How I see nuclear structure study: by John, as presented by Nico

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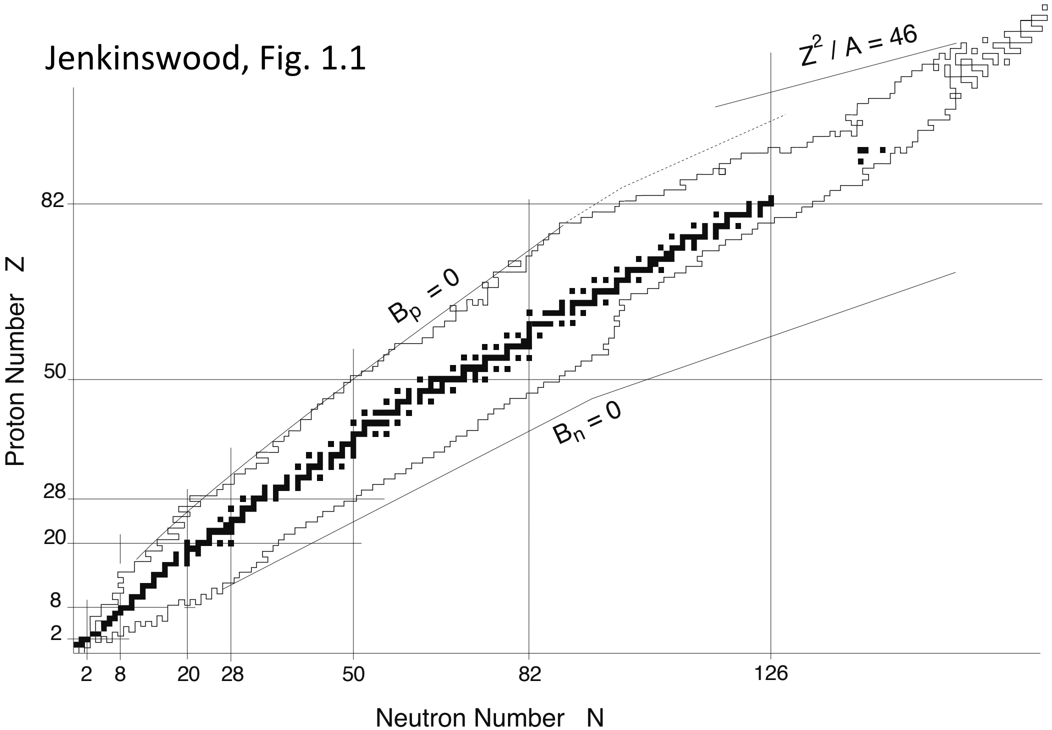
Reference:
"Nuclear Data: a Primer", David G. Jenkins and John L. Wood,
IOP Series in Nuclear Spectroscopy and Nuclear Structure,
eds. JLW, DGJ (U. York), and Kris Heyde (U. Gent), Vol. 3, tbp early 2021
-- "Jenkinswood"

PART I.

SOME BASIC FEATURES OF NUCLEAR STRUCTURE

The Arena: Chart of the Nuclides

Jenkinswood, Fig. 1.1



We are studying a many-body problem:

we must *systematically* acquire data as a function of A, Z, and N;

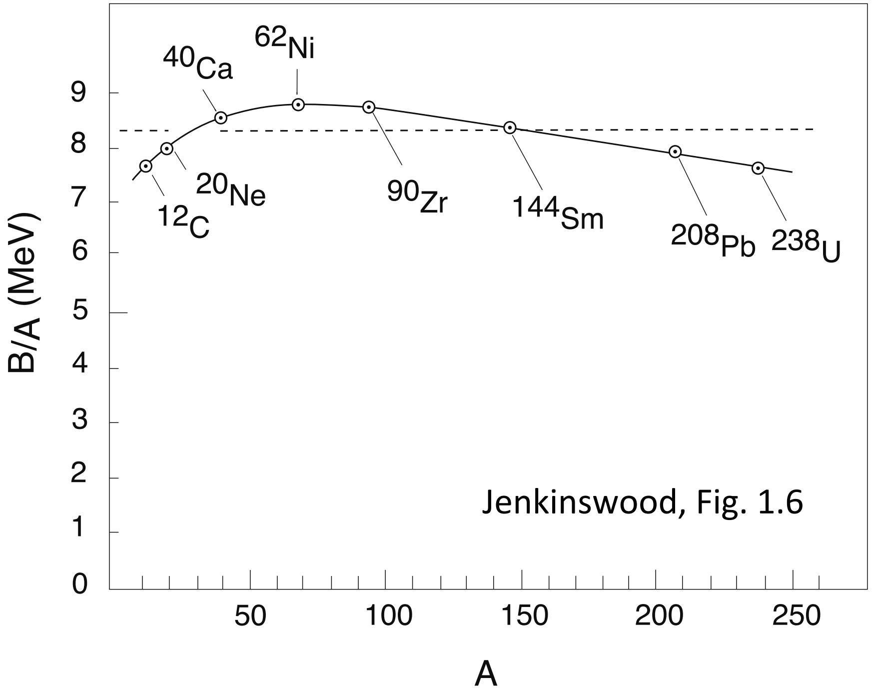
we possess access to the many-body "parameters" at the level of precise selection of A (mass separation) and Z (charge selectivity) and, therefore N;

we possess a large selection of spectroscopic techniques (multi-faceted "eyes").

The nucleus is a fundamental level of organization of matter.

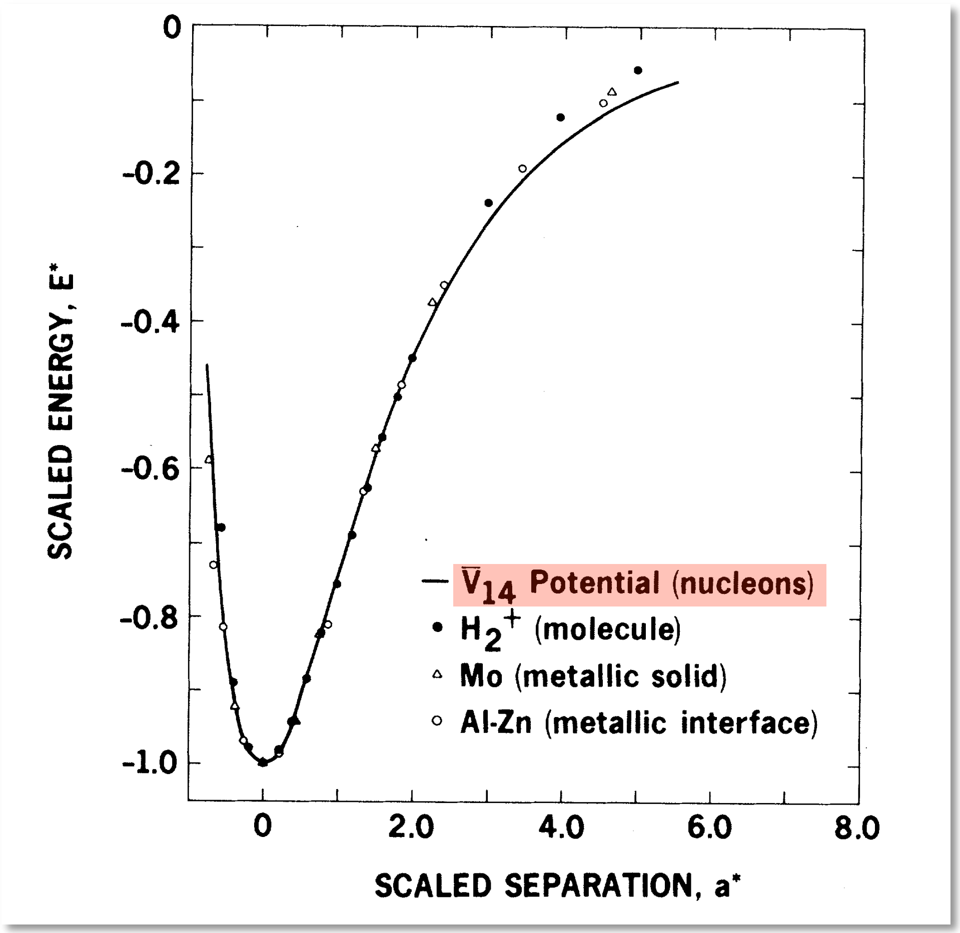
The nucleus is a unique manifestation of many-body quantum mechanics.

The force that binds nucleons together in nuclei is short ranged



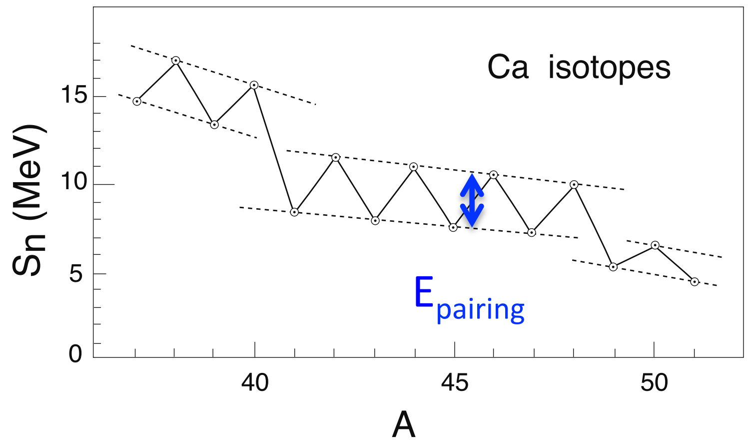
Classes of bound systems exhibiting the same scaled potential energy vs. distance curves— over 21 orders of magnitude in density—

J.H. Rose et al., Phys. Rev. lett. 53 (1984) 344.



Nuclei:
binding energy per nucleon is independent of the size of the system; much as water boils (becomes unbound) at the same temperature (energy) for all bulk amounts.

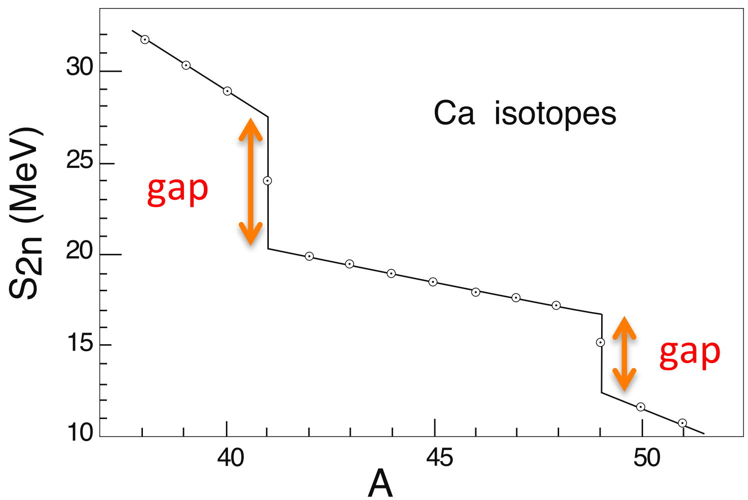
Differential binding energies:
(separation energies, S_n, S_{2n}) reveal quantum structure



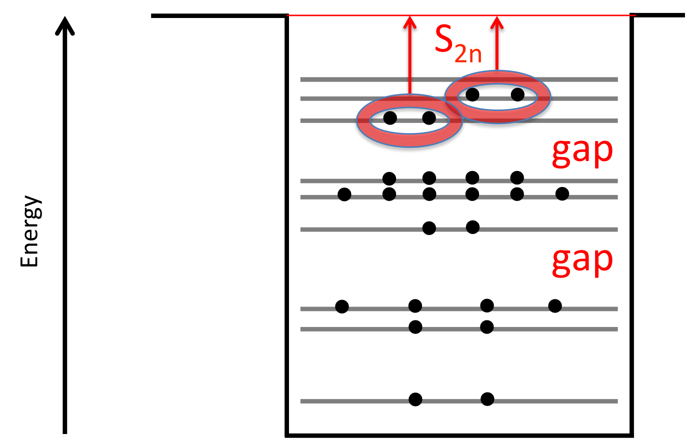
Jenkinswood, Fig. 1.10

Staggering in S_n reveals pairing "correlations" in nuclei.

Steps in S_{2n} reveal energy (shell) gaps.

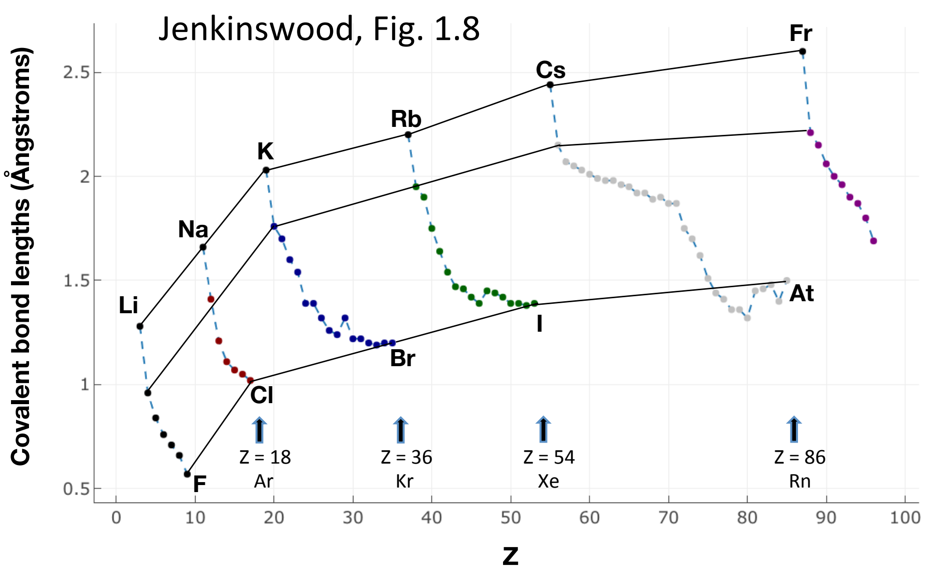


Jenkinswood, Fig. 1.11

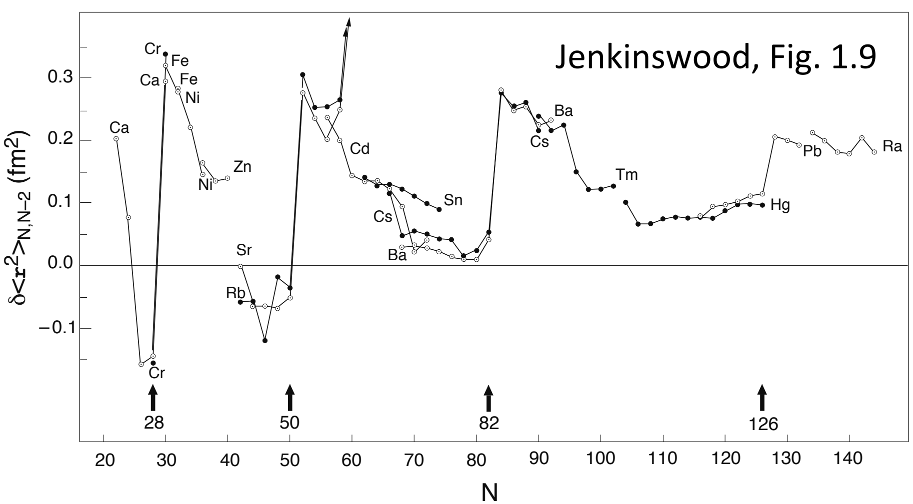


Jenkinswood, Fig. 1.12

Bond lengths and isotope shifts, $\delta\langle r^2\rangle$ reveal quantum structure (energy shells) in atoms and nuclei



Sudden increases in chemical bond lengths match shell gaps in atoms (1Å = 0.1nm).

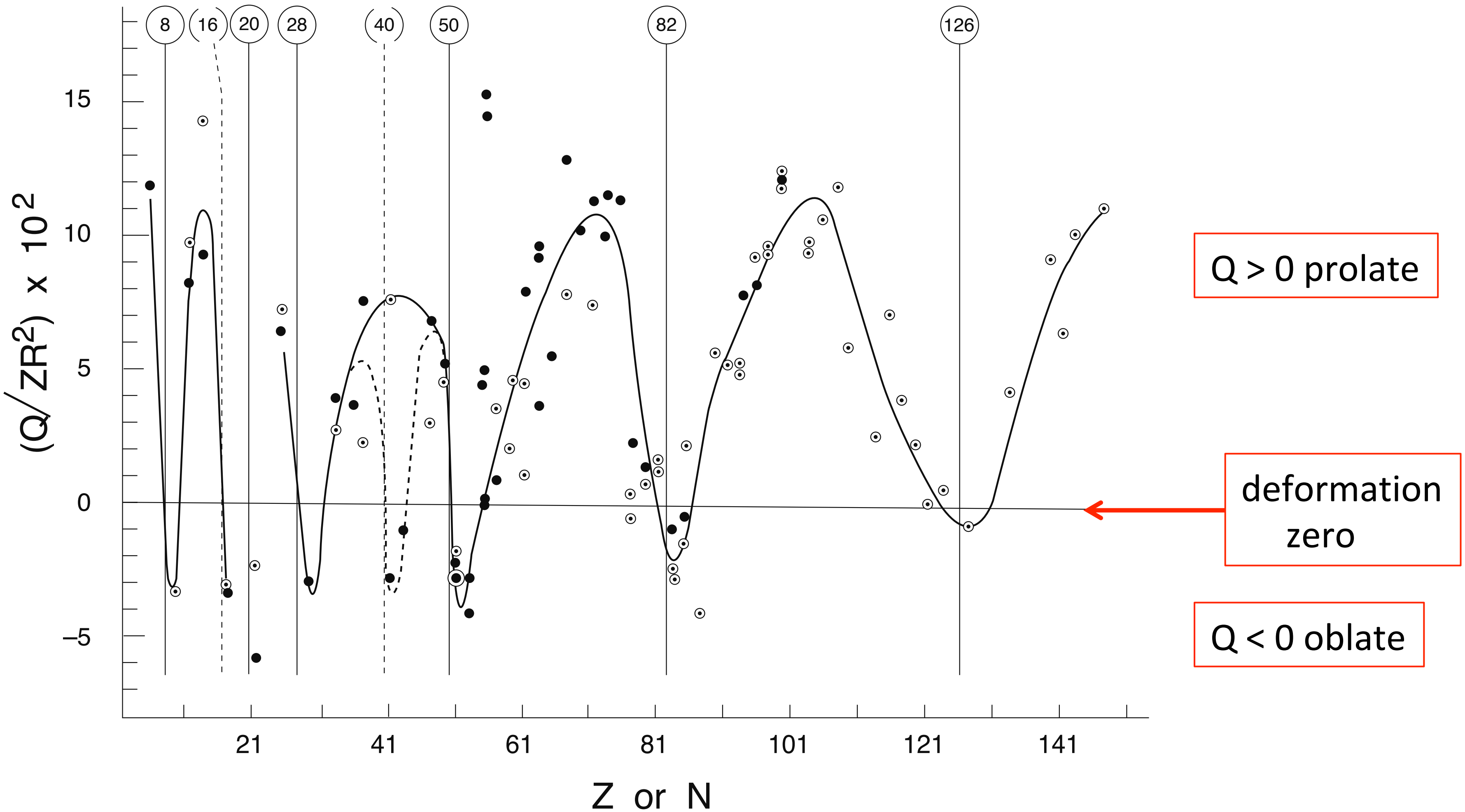


Sudden increases in $\delta\langle r^2\rangle$ match shell gaps from S_{2n}.

Nucleons in nuclei and electrons in atoms can behave as independent particles.

QUADRUPOLE MOMENTS OF NUCLEAR GROUND STATES:

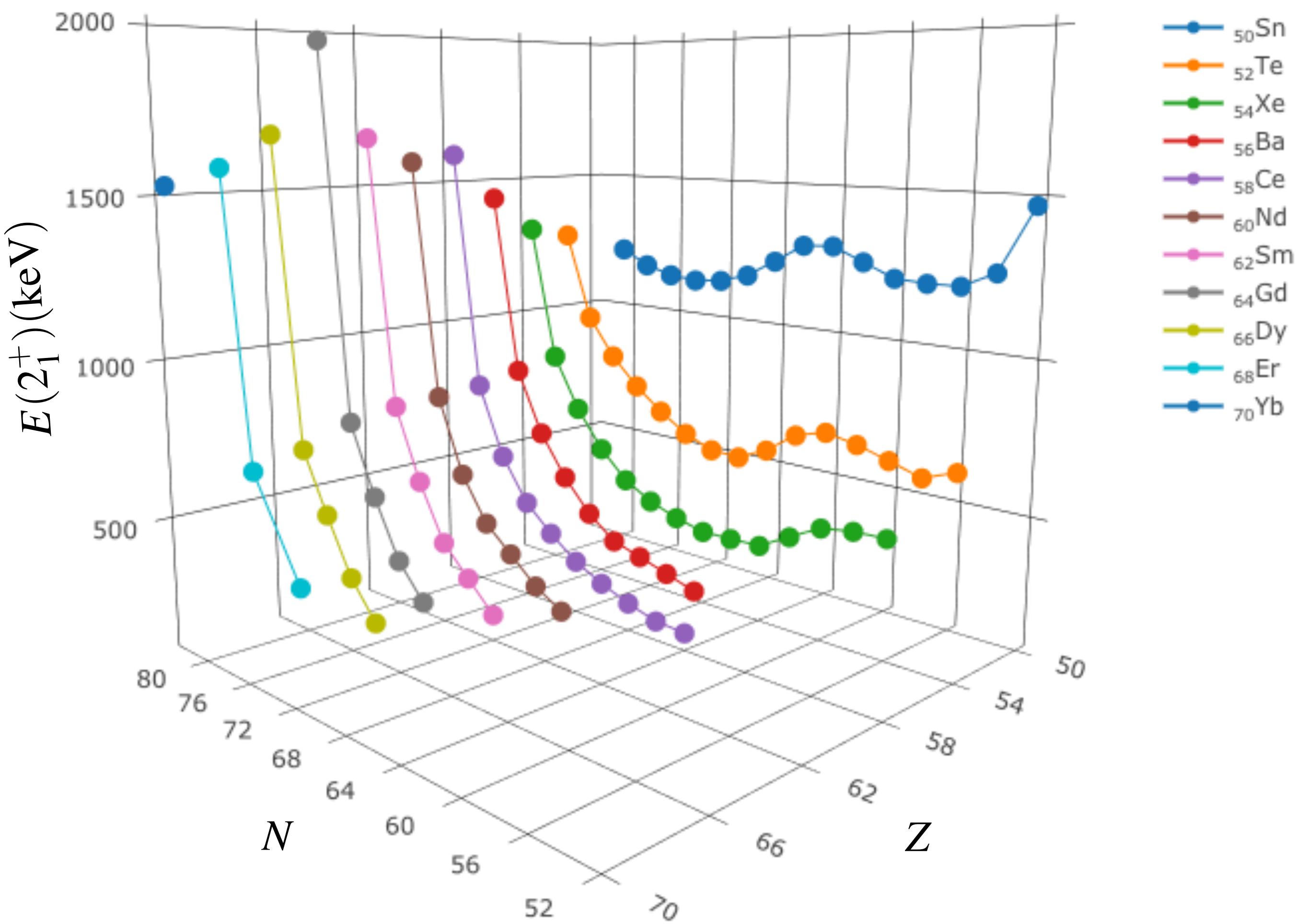
nuclei are (usually) spherical at closed shells, but always have large deformations far from closed shells (all prolate)



Jenkinswood, Fig. 1.14

EVEN-EVEN NUCLEI:

most have first excited states with spin-parity 2^+,
with high energies at closed shells, low energies far from closed shells



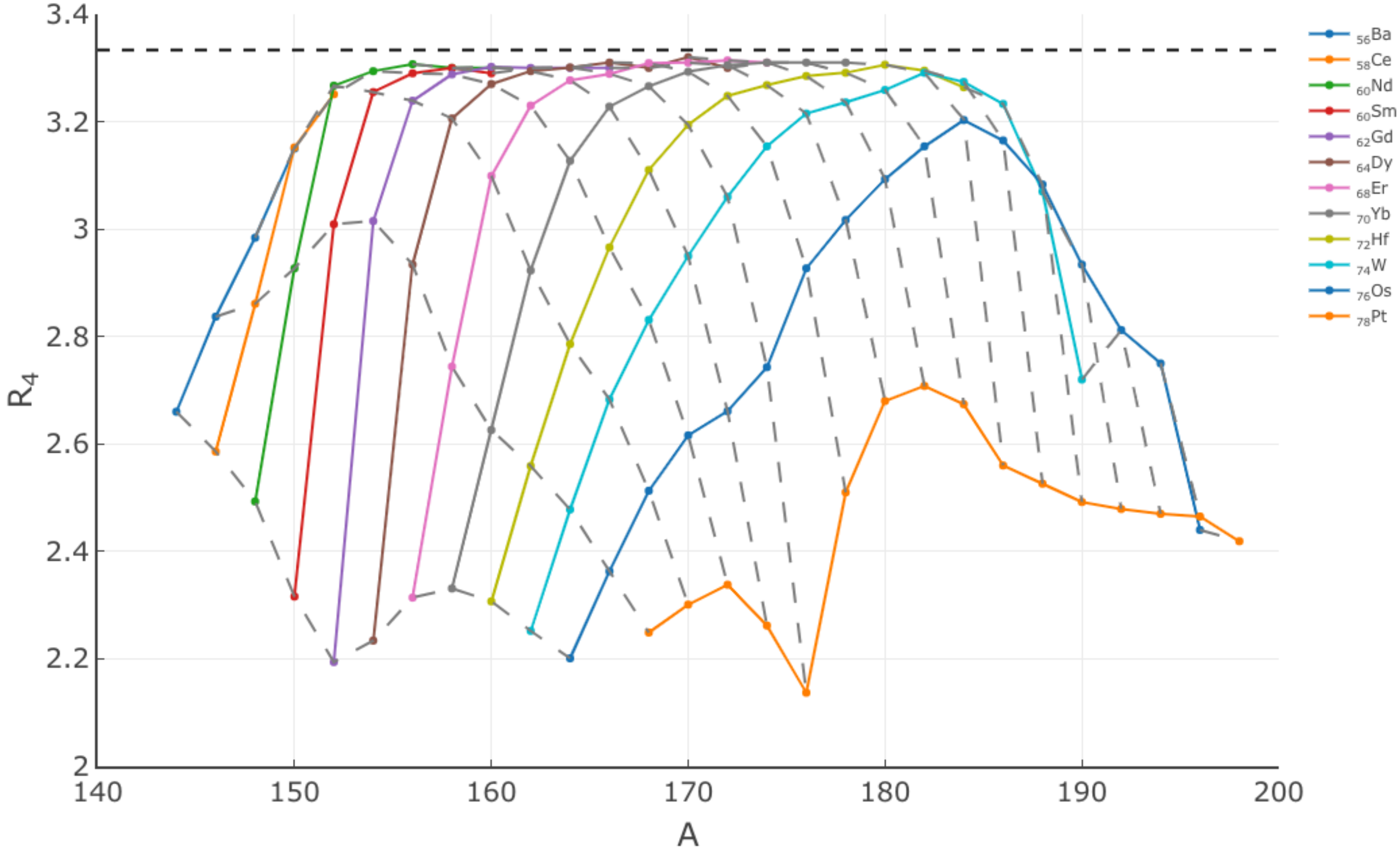
Jenkinswood, Fig. 2.7

PART II.

DEFORMED NUCLEI AND ROTATIONS

Even-even nuclei:

$R_4 = E(4_1^+)/E(2_1^+) \sim 3.33$ indicates an axially symmetric rotor limit

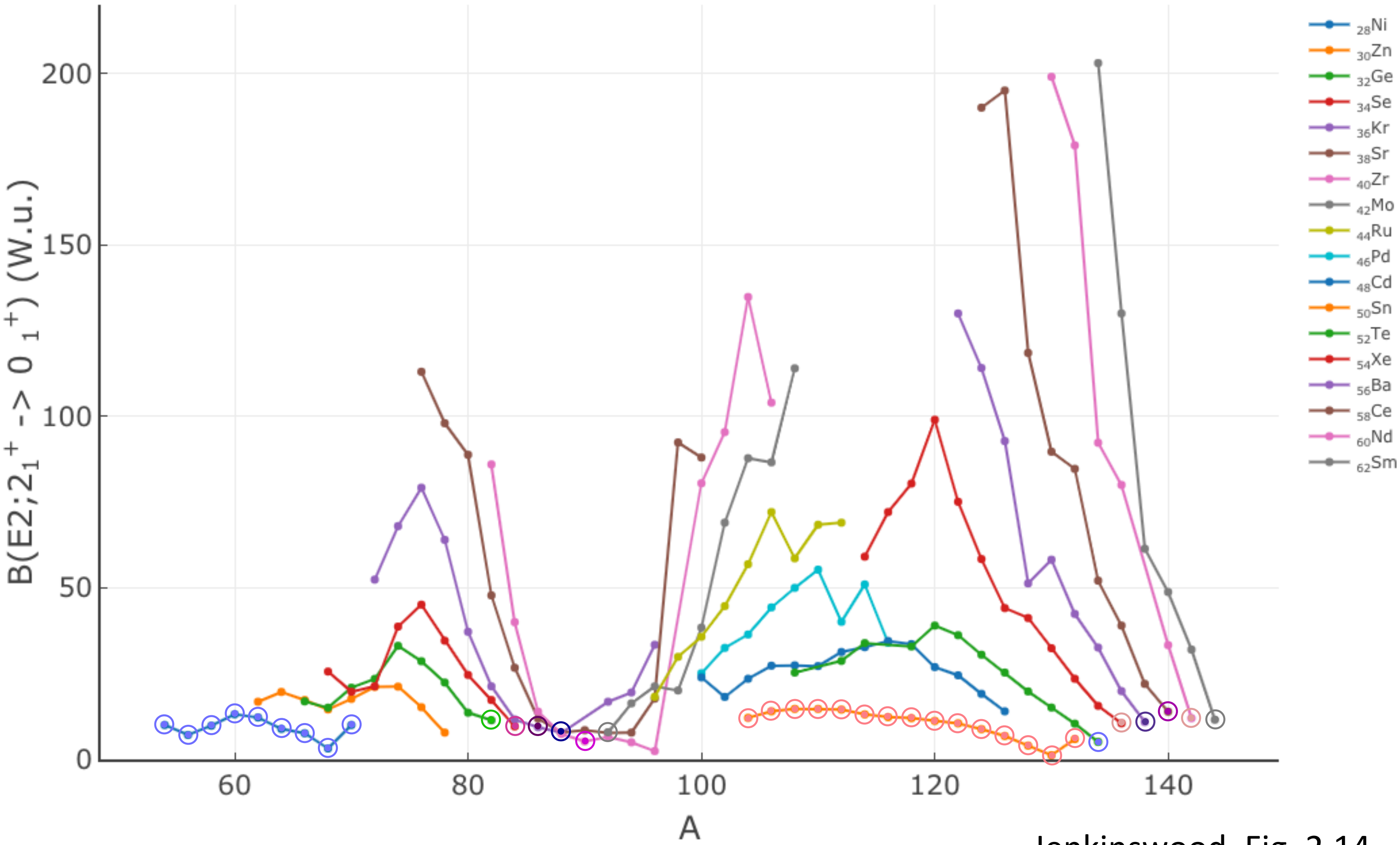


Jenkinswood, Fig. 2.9

Even-even nuclei:

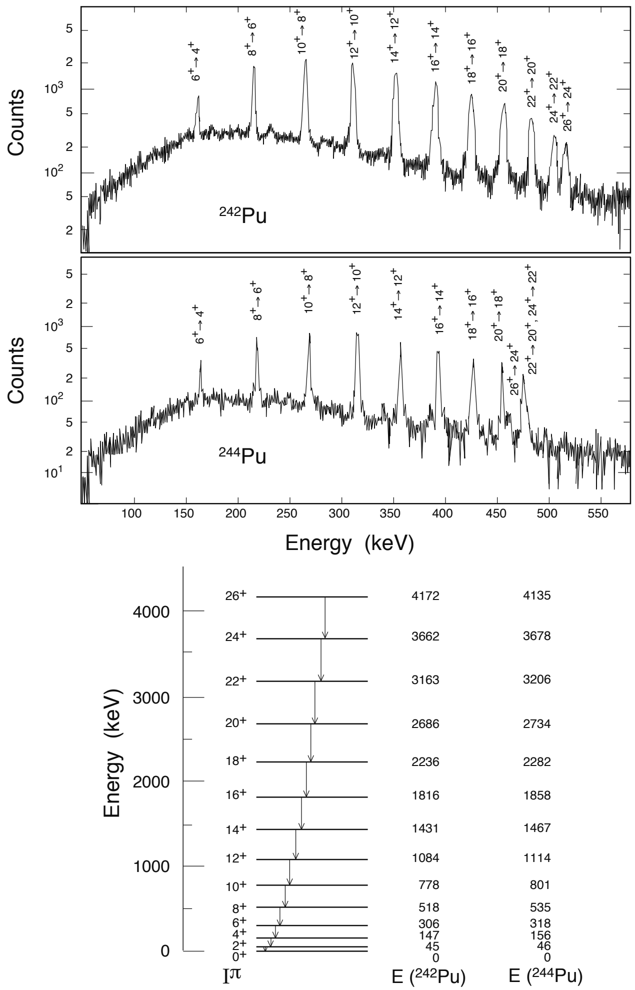
electric quadrupole transition strengths, B(E2; $2_1^+ \rightarrow 0_1^+$), weak at closed shells and strong far away from closed shells

⊙ -- closed shell nuclei



Jenkinswood, Fig. 2.14

Signature of the rotor model in nuclei



Jenkinswood, Fig. 3.4

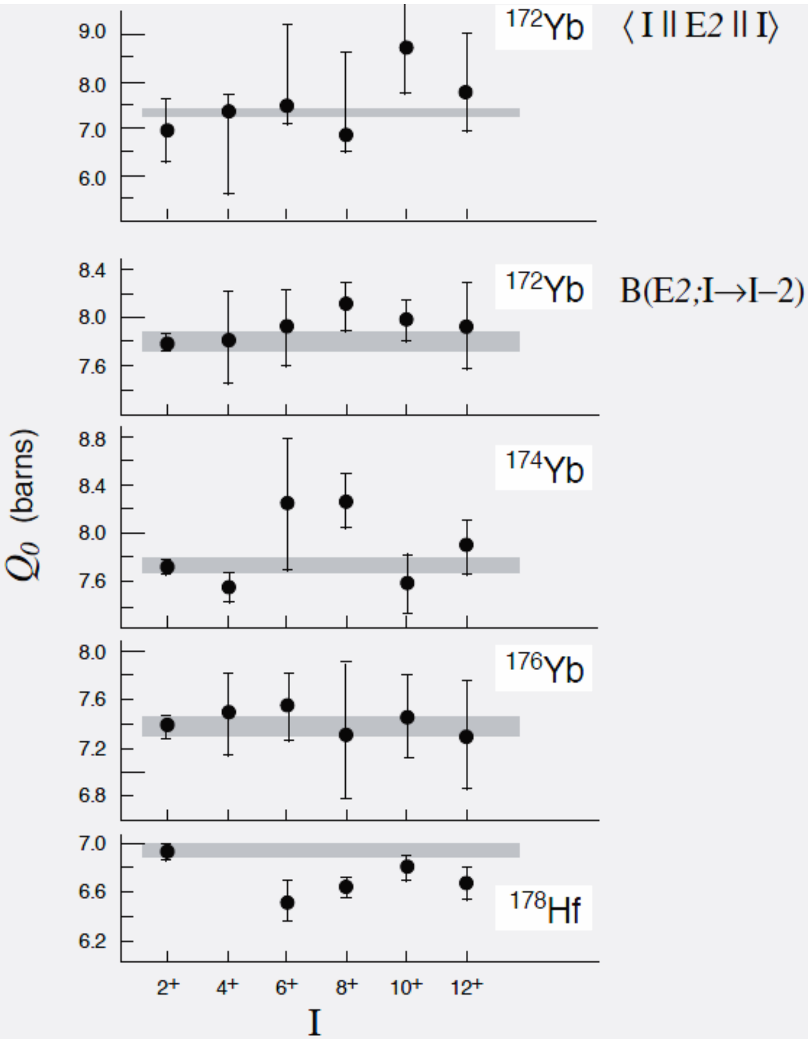
$E_I = A\,I\,(I + 1)$

$E_\gamma = \Delta E = A\,(2I + 1)$

Constant spacing between E_γ
→ constant A—"rigid rotor".

Observation: A decreases with increasing spin.

The intrinsic deformation of nuclei is consistent* with no change as spin increases



Jenkinswood, Fig. 3.5

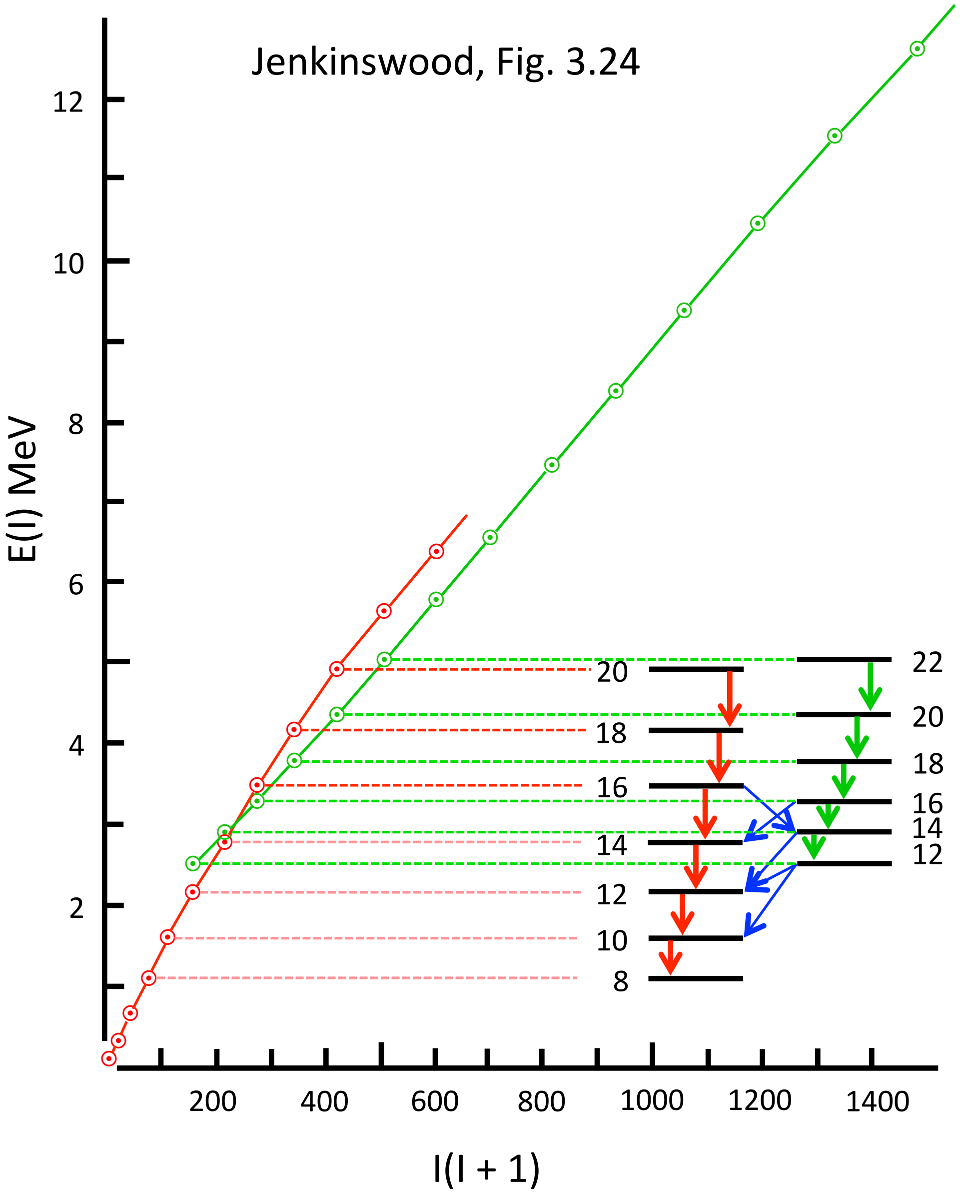
$$\langle IMK=0|T(E2)|IMK=0\rangle = (2I+1)^{\frac{1}{2}}\left(\frac{5}{16\pi}\right)^{\frac{1}{2}}\langle I020|I\,2,0\rangle\, eQ_0$$

$$B_{I,I-2} := B(E2;I\rightarrow I-2) = \frac{\langle IMK=0|T(E2)|I-2,MK=0\rangle^2}{2I+1}.$$

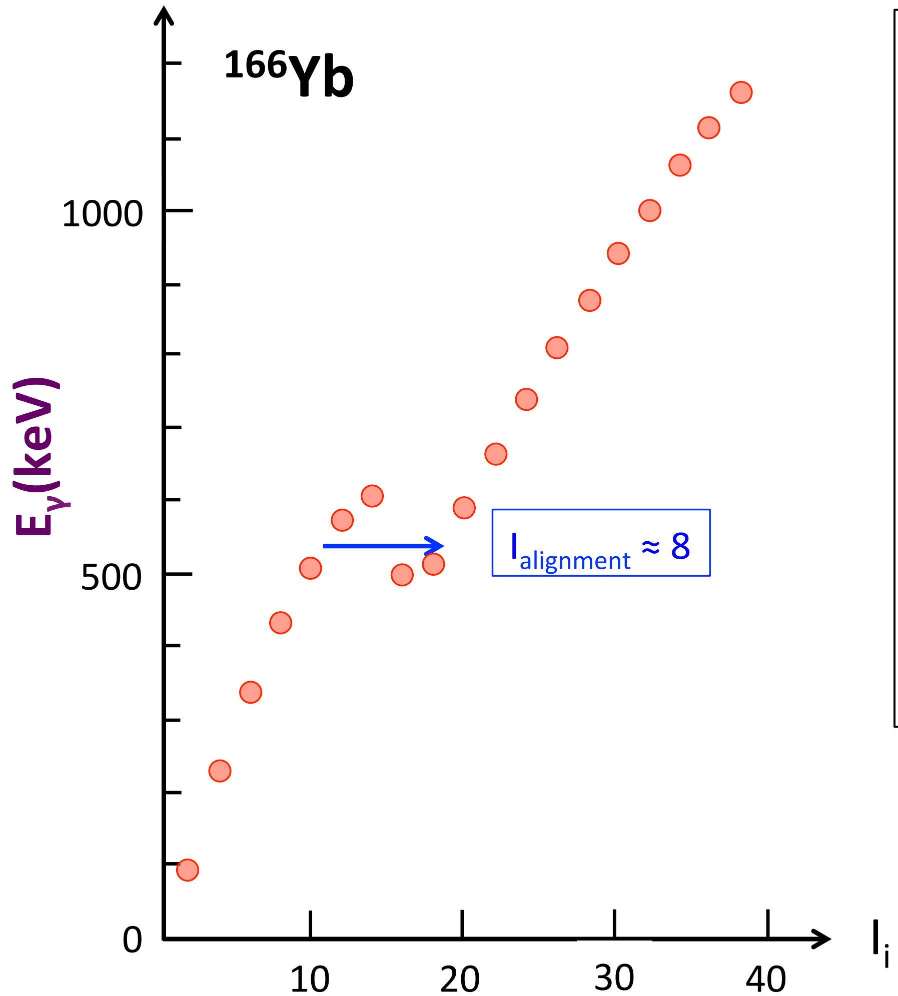
$$\langle IMK=0|T(E2)|I-2,MK=0\rangle = (2I+1)^{\frac{1}{2}}\left(\frac{5}{16\pi}\right)^{\frac{1}{2}}\langle I020|I-2,0\rangle\, eQ_0$$

*But we certainly need some higher precision B(E2)'s and <E2>'s

BUT now we come to the awkward part: problems with (e.g.) ^{166}Yb and the nature of the "crossing" band



E_γ vs. $I_{initial}$ plots* reveal key details of nuclear rotation: yrast band transitions in ^{166}Yb.



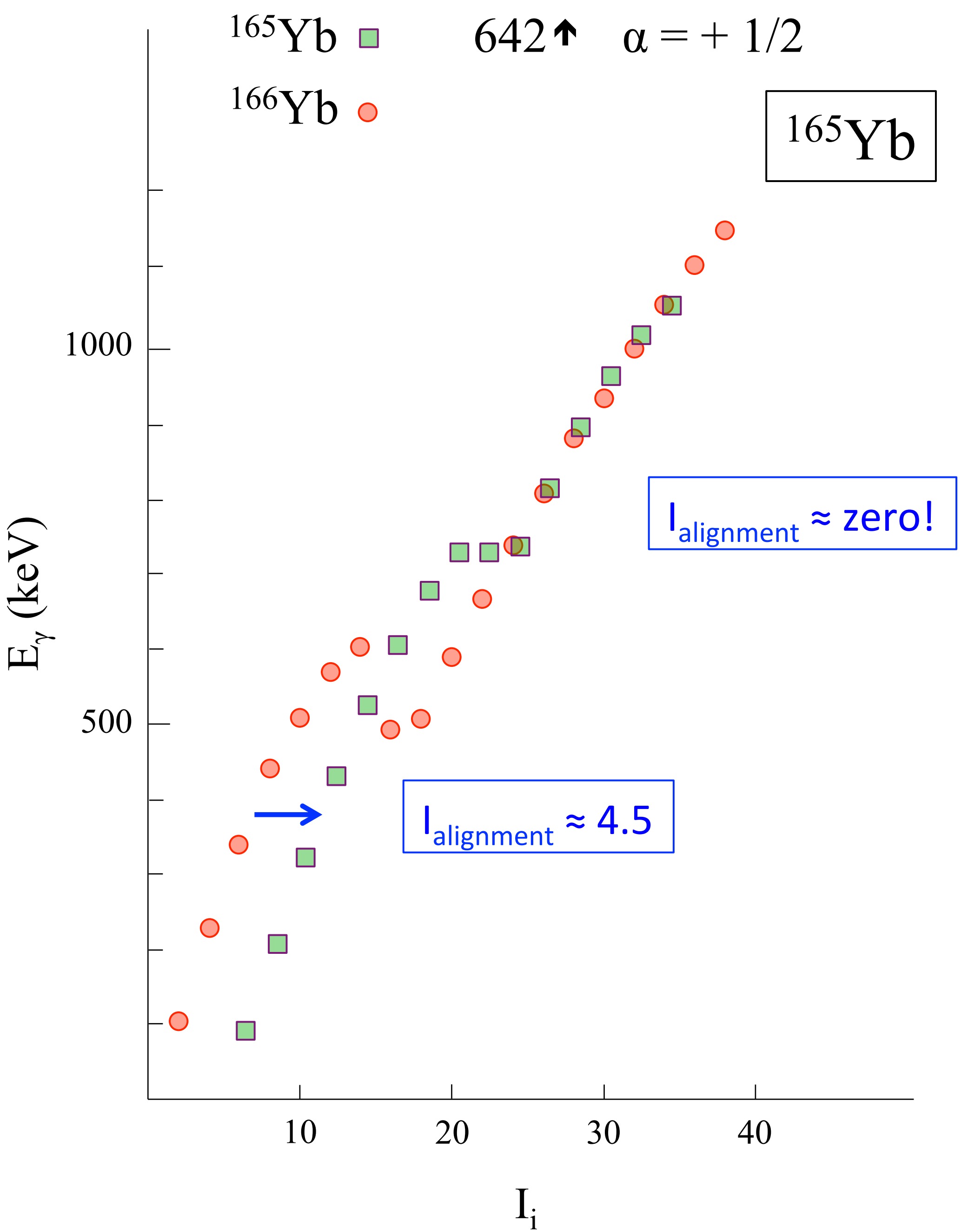
Jenkinswood, Fig. 3.25b

The plot suggests a contribution of ~ 8 units of spin from a non-rotational, i.e., “intrinsic” source: for example, a “broken” pair with spin 8.

A popular view has been that Coriolis effects produce such pair breaking by so-called “rotation alignment” or “Coriolis anti-pairing”.

The further popular view is that the pair occupies Nilsson configurations from the highest-j orbital, i.e., $1i_{13/2}$.

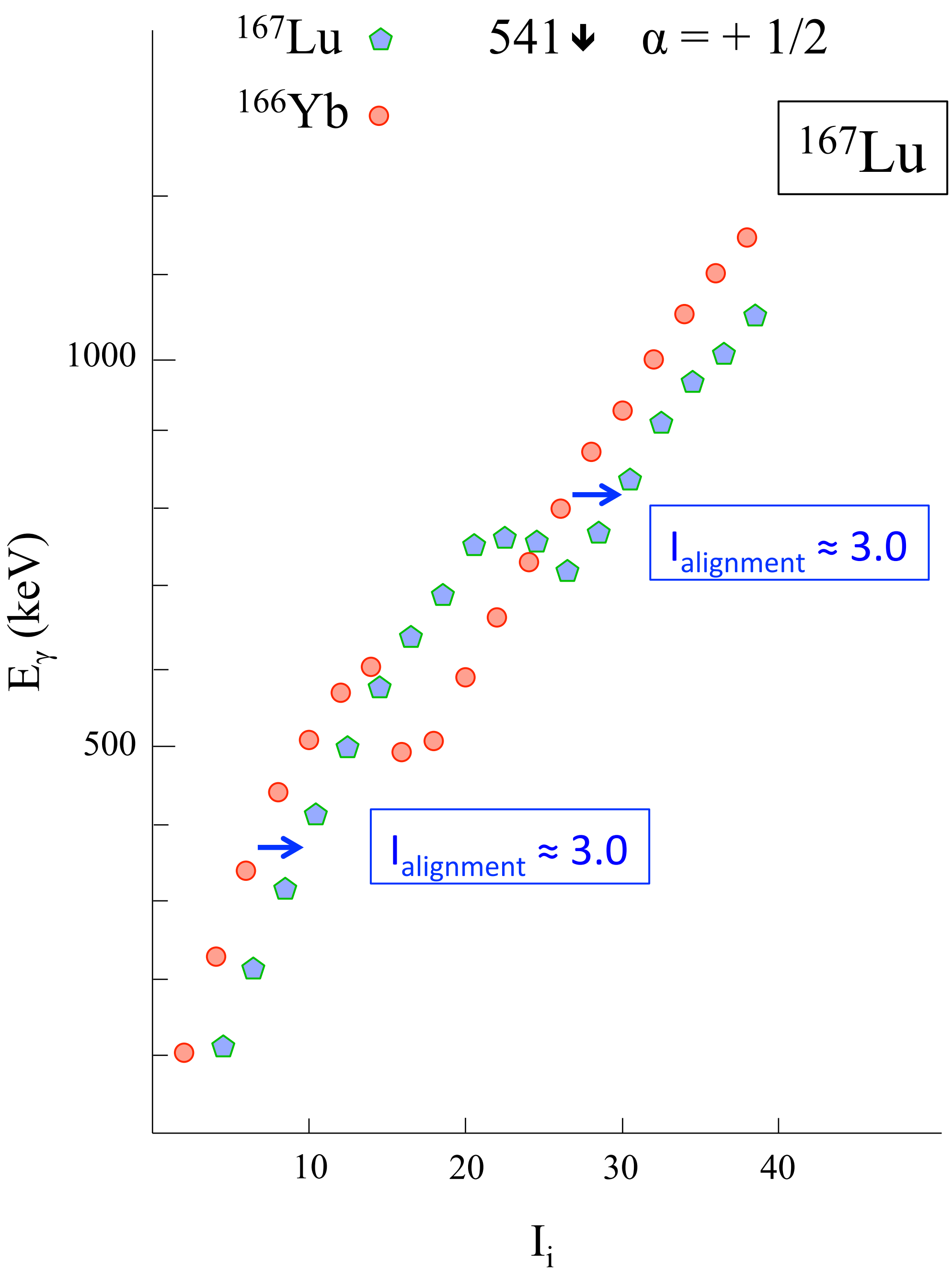
*Such plots do not appear to be used in any published work.



OBSERVATIONS:

1). The band crossing appears to be affected by the 642 configuration: this would be consistent with this configuration originating from the $1i_{13/2}$ high-j orbital.

2). But this is contradicted by the "alignment" above the crossing being zero: the unpaired neutron should "block" the core alignment.

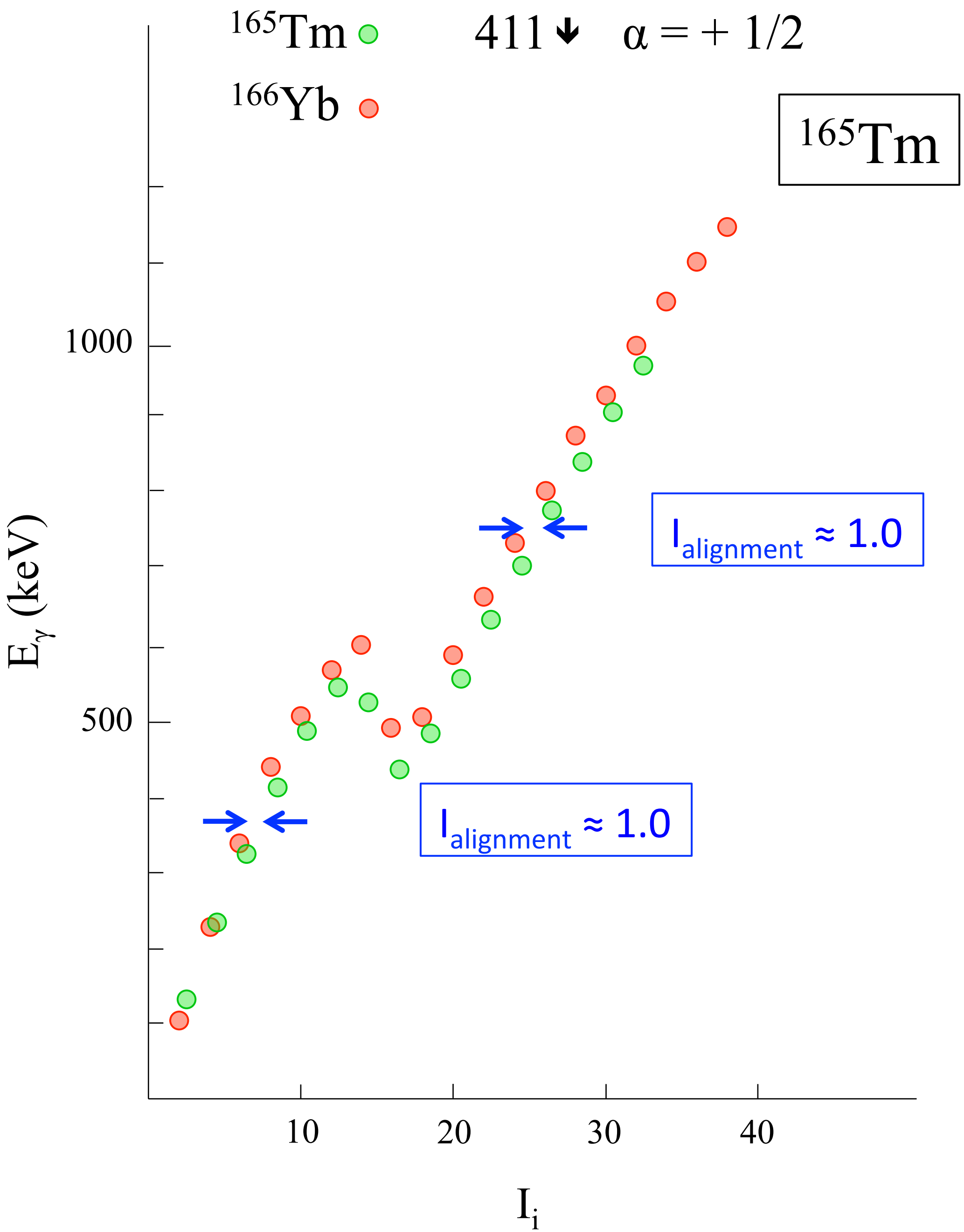


OBSERVATIONS:

1). The band crossing appears to be affected by the 541 configuration (which originates from the *$1h_{9/2}$* orbital).

2). This is inconsistent with the role of the neutron *$1i_{13/2}$* high-j orbital as the cause of the band crossing.

3). The 541 alignment appears to be independent of the core structure.



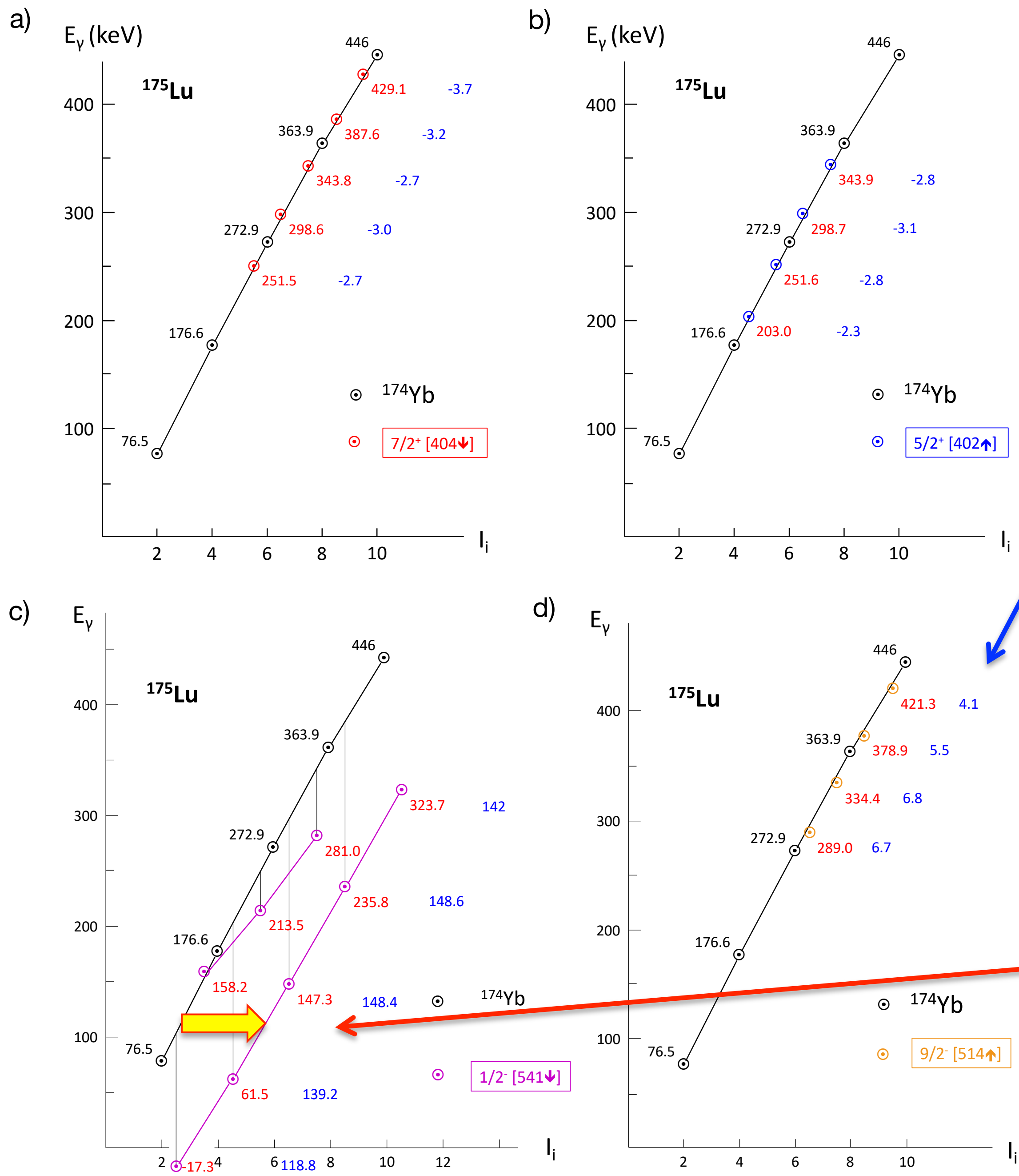
OBSERVATIONS:

1). The band crossing is unaffected by the 411 configuration.

2). The 411 alignment is independent of the core structure.

Most alignments are small or near zero

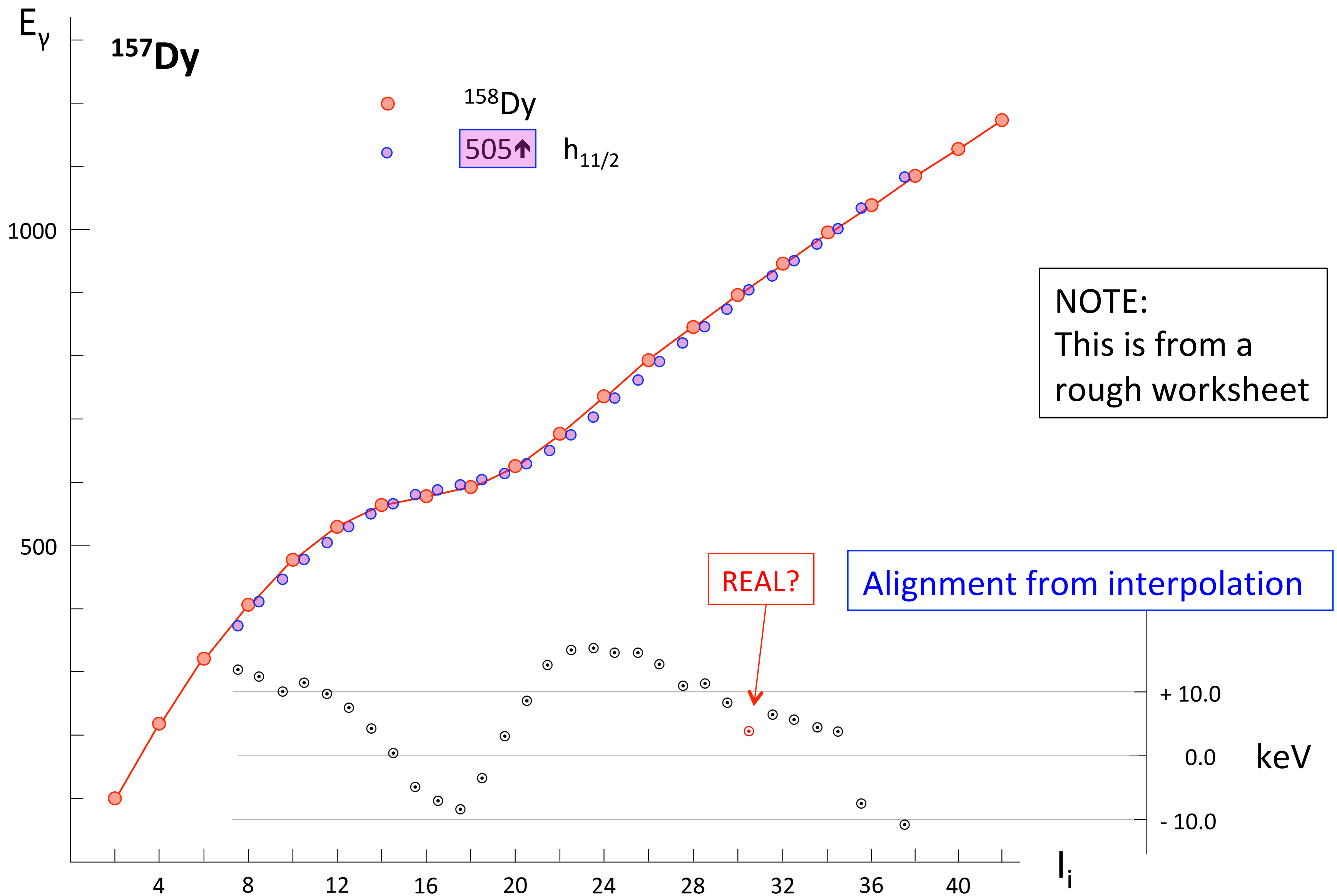
Alignment from interpolation:
~ few keV



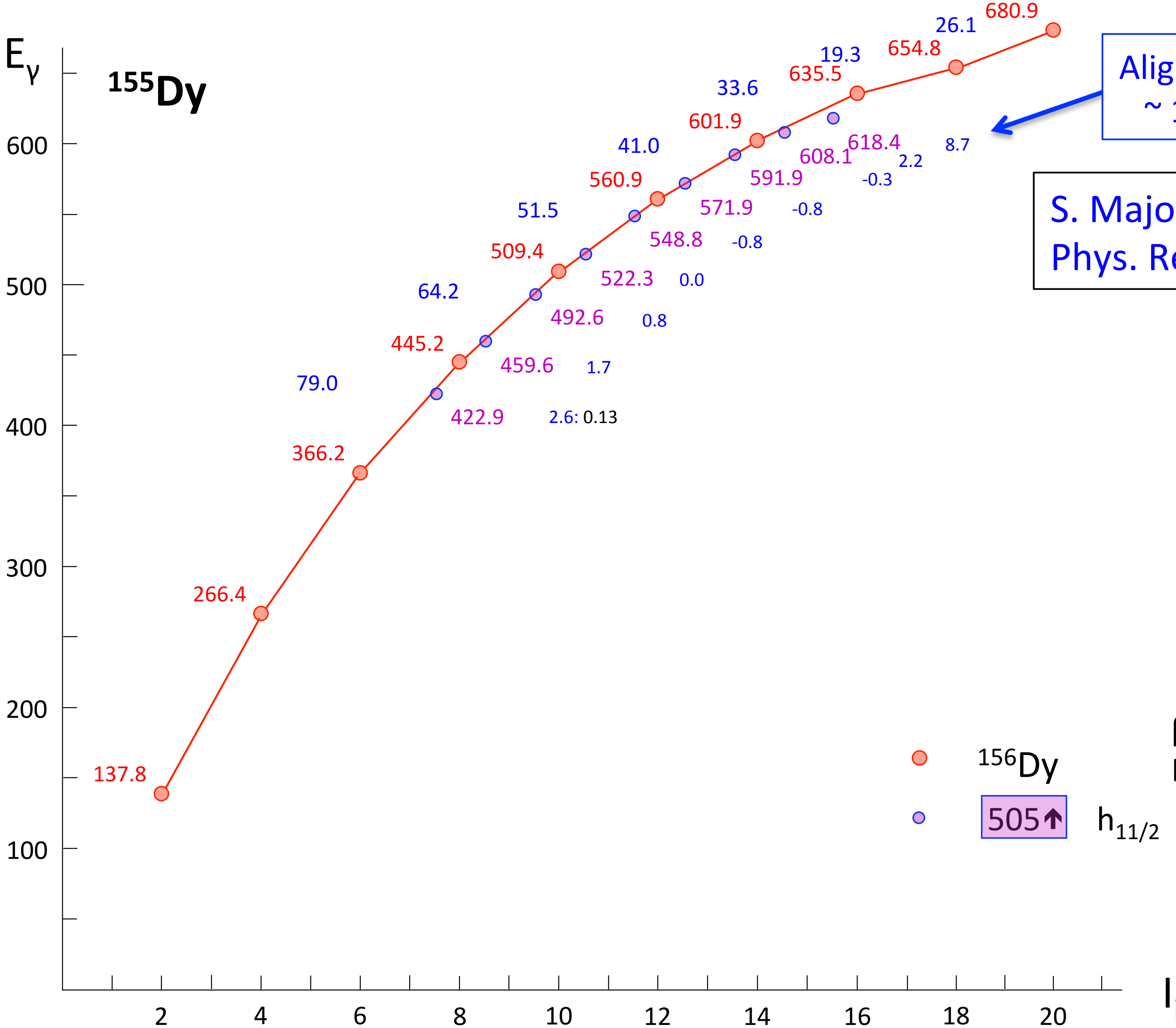
Large alignment case:
½- [541] (j = 9/2) I_{align} ≈ 3.0
~ 150 keV

Jenkinswood, Fig. 3.9

How small an alignment would you like it to be?



Smaller?



Alignment from interpolation: ~ 1 keV

S. Majola et al., Phys. Rev. **C101** (2020) 044312

NOTE: This is from a rough worksheet

$\beta = 0.2929^{16}$

$B_{20} = 147.9^{16}$

CRISIS!

There would appear to be no doubt that nuclei "rotate".

But the simplest and long held view by all of us (older folks*) is that there are "Coriolis" effects, whereby nucleon spins align with the collective rotation.

To the contrary, odd nucleons have identical rotational "profiles" to their even-even neighbors; some have nearly collinear profiles.

There is a vast literature which now seems to be in question.

Essentially: *we do not know how nuclei rotate*.

P.S. I have explored some ideas—for the specialists, the so-called $\boldsymbol{I \cdot j}$ term--but I have only identified qualitative patterns that fit this term.

*In other words, it is up to you young folks!

CONSEQUENCES (for the specialists)

There is no role for pairing in any model of nuclear moments of inertia.
There is no odd-particle "blocking" effect.

There is no such thing as "type-I" and "type-II" moments of inertia.
One must always use the double differences with respect to spin, ΔEγ;
single differences possess the effects of alignment—see next item.

The role of the ***I•j*** term was never thoroughly explored.
This term contributes a constant to single differences with respect to spin, Eγ.
But it is often near zero.

It would be wise to reassess the cranked shell models.
The ***I•j*** term accounts for many, most, maybe all of the effects attributed to "cranking". One can see similarities in the dynamics of a cranking term and the ***I•j*** term. The ***I•j*** term is fundamental to the particle-rotor coupling model.

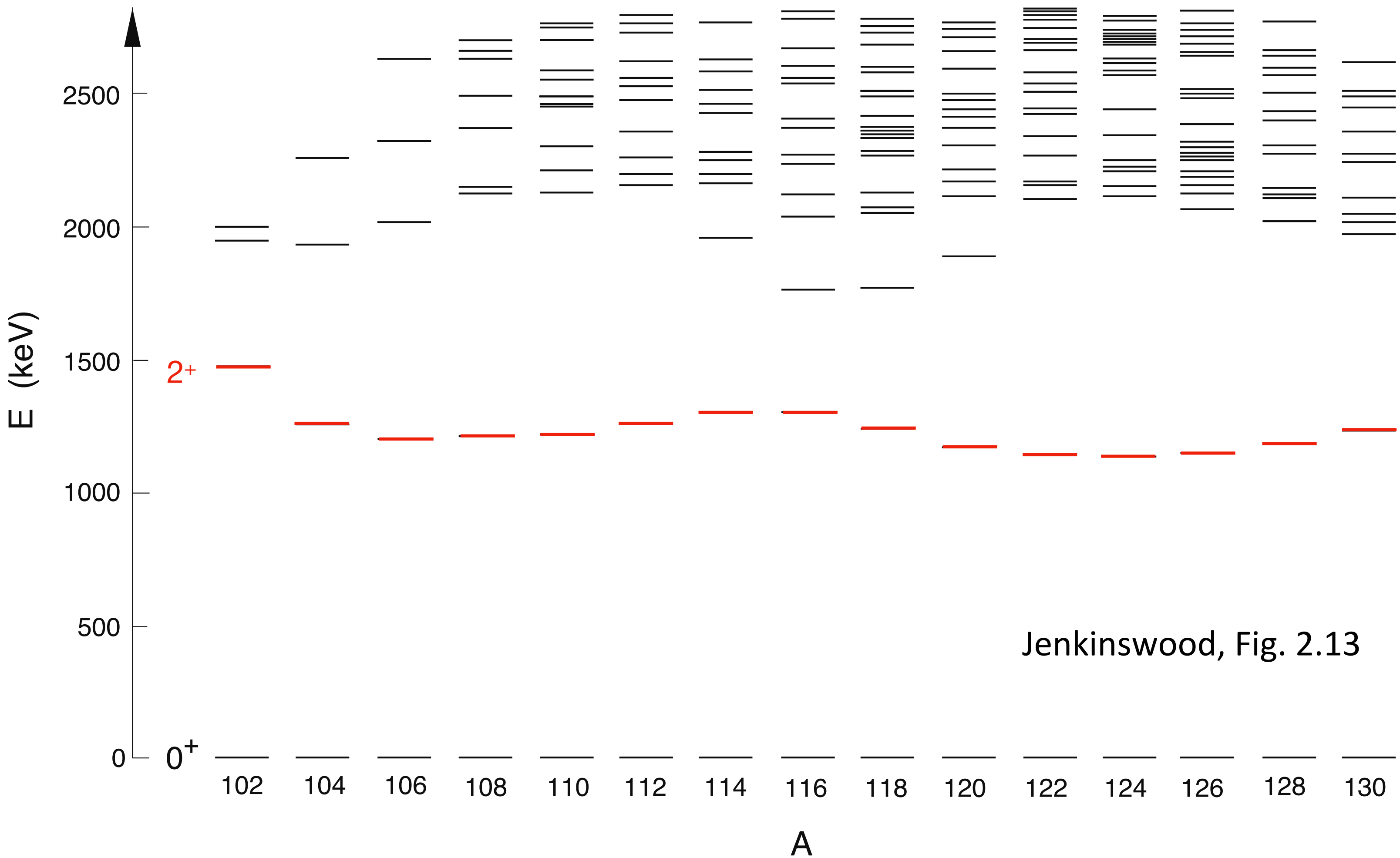
PART III.

SPHERICAL AND WEAKLY DEFORMED NUCLEI:

IN SEARCH OF PATTERNS

The tin isotopes (Z = 50):

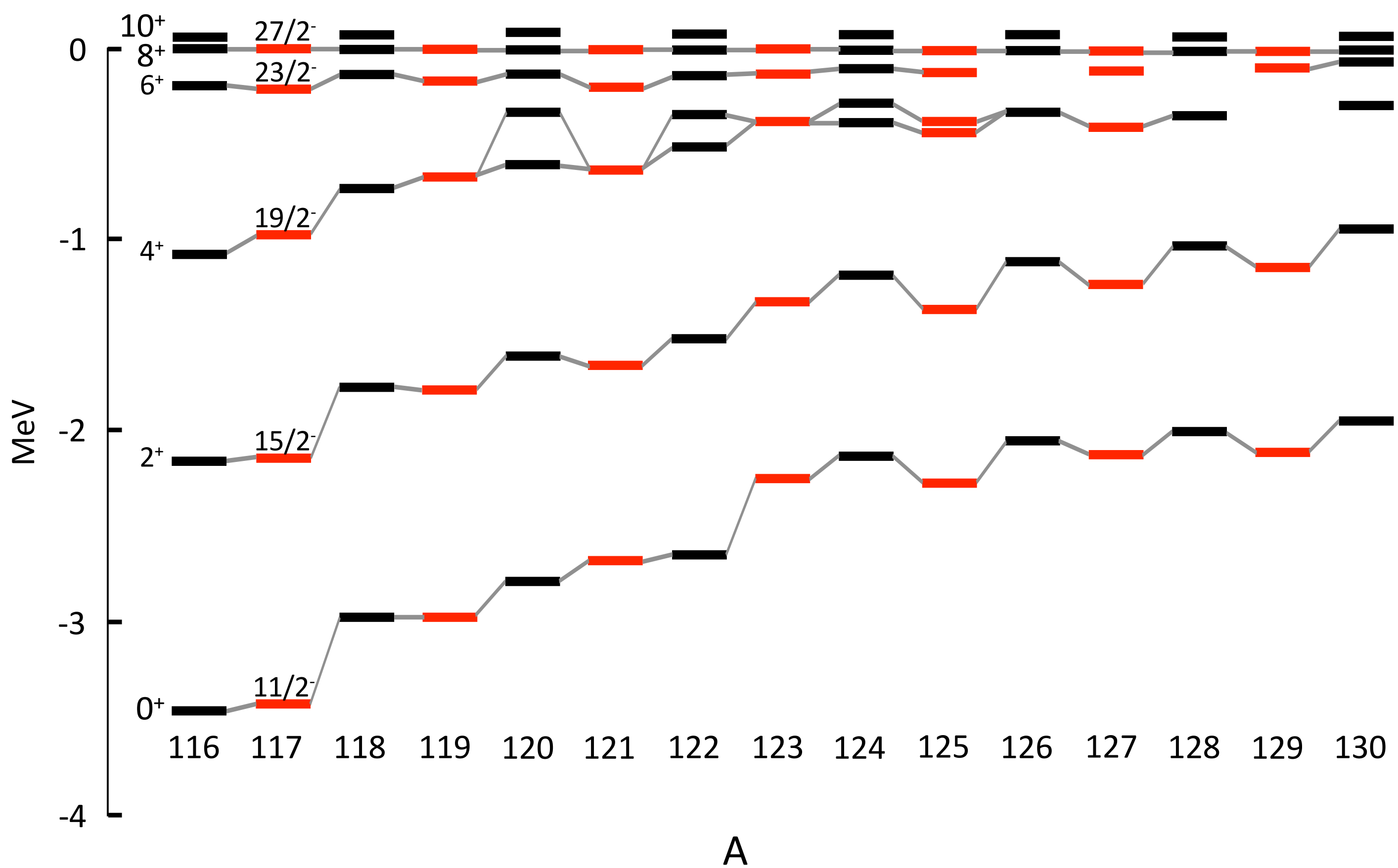
isolated 2_1^+ states … and a lot of complex spectroscopy



BUT—Sn isotopes:
high-spin (yrast) states in neutron-rich nuclei

$1h_{11/2}$ m scheme, one broken pair even mass $m_{max} = 11/2 + 9/2 = 10 \rightarrow J = 10$

odd mass $m_{max} = 11/2 + 9/2 + 7/2 = 27/2 \rightarrow J = 27/2$

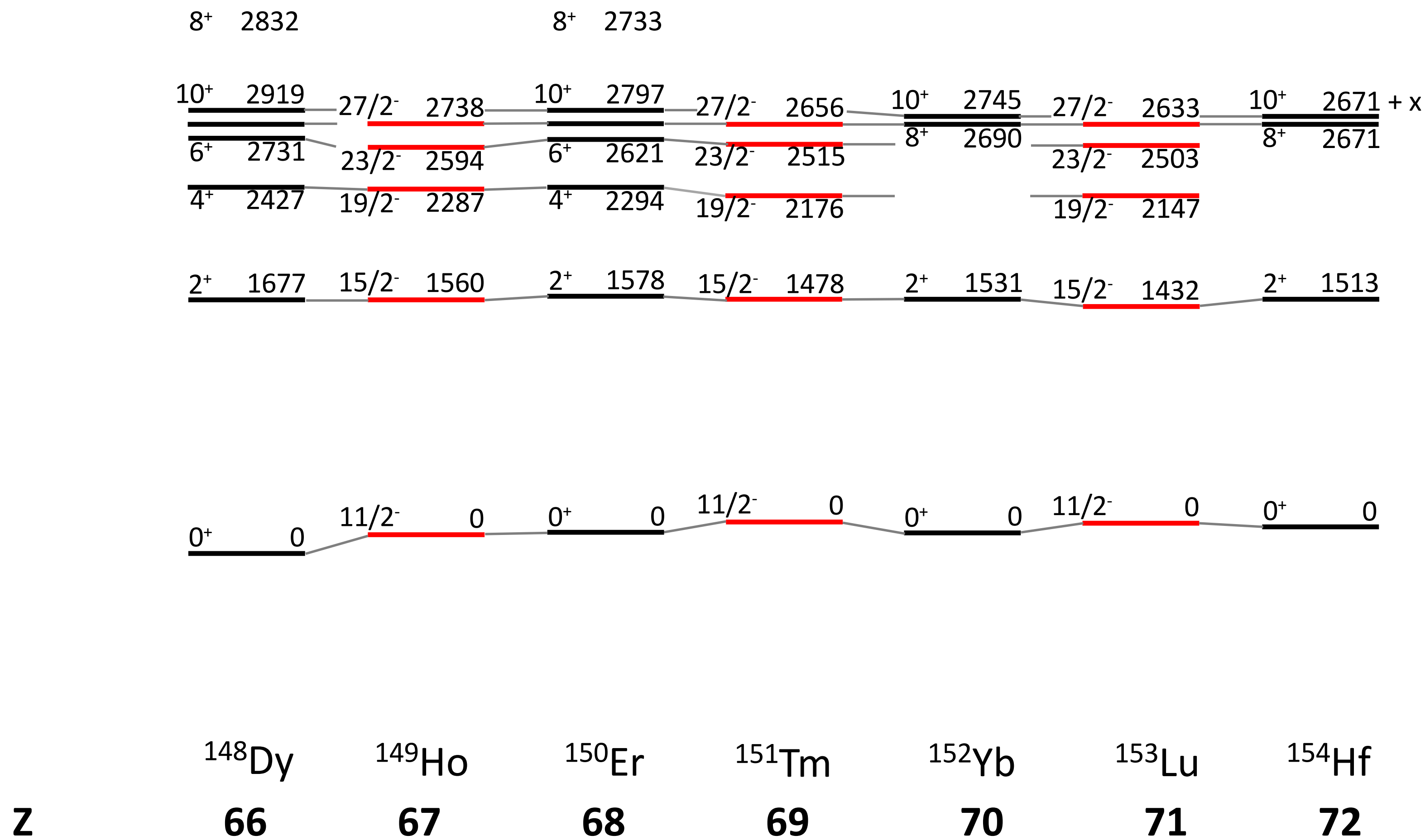


Jenkinswood, Fig. 4.19

N = 82 isotones:
high-spin (yrast) states in proton-rich nuclei

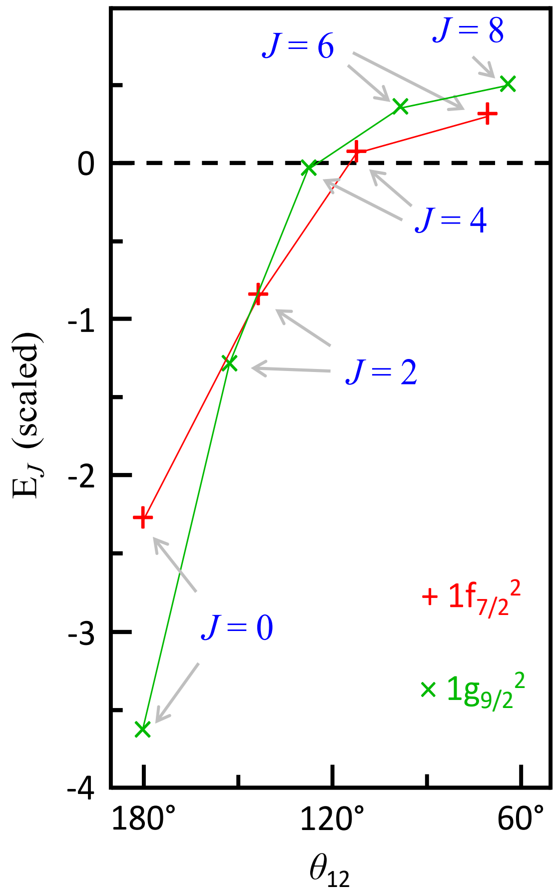
$1h_{11/2}$ m scheme, one broken pair even mass $m_{max} = 11/2 + 9/2 = 10 \rightarrow J = 10$

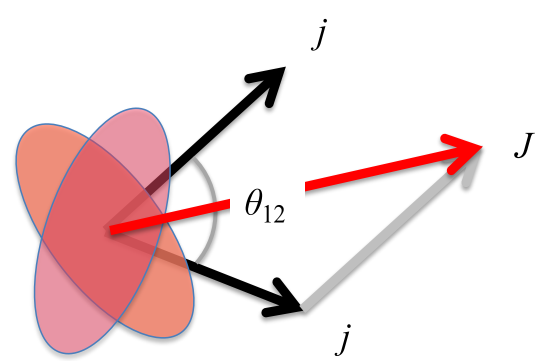
odd mass $m_{max} = 11/2 + 9/2 + 7/2 = 27/2 \rightarrow J = 27/2$



Jenkinswood, Fig. 4.18

Short-range attractive interaction and orbital overlap describes coupling in spherical nuclei



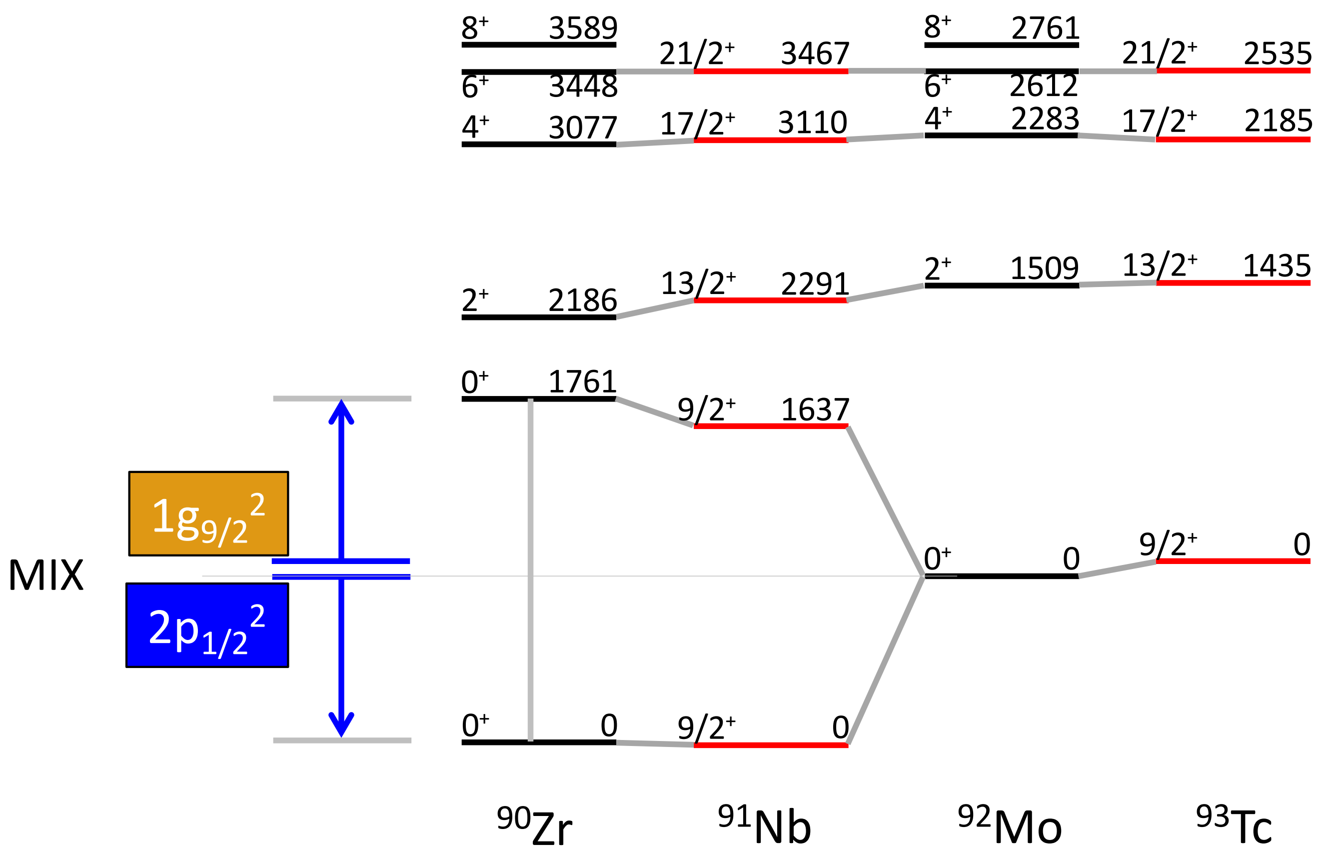


Jenkinswood, Fig. 4.20

Effect of two j subshells:

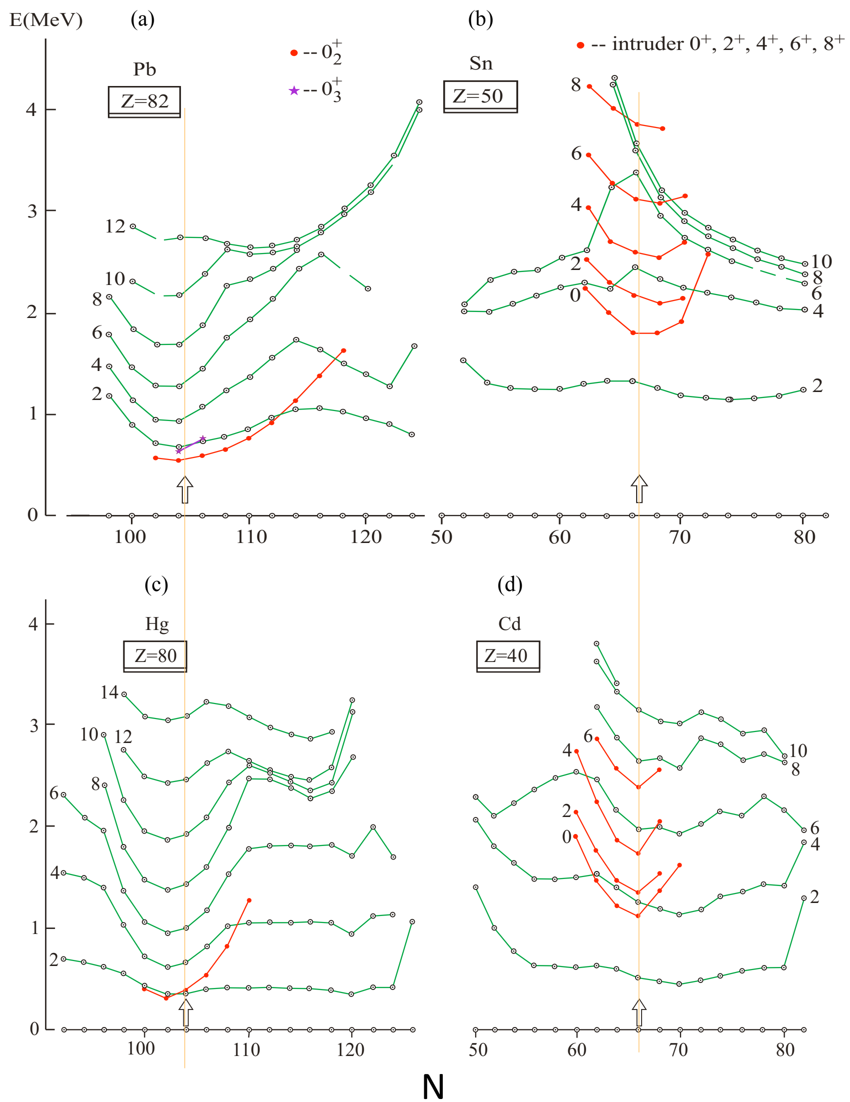
j = ½ produces a high 2_1^+ energy via mixing and “repulsion” of 0^+ configurations

$1g_{9/2}$ m scheme, one broken pair even mass m_{max} = 9/2 + 7/2 = 8 → J = 8
odd mass m_{max} = 9/2 + 7/2 + 5/2 = 21/2 → J = 21/2



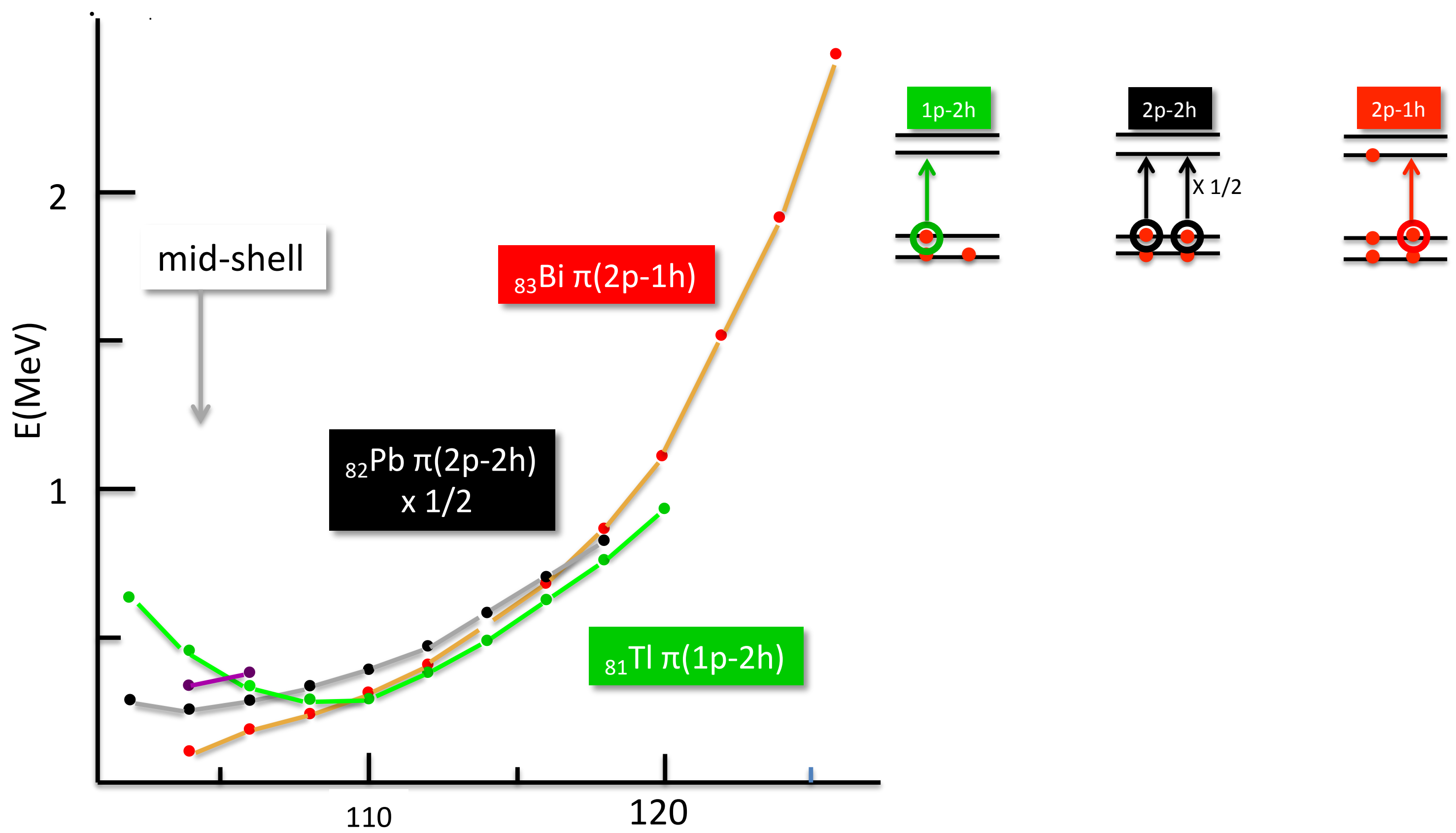
Jenkinswood, Fig. 4.21

Intruder state "parabolas":
the signature of shape coexistence



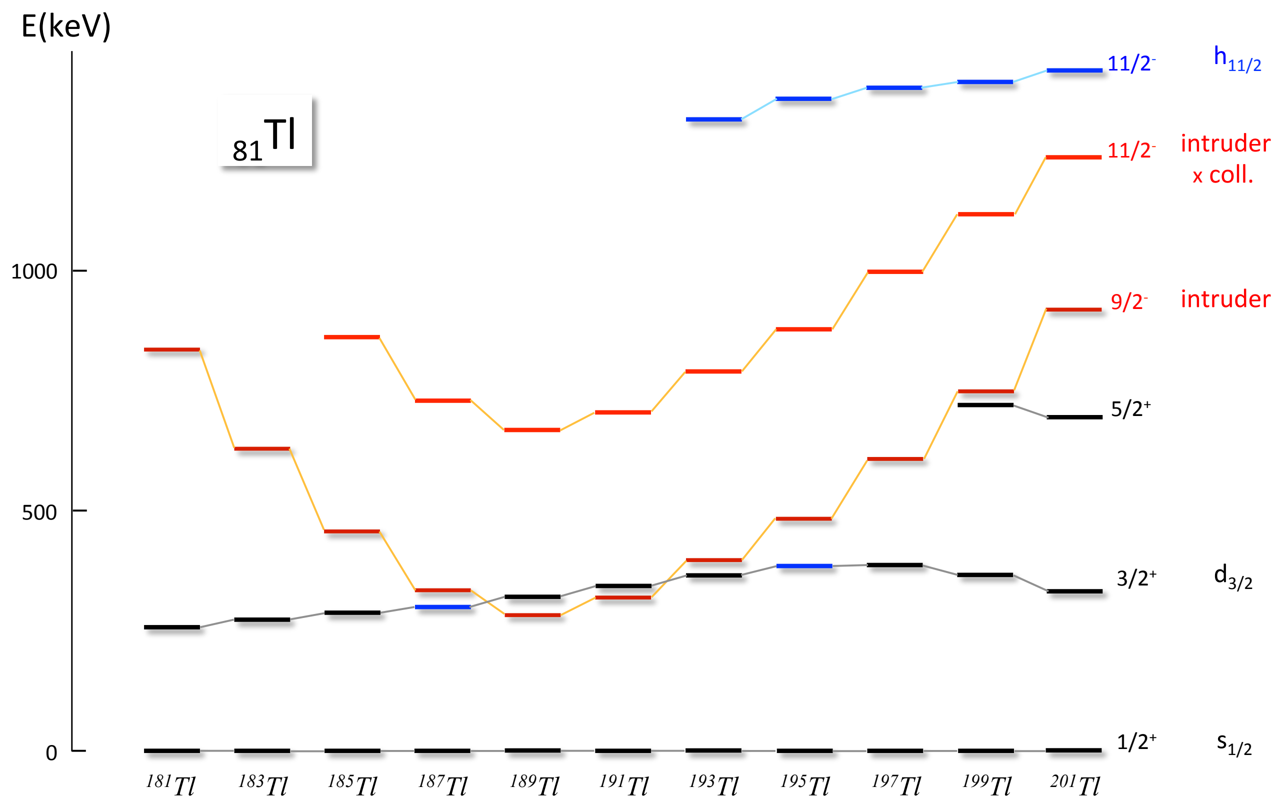
Jenkinswood, Fig. 4.3

Intruder state parabolas scale in the number of pairs (no "deformation-driving" orbitals)



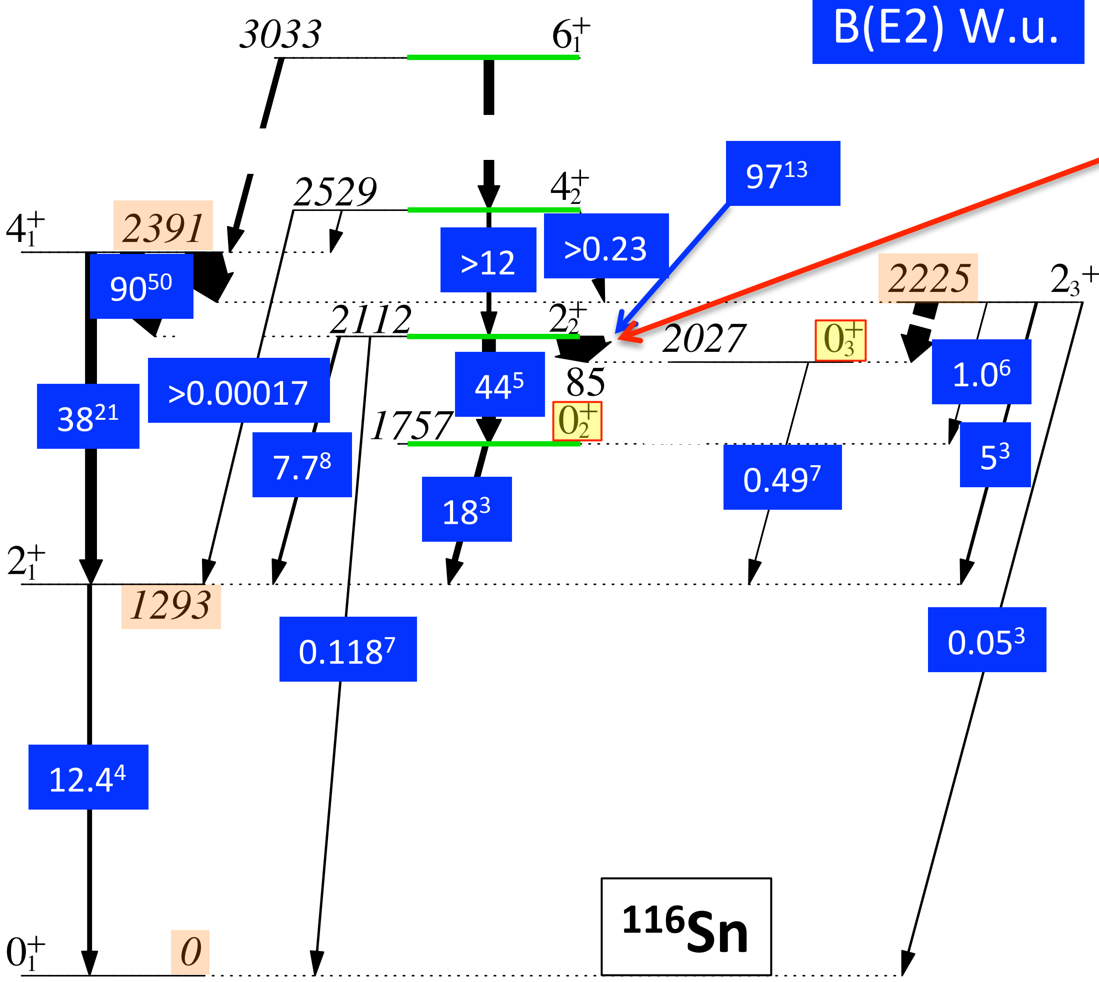
Jenkinswood, Fig. 4.14

Intruder state parabolas in the Tl (Z = 81) isotopes



Jenkinswood, Fig. 4.13

Complex spectroscopy in ^{116}Sn



Critical need:
Intensities of high-lying low-energy transitions.

See:
J.L. Pore et al.,
Eur. J. Phys. **A53** (2017) 27;
D.S. Cross et al.,
ibid. **A53** (2017) 216.
TRIUMF-ISAC-8pi-PACES
+ ENSDF $T_{1/2}$

Jenkinswood, Fig. 4.6

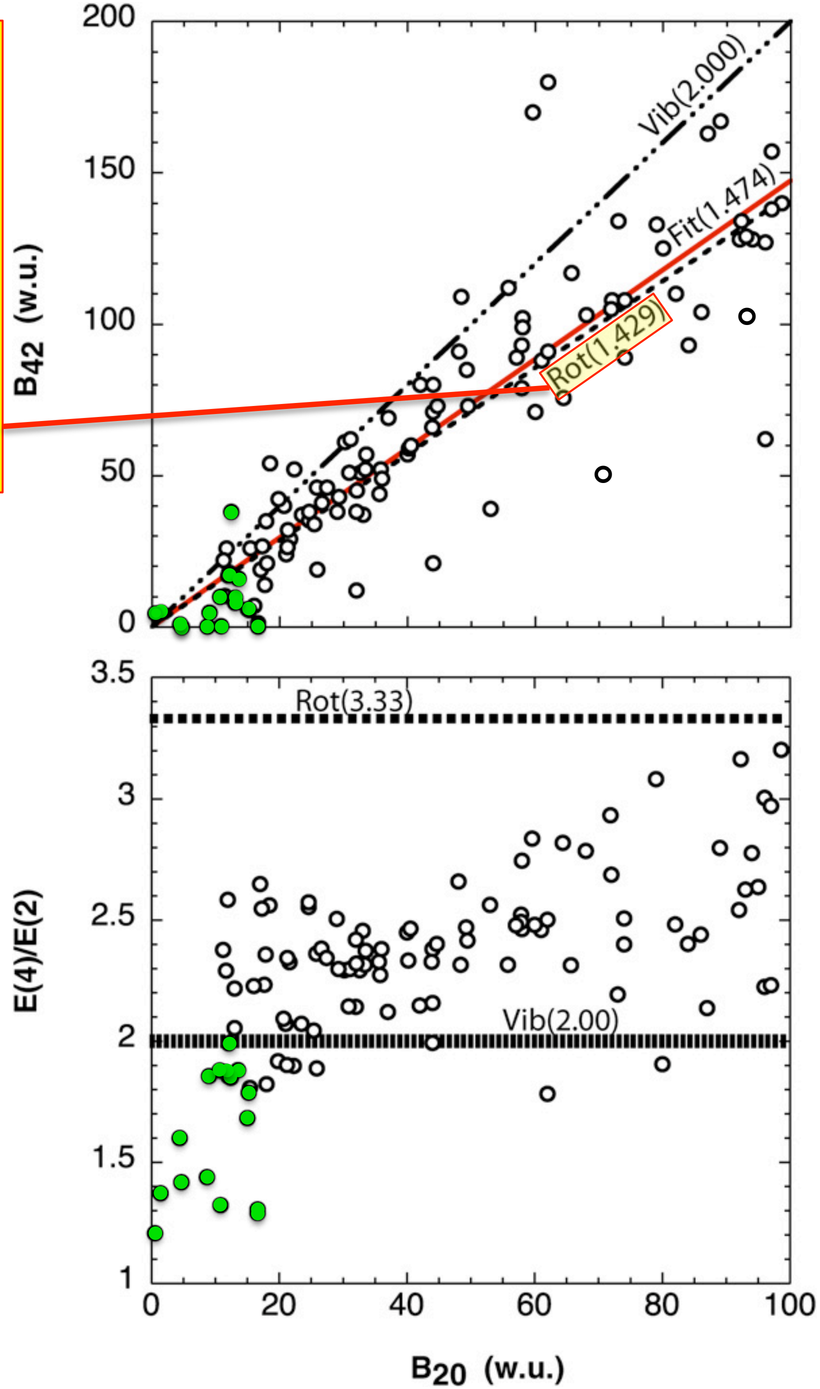
The biggest remaining challenge:

weakly deformed nuclei

Global view of all weakly deformed nuclei:

energies --no pattern

E2 trans. --rotor?
10/7 = 1.429



Green points:
singly closed shell nuclei

$B_{42} = B(E2; 4_1^+ \rightarrow 2_1^+)$

$B_{20} = B(E2; 2_1^+ \rightarrow 0_1^+)$

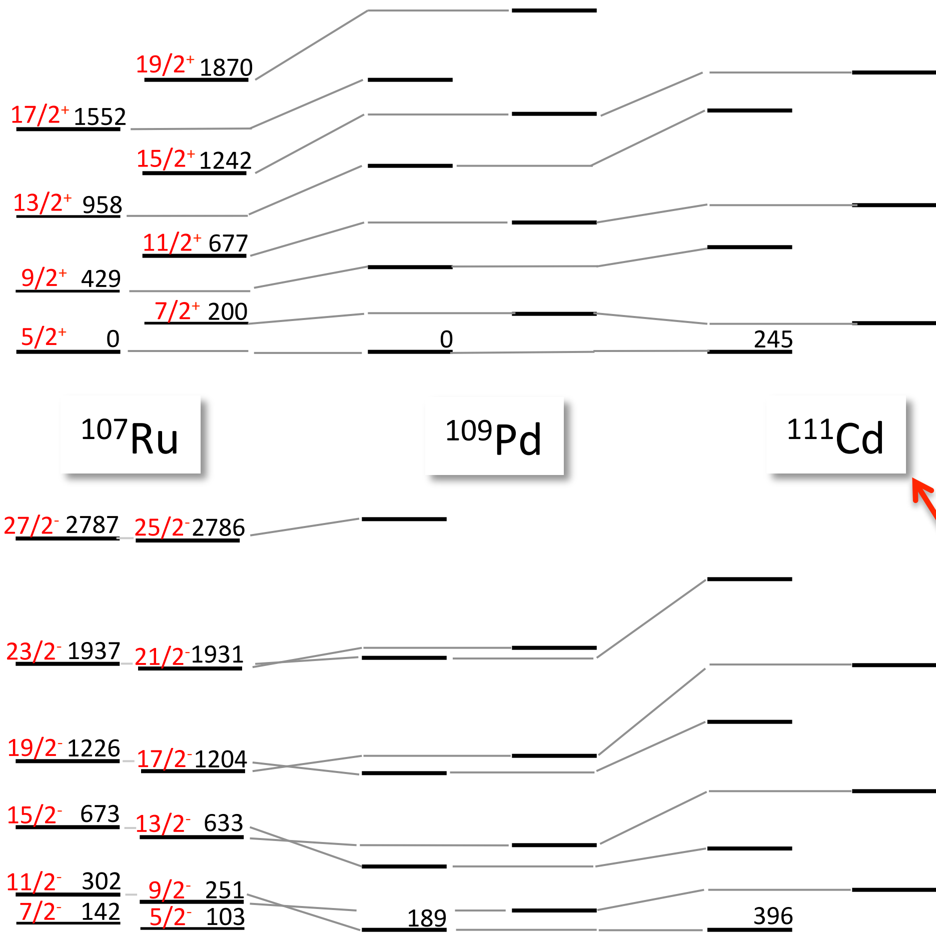
$E(4) = E(4_1^+)$

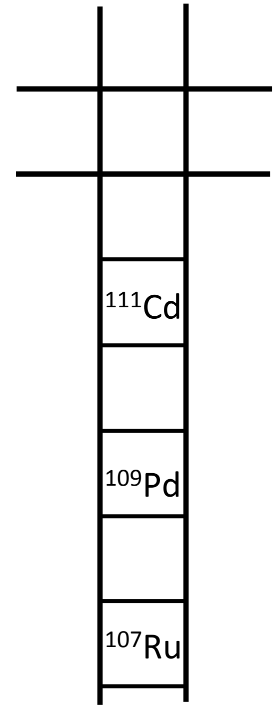
$E(2) = E(2_1^+)$

	$E(4)/E(2)$	B_{42}/B_{20}
Rotor	10/3	10/7
Vibrator	2	2

Rotor model:
applicable to nuclei with small deformations

See, e.g., P.C. Simms et al., NP **A347** (1980) 205;
J Rekstad, NP **A247** (1975) 7





anharmonic vibrator?
NO--see A. Stuchbery et al.,
PR C **93** 031302 (2016)

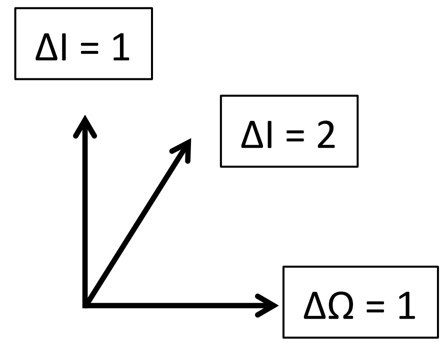
Triaxial rotor "hyper" band A ~ 125 region

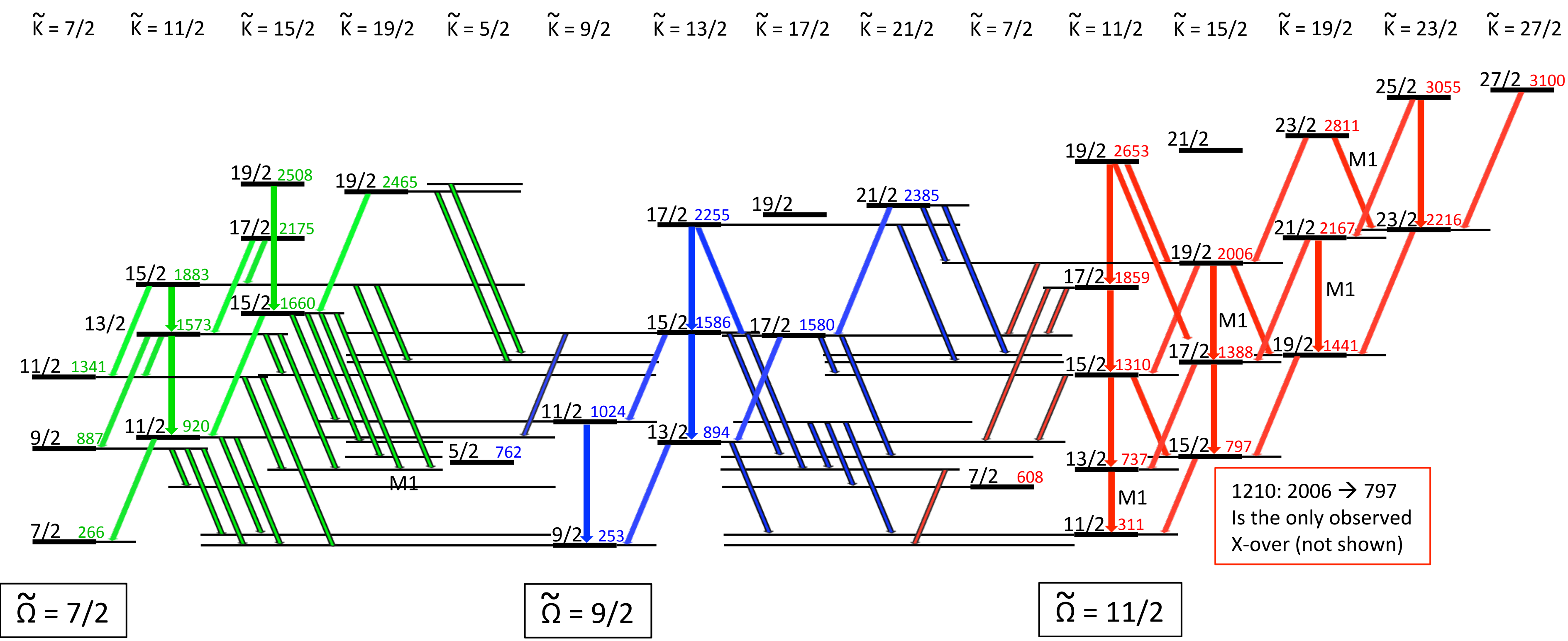
^{125}Xe

$h_{11/2}$

Pattern after J. Meyer-ter-Vehn, NP **A249** (1975) 111

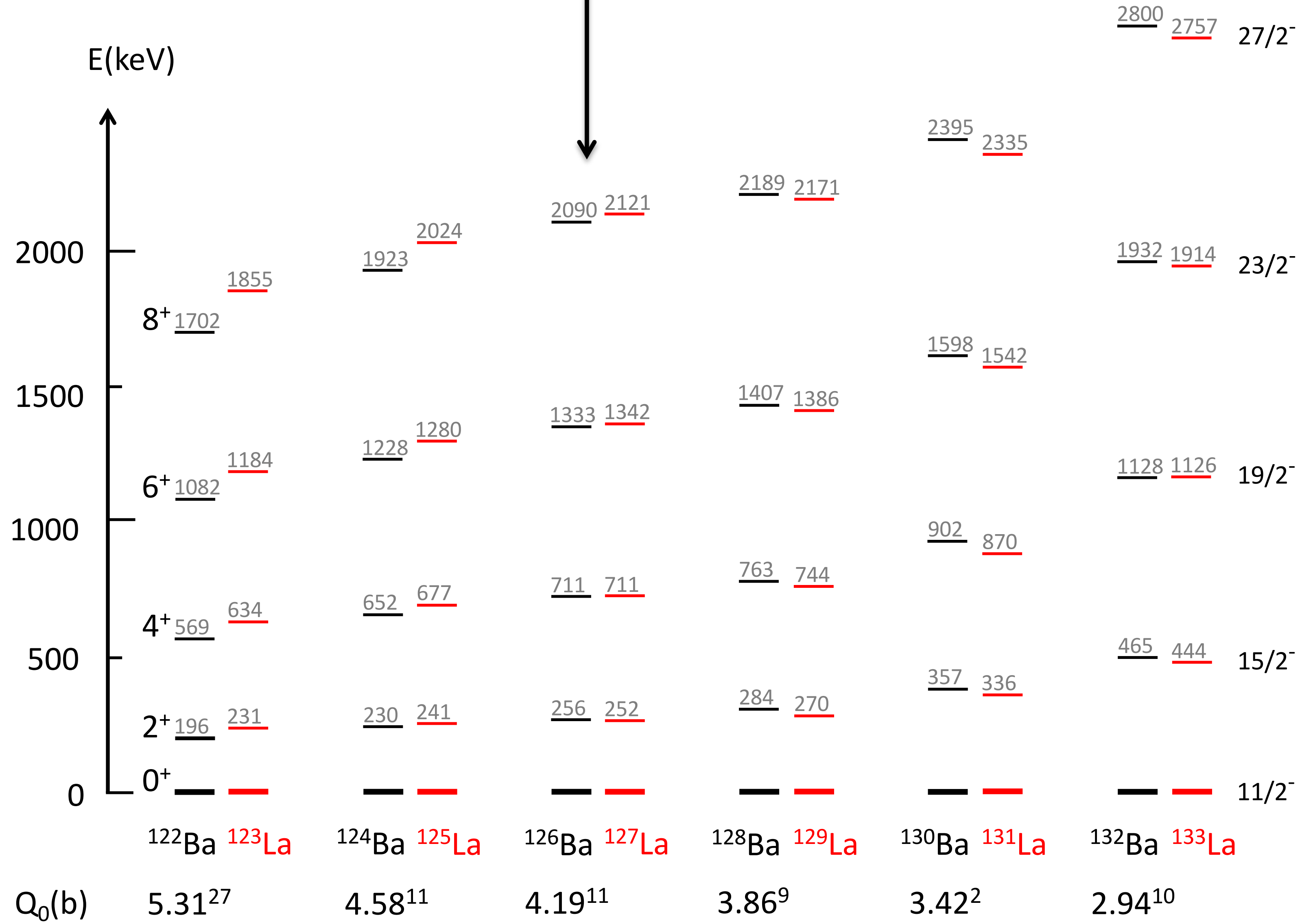
Data from:
I. Wiedenhöver et al.
NP **A582** (1995) 77





There are configurations with (near) perfect rotation alignment

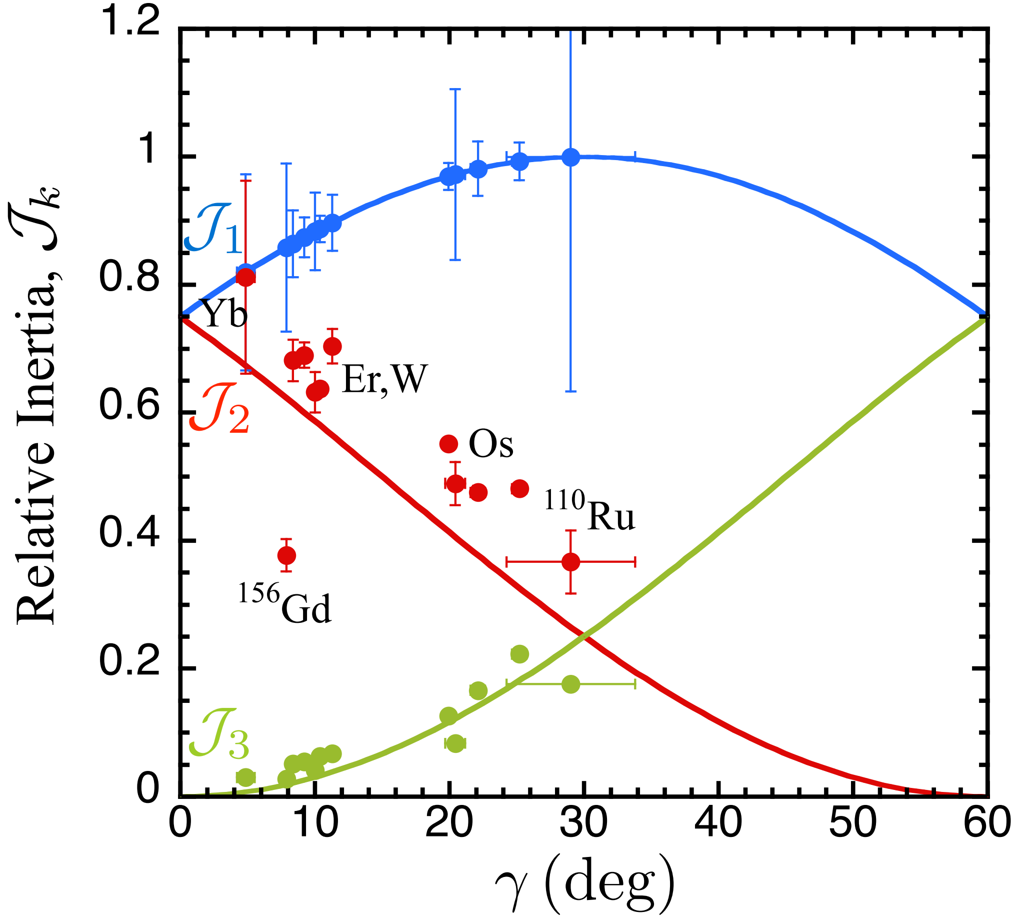
Jenkinswood, Fig. 4.35



Nuclear moments of inertia fitted to a triaxial rotor model with independent components of the inertia tensor

$$\mathcal{J}_{irrot.,\,k} = 4B_{irrot.}\beta^2 \sin^2\left(\gamma - k\frac{2\pi}{3}\right)$$

J.M. Allmond and JLW
Phys. Lett. **B767** 226 (2017)



k = 1 norm. to data

k = 2

k = 3 symm. axis
@ $\gamma = 0°$ and $60°$

NOTE: relative values do not prove irrotational flow—they conform to the SO(5) invariant form of the inertia tensor.

NEED MORE DATA

Headache: shell model calculations have to use effective E2 "charges": STANDARD VALUES– $e_n = +0.5\ e$, $e_p = +1.5\ e$; but here ... ?

E_x (keV)
$B(E2; 2_1^+ \rightarrow 0_1^+)$ W.u.

N = Z

N > Z

Isospin mirror pairs

^{54}Ni 1392.3 10.0^{20}

$^{56}_{28}$Ni$_{28}$

^{58}Ni 1454.2 10.0^{4}

^{54}Fe 1408.2 11.1^{3}

^{42}Ti 1554.6 16^{4}

^{38}Ca 2213.2 2.5^{6}

$^{40}_{20}$Ca$_{20}$

^{42}Ca 1524.7 9.5^{4}

^{38}Ar 2167.5 3.40^{16}

^{18}Ne 1887.3 17.7^{18}

$^{16}_{8}$O$_{8}$

^{18}O 1982.1 3.32^{9}

^{14}C 7012.4 1.8^{3}

^{50}Ti 1553.8 5.46^{19}

^{46}Ca 1346.0 3.63

$^{48}_{20}$Ca$_{28}$

^{50}Ca 1026.7 0.68^{2}

^{46}Ar 1577[1] 4.0^{8}

^{134}Te 1279.1 5.12^{21}

$^{132}_{50}$Sn$_{82}$

^{210}Po 1181.4 0.56^{12}

^{206}Pb 803.1 2.80^{9}

$^{208}_{82}$Pb$_{126}$

^{210}Pb 799.7 1.4^{4}

Use of effective charges abandons any prospect of discovering where E2 collectivity comes from.

CONCLUSION:
neutrons can have effective electric quadrupole "charges" as large as protons.

Weakly deformed nuclei

There is a serious lack of systematic data.

Triaxial rotor descriptions need thorough exploration.

Shape coexistence needs to be systematically identified.

How weak can deformation be and still yield a useful coupling scheme?

FOOTNOTE: When David Jenkins and I came to weakly deformed nuclei and a planned chapter in "Nuclear Data: a Primer", after extensive scrutiny of the data base we decided that there was such a serious lack of systematic data that it was not possible to present a useful view at an introductory level.