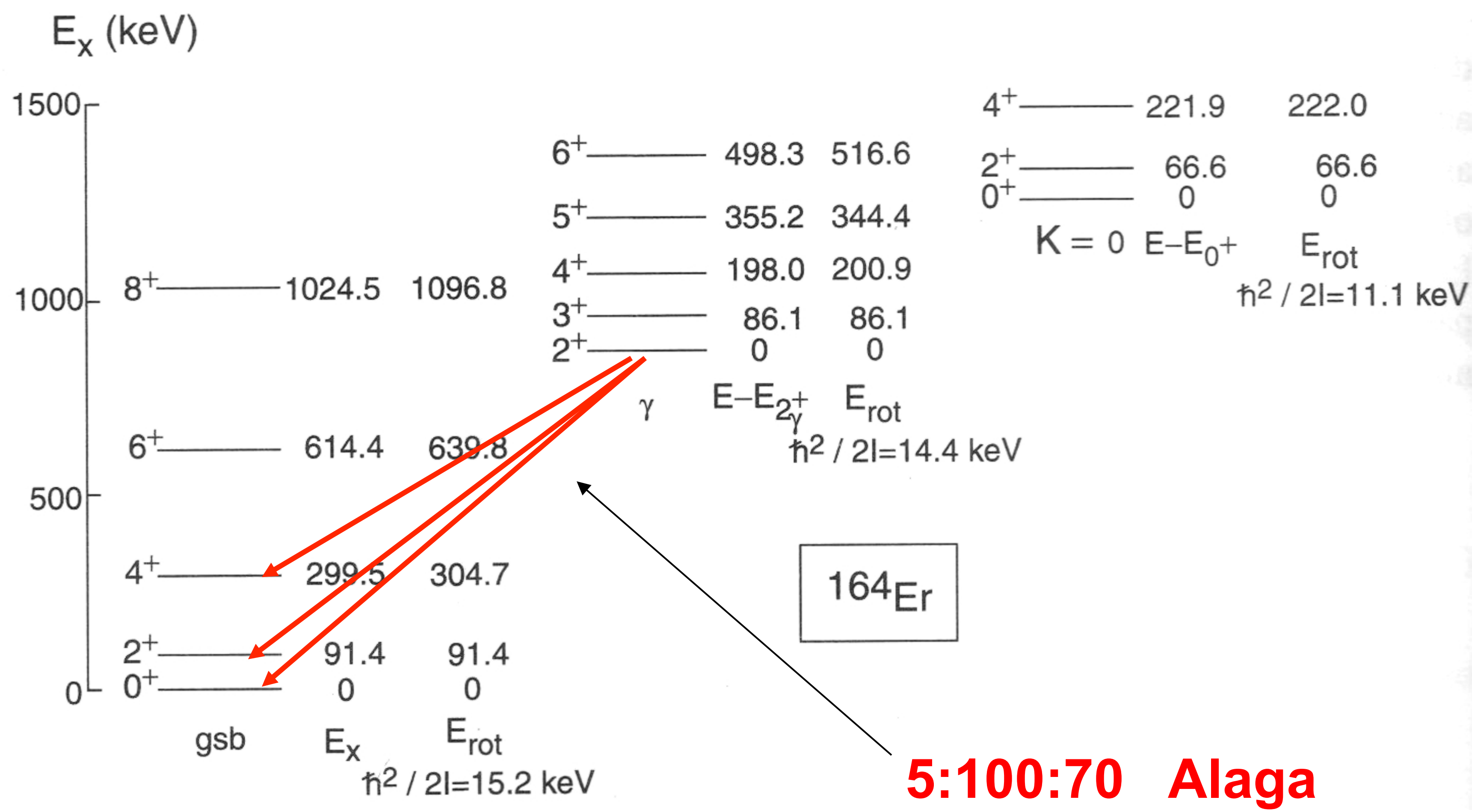
47(22) rare earth nuclei

Overall good agreement for well-deformed nuclei

Systematic disagreements for spin INcreasing transitions. Exp. stronger than PDS.



Lets look into these predictions and comparisons a little deeper. Compare to “Alaga Rules” – what you would get for a pure rotor for relative B(E2) values from one rotational band to another.



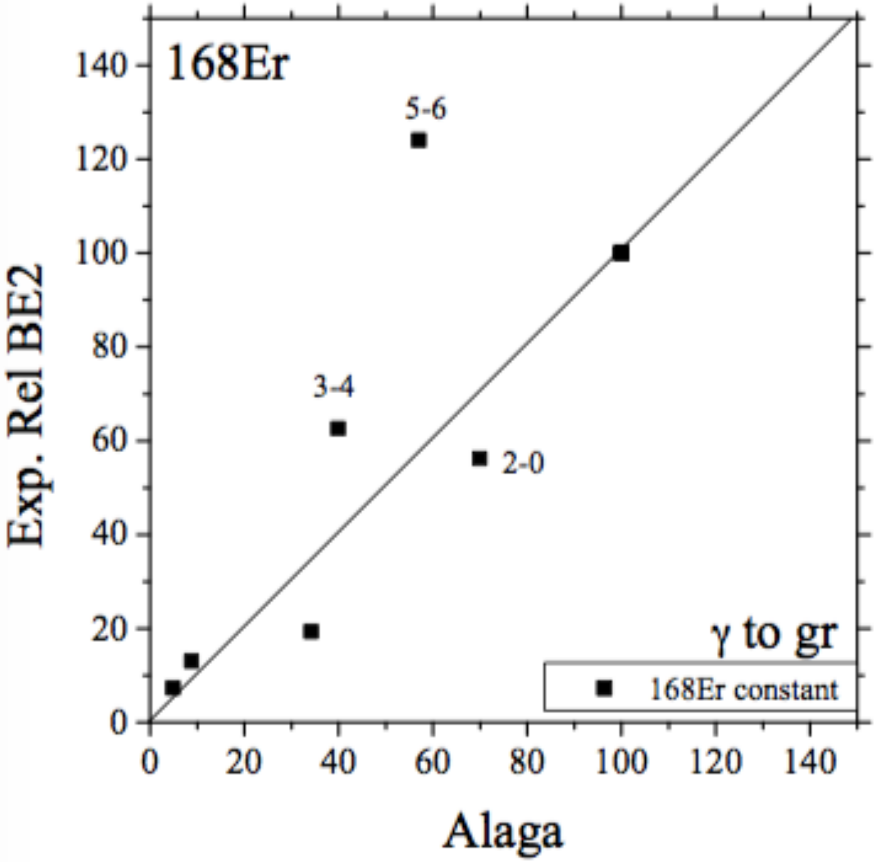
Data vs Alaga for γ band to ground band E2 transitions

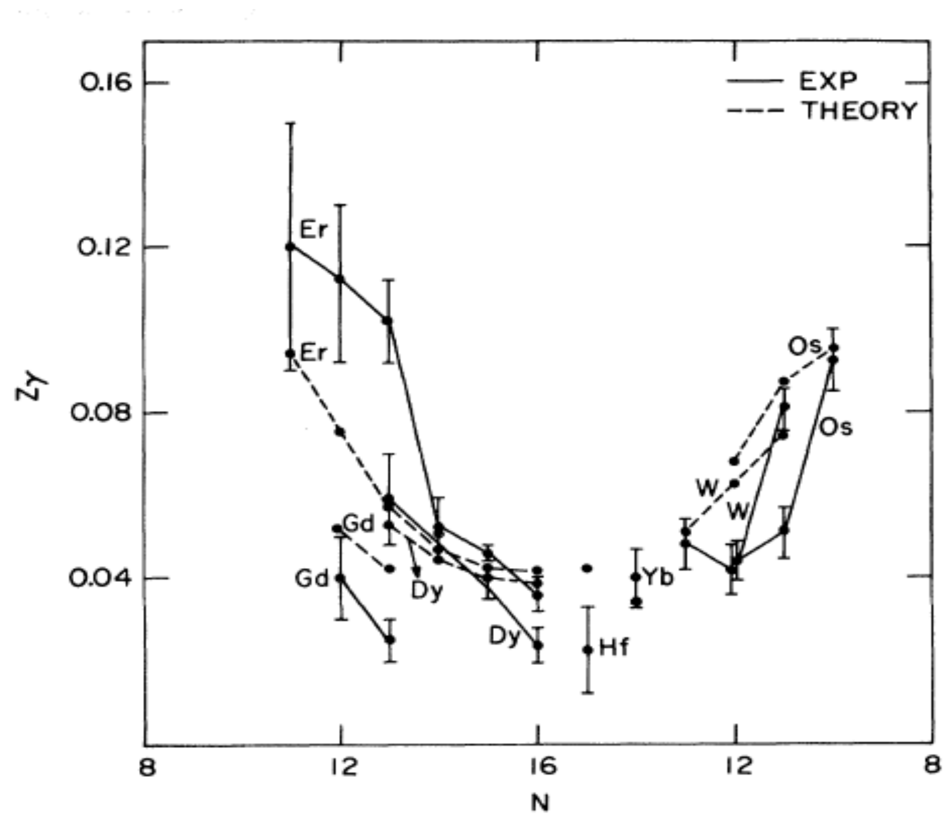
$I_i^\pi \rightarrow I_f^\pi$	^{168}Er	ALAGA
$2_\gamma^+ \rightarrow 0^+$	58.5	70
$2_\gamma^+ \rightarrow 2^+$	100	100.0
$2_\gamma^+ \rightarrow 4^+$	7.6	5.0
$3_\gamma^+ \rightarrow 2^+$	100	100
$3_\gamma^+ \rightarrow 4^+$	62.2	40
$4_\gamma^+ \rightarrow 2^+$	19.8	34
$4_\gamma^+ \rightarrow 4^+$	100	100
$4_\gamma^+ \rightarrow 6^+$	13.1	8.64
$5_\gamma^+ \rightarrow 4^+$	100	100.0
$5_\gamma^+ \rightarrow 6^+$	123.6	57.1
$6_\gamma^+ \rightarrow 4^+$	11.3	26.9
$6_\gamma^+ \rightarrow 6^+$	100	100
$6_\gamma^+ \rightarrow 8^+$	37.7	10.6

Spin **DE**creasing transitions smaller than Alaga
Spin **IN**creasing transitions larger than Alaga;
Deviations **increase** with J

These are signature characteristics of mixing
of γ and ground band intrinsic excitations.

Characteristic signatures of γ – ground mixing

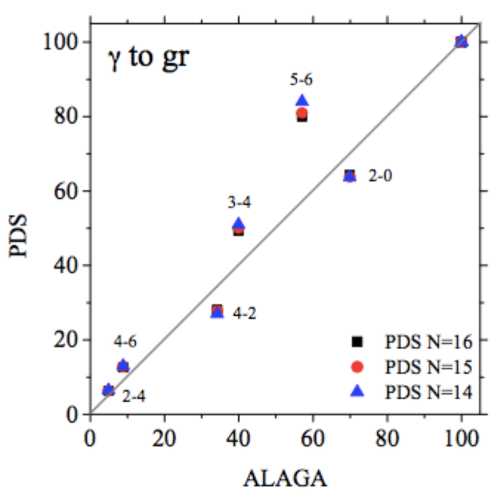




Works extremely well: mixing parameter Z_γ

168-Er: Alaga, PDS, valence space, and mixing

$I_i^\pi \to I_f^\pi$	^{168}Er	ALAGA	PDS	WCD	CQF
$2_\gamma^+ \to 0^+$	58.5	70	64.3	66	54
$2_\gamma^+ \to 2^+$	100	100.0	100	100	100
$2_\gamma^+ \to 4^+$	7.6	5.0	6.3	6	8
$3_\gamma^+ \to 2^+$	100	100	100	100	100
$3_\gamma^+ \to 4^+$	62.2	40	49.3	48	69
$4_\gamma^+ \to 2^+$	19.8	34	28.1	30	18
$4_\gamma^+ \to 4^+$	100	100	100	100	100
$4_\gamma^+ \to 6^+$	13.1	8.64	12.5	12	16
$5_\gamma^+ \to 4^+$	100	100.0	100	100	100
$5_\gamma^+ \to 6^+$	123.6	57.1	79.6	72	125
$6_\gamma^+ \to 4^+$	11.3	26.9	20.3	23	9
$6_\gamma^+ \to 6^+$	100	100	100	100	100
$6_\gamma^+ \to 8^+$	37.7	10.6	18.0	17	20



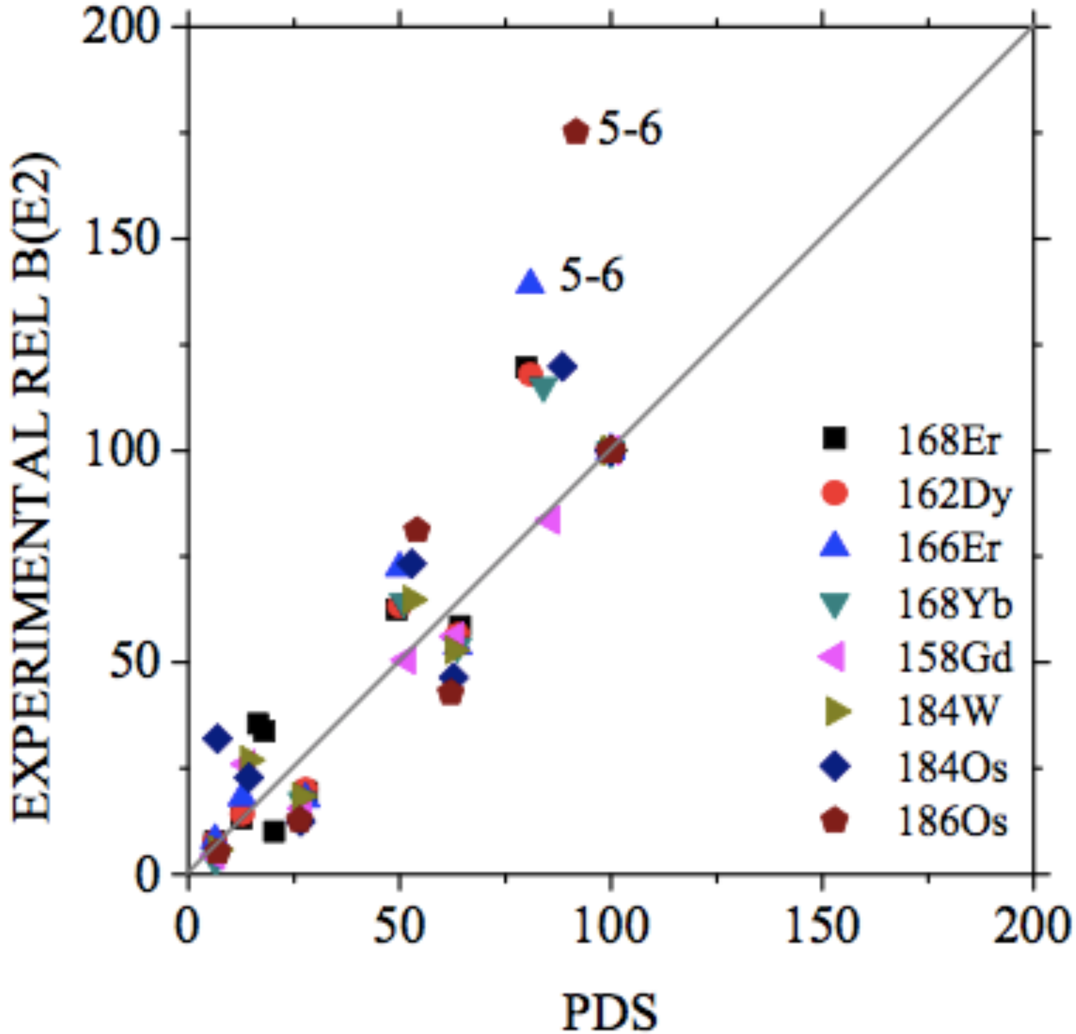
PDS always closer to data than Alaga. PDS simulates bandmixing without mixing. PDS has pure γ, gr bands

Why differs from Alaga? Ans: PDS (from IBA) is valence space model: predictions are N_{val} – dep. (Sole reason)

CQF: Numerical IBA calculation with one parameter. Works well.

Why two such different descriptions give similar predictions?

Overview Exp vs PDS

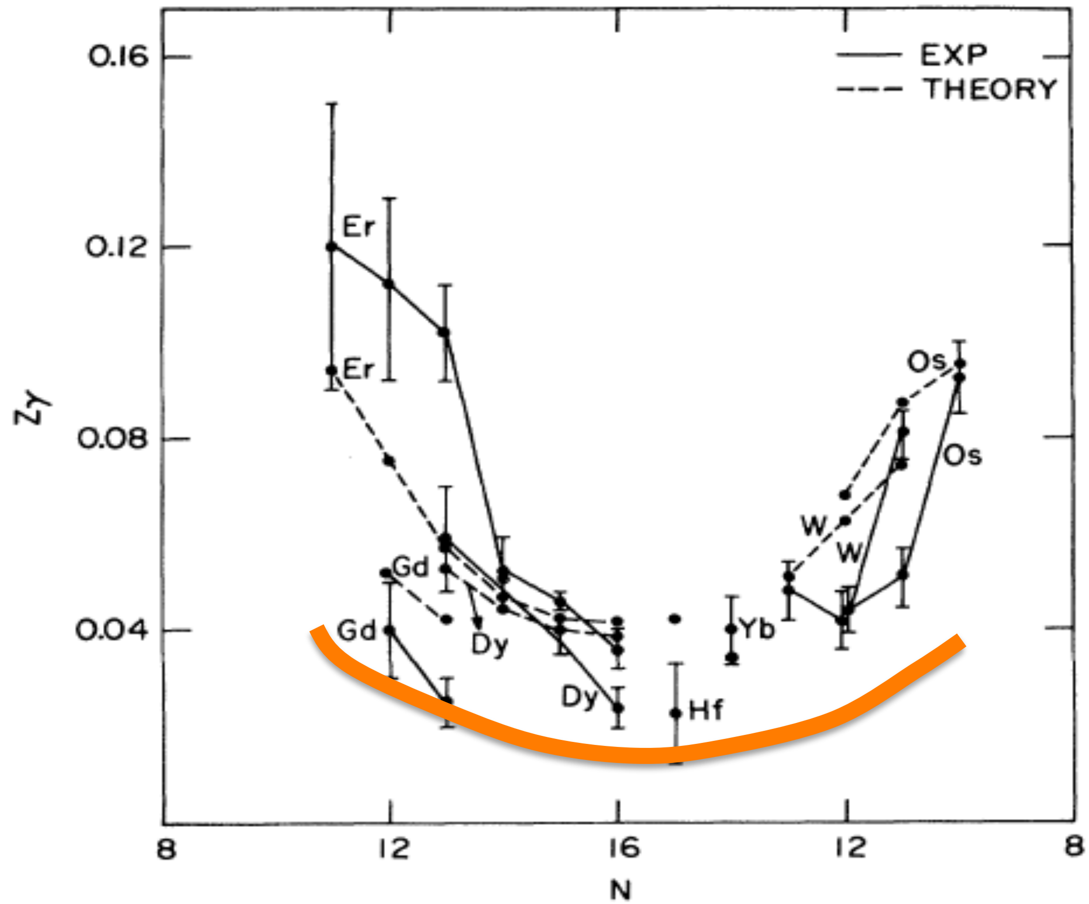


Deviations from PDS indicate some other degree of freedom. Grow with spin. Suggest bandmixing. But, clearly much less bandmixing is needed than before PDS.

Bandmixing and deviations from Alaga

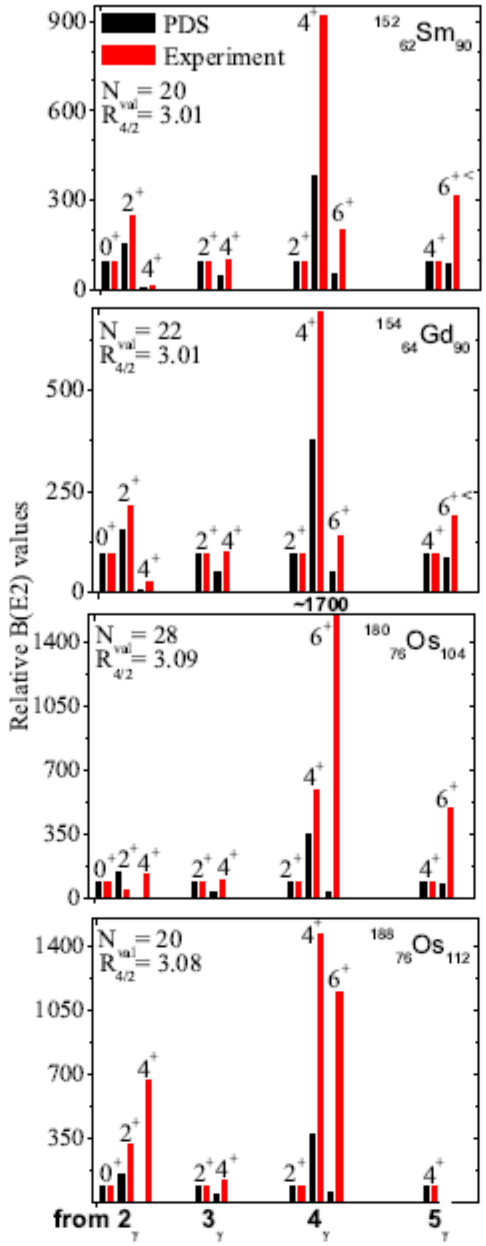
Finite N effects have same effects as mixing on Rel. B(E2) values.

So, new (net) mixing is about half what we have thought for 50 yrs. [(e.g., Z_γ (^{168}Er) changes from ~0.042 to 0.019]



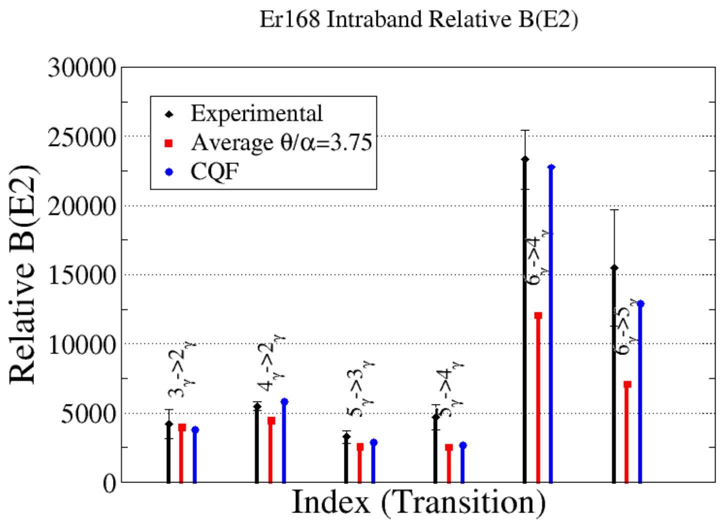
Recognition of importance of purely finite nucleon number effects. Reduced need for mixing. How to distinguish from interactions? What observables?

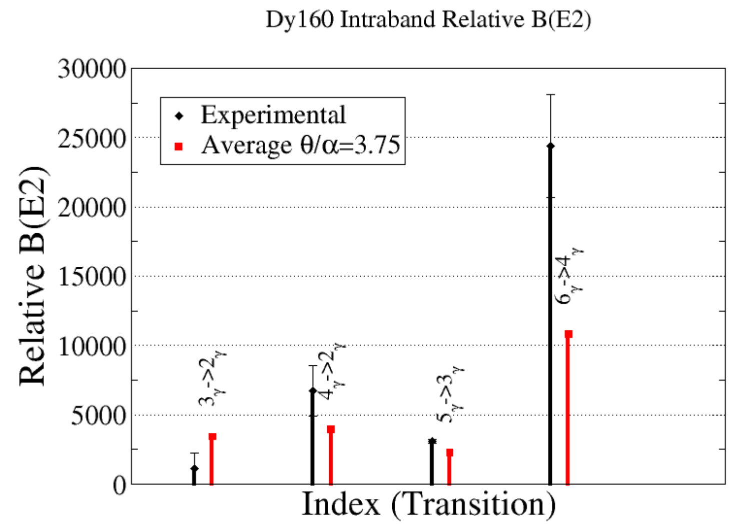
Transitional nuclei: How does PDS perform?

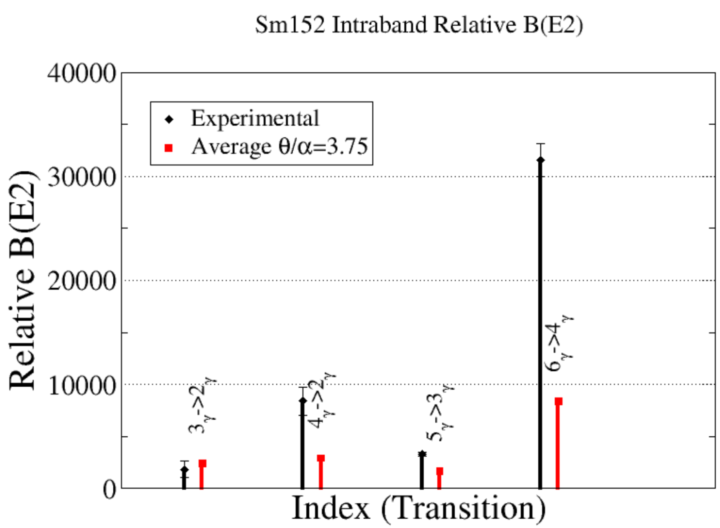


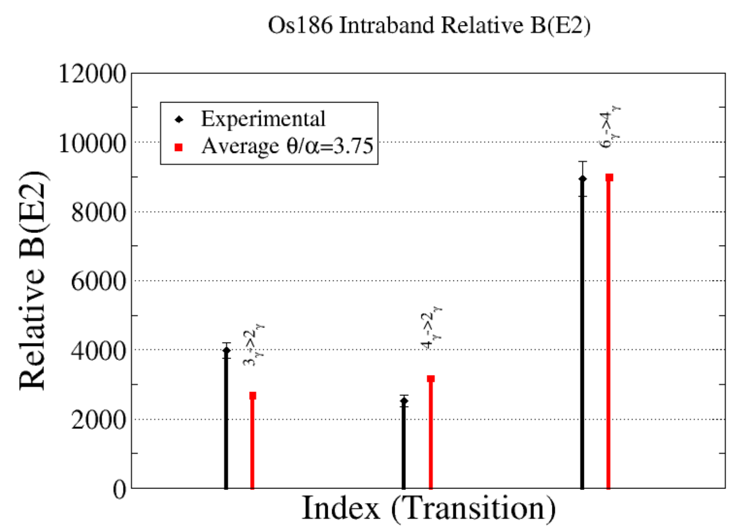
Intraband Transitions within γ band

These transitions depend on one parameter per nucleus, called θ/α:
A single average value suffices for all the rare earth nuclei (except ^{156}Dy).

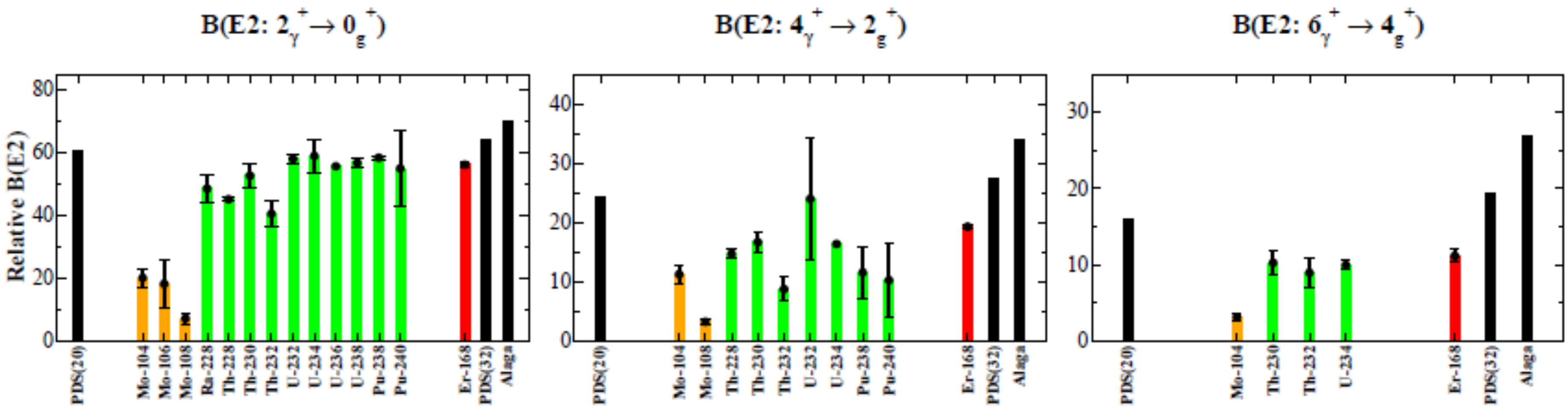








Actinides and A ~ 100 as function of spin



Spin decreasing B(E2) values get smaller with increasing spin.

Clear signal of a mixing effect since the K mixing matrix elements increase with spin: $V_{mix} \sim J_{init}$

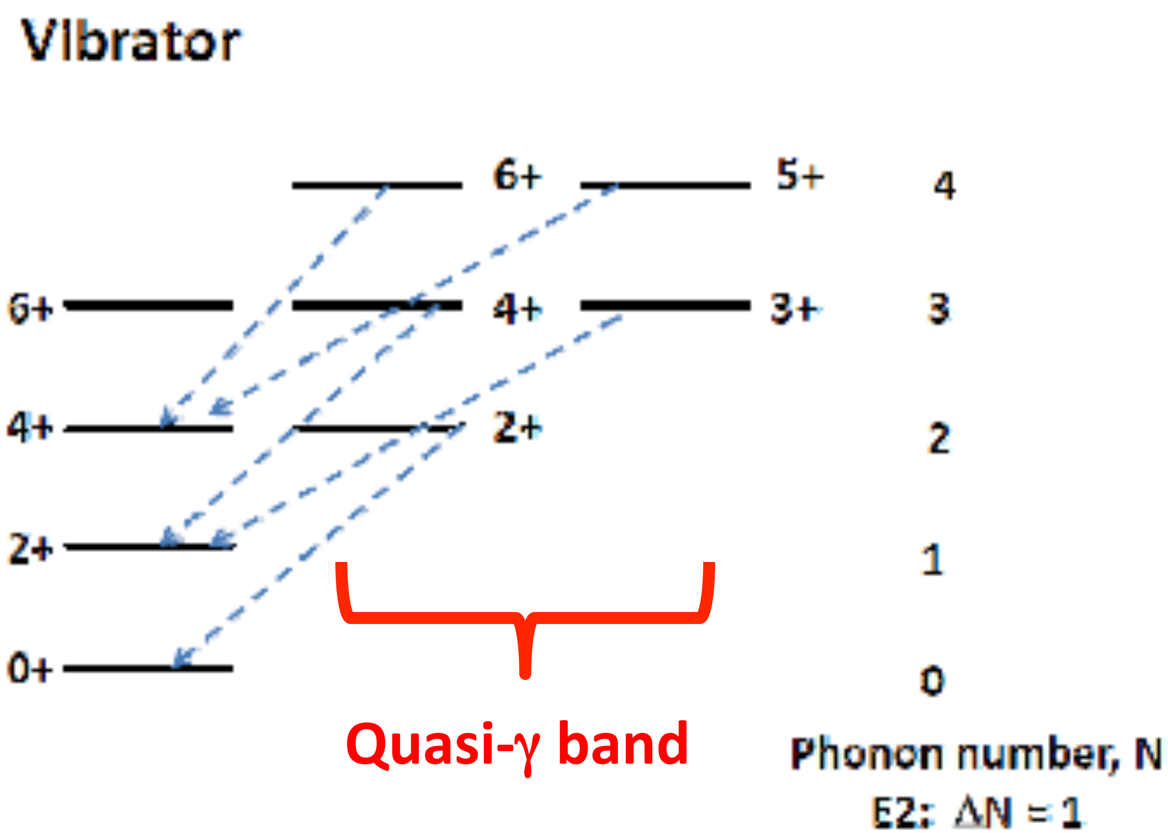
Data desperately needed (Missing transitions, no δ's at all)

TABLE I. Relative B(E2) values for the actinides.[a]

$J_i^\pi \to J_f^\pi$	PDS	^{228}Ra	^{228}Th	^{230}Th	^{232}Th[b]	^{232}U	^{234}U	^{236}U[c]	^{238}U[b]	^{238}Pu	^{240}Pu	^{168}Er	PDS	ALAGA
N_{val}	20	20	20	22	24	24	26	28	30	30	32	32	32	
$R_{4/2}$		3.21	3.23	3.23	3.28	3.29	3.30	3.30	3.30	3.31	3.31	3.31		
$2_\gamma^+ \to 0_g^+$	60.9	48.6 (42)	45.2 (7)	52.7 (39)	40.6 (40)	58.1 (16)	59.0 (52)[d]	55.7	56.8 (16)	58.4 (6)	55 (12)	56.2 (11)	64.0	70
$2_\gamma^+ \to 2_g^+$	100	100	100	100	100	100	100	100	100	100	100	100	100	100
$2_\gamma^+ \to 4_g^+$	6.9		4.0 (2)	7 (3)		5.7 (2)	5.6 (7)		6.2 (4)	5.6 (1)		7.3 (4)	6.2	5
$3_\gamma^+ \to 2_g^+$	100	100	100	100	100	100	100	100		100	100	100	100	100
$3_\gamma^+ \to 4_g^+$	55.6	53.2 (42)	68.3 (24)	62 (10)	55 (13)	55.0 (45)	42.5 (55)	23.2		50.6 (8)	52 (7)	62.6 (14)	49.3	40
$4_\gamma^+ \to 2_g^+$	24.4		14.8 (7)	16.7 (16)	9 (2)	24 (10)	16.4			11.6 (43)	10 (6)	19.3 (4)	27.5	34
$4_\gamma^+ \to 4_g^+$	100		100	100	100	100	100			100	100	100	100	100
$4_\gamma^+ \to 6_g^+$	14.6		6.3 (14)	28 (7)	19 (6)		4.7 (4)				480 (130)	13.1 (12)	12.0	8.64
$5_\gamma^+ \to 4_g^+$	100			100	100		100	100				100	100	100
$5_\gamma^+ \to 6_g^+$	96.4			184 (18)	174 (19)		98.7					123 (14)	79.6	57.1
$6_\gamma^+ \to 4_g^+$	16.0			10.3 (16)	9 (2)		10.0 (6)					11.2 (10)	19.3	26.9
$6_\gamma^+ \to 6_g^+$	100			100	100		100					100	100	100
$6_\gamma^+ \to 8_g^+$	21.9						14.7 (15)					37.6 (72)	16.7	10.6

Why are Mo B(E2) values weaker?
Transitional nuclei ($R_{4/2}$ ~ 2.5) – between rotor and vibrator

All spin DEcreasing γ band to ground band transitions are forbidden in the vibrator limit



Using the PDS to better understand collective model calculations (and collectivity in nuclei)

- PDS B(E2: γ – gr): sole reason differ from Alaga rules is they take account of the finite number of valence nucleons.

  Why do nucleon number effects simulate bandmixing?

- IBA – CQF deviates further from the Alaga rules, agrees better with the data (but has one more parameter).

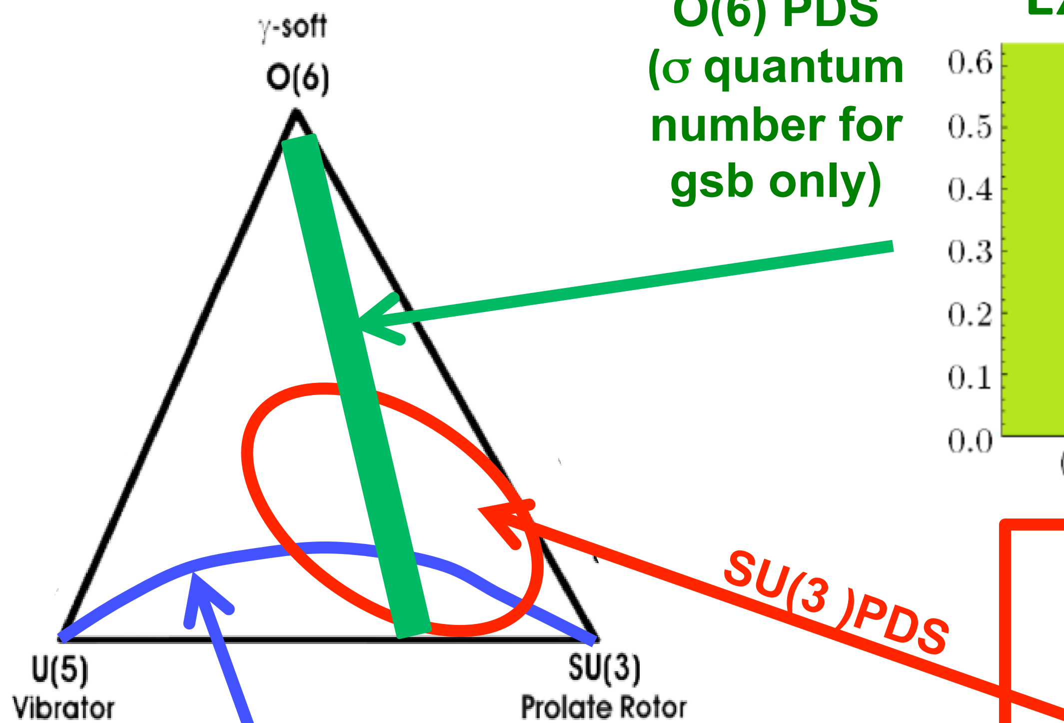
- IBA – CQF: The differences from the PDS are due to mixing.

- Can use the PDS to disentangle valence space from mixing!

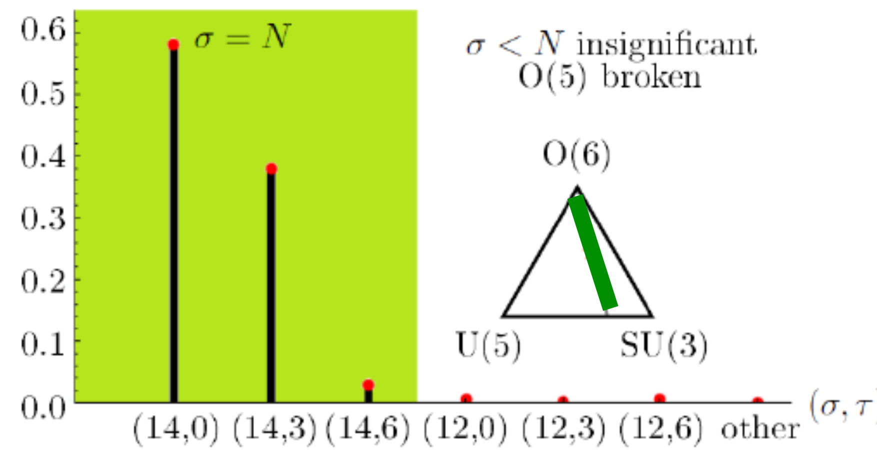
- δ values are sorely needed.

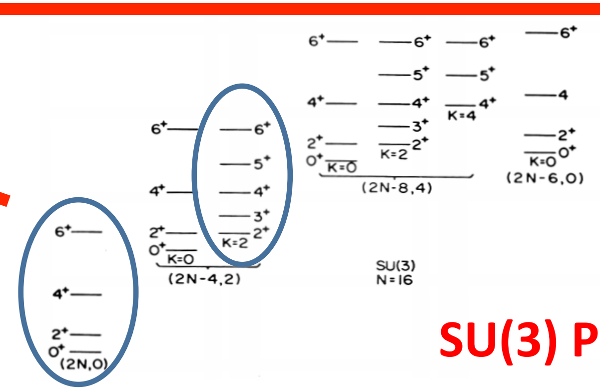
Partial, quasi dynamical symmetries in the symmetry triangle
(Color coded guide)

O(6) PDS
(σ quantum number for gsb only)



Expansion in O(6) basis (σ,τ)

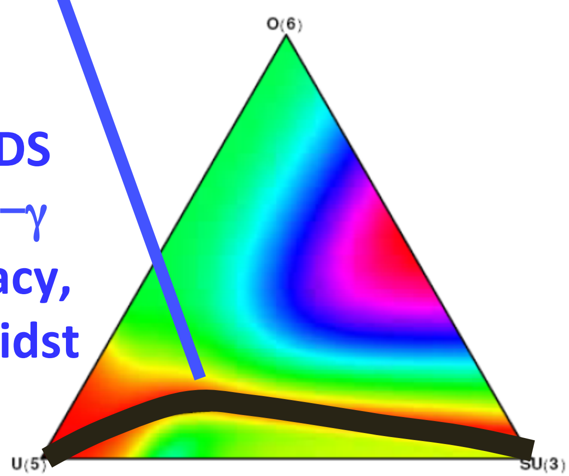




SU(3) PDS

γ, ground states pure SU(3). Others highly mixed. Valid in *most* deformed nuclei! Relation to previous models.

SU(3) QDS
Arc of $\beta-\gamma$ degeneracy, order amidst chaos



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Congratulations Angela and Adam for your wonderful research careers and your service to our community and beyond.

May this continue for years to come.

Happy Birthdays

(to my much younger colleagues)