Coexistence in Nuclei

John L. Wood
School of Physics
Georgia Institute of Technology
Atlanta

References:
"Fundamentals of Nuclear Models: Foundational Models"
--David J. Rowe and JLW, World Scientific, 2010 [Rowe & Wood]

"Shape Coexistence in Atomic Nuclei"
--Kris Heyde and JLW, Reviews of Modern Physics Vol. 83 1467 2011
[Heyde & Wood]

To study the structure of the nucleus is to study the quantum-mechanical finite many-body problem

- In the 63 years from 1900 to 1963 we went "from quantum to quark"—three fundamental levels of organization of matter (atomic, nuclear, hadronic).

- In the 63 years from 1952 to 2015 we went "from the collective model of the nucleus to the collective model of the nucleus"--!?

- Observation: the study of many-body quantum systems is enormously more complicated than the study of one-body quantum systems.

Shape Coexistence in Nuclei:

origin of the idea

PHYSICAL REVIEW VOLUME 101, NUMBER 1 JANUARY 1, 1956

Interpretation of Some of the Excited States of 4*n* Self-Conjugate Nuclei*

H. MORINAGA†
Department of Physics, Purdue University, Lafayette, Indiana

(Received August 5, 1955)

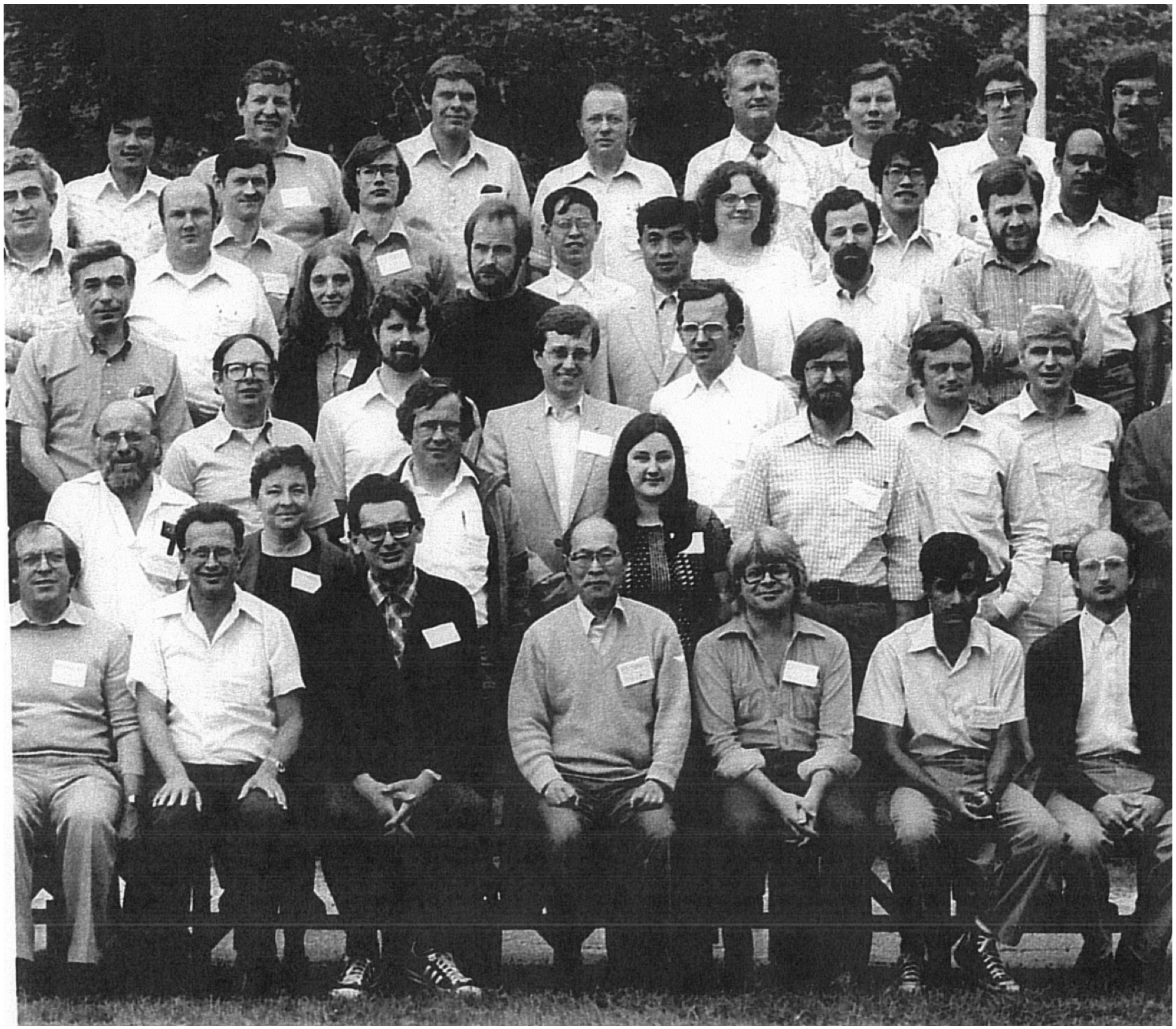
An attempt is made to give a general account for some of the excited levels of 4*n*-type self-conjugate light nuclei, especially for characteristic low-lying 0^+ levels and also for the 2^+ levels which appear not too far above the 0^+ levels in every case except the O^{16} ground state. It is pointed out that these 2^+ levels may arise from the same configuration as the lower lying 0^+ states which are considered to be deformed. The degree of deformation is estimated from the 0^+-2^+ energy separation and found to correspond to quite high deformations in some cases. The 6.06-Mev, 0^+, pair emitting state in O^{16}, which is considered to be a "hole configuration" by Christy and Fowler, may be deformed and is suspected to have a shape like a line of four alpha particles. Also, a rotation-like series of levels with spins and parities, 0^+, 1^-, 2^+, 3^-, and 4^+ among the highly excited states of Mg^{24} which appears to correspond to a series expected for a linear rotator with six alpha particles in a line is discussed. With Ne^{20}, indications of medium-deformed states are found. Analogous discussions on the levels in Be^8 and C^{12} are tried although the experimental evidence is less conclusive.

The 6.06-Mev, 0+ … state in 0^{16},… may be deformed …

† On leave from the University of Tokyo, Tokyo, Japan.

Where Haruhiko Morinaga liked to go fishing (Hope's Nose, Torbay, England)
--JLW recollection of a conversation with Morinaga-san,
Amsterdam Conference, 1974

Solvers of the nuclear many-body problem: Gordon Research Conference, 1981



Solvers of the nuclear many-body problem: Boson-ists—Erice, Sicily, 1982

Shape coexistence in ^{16}O, ca. 2010

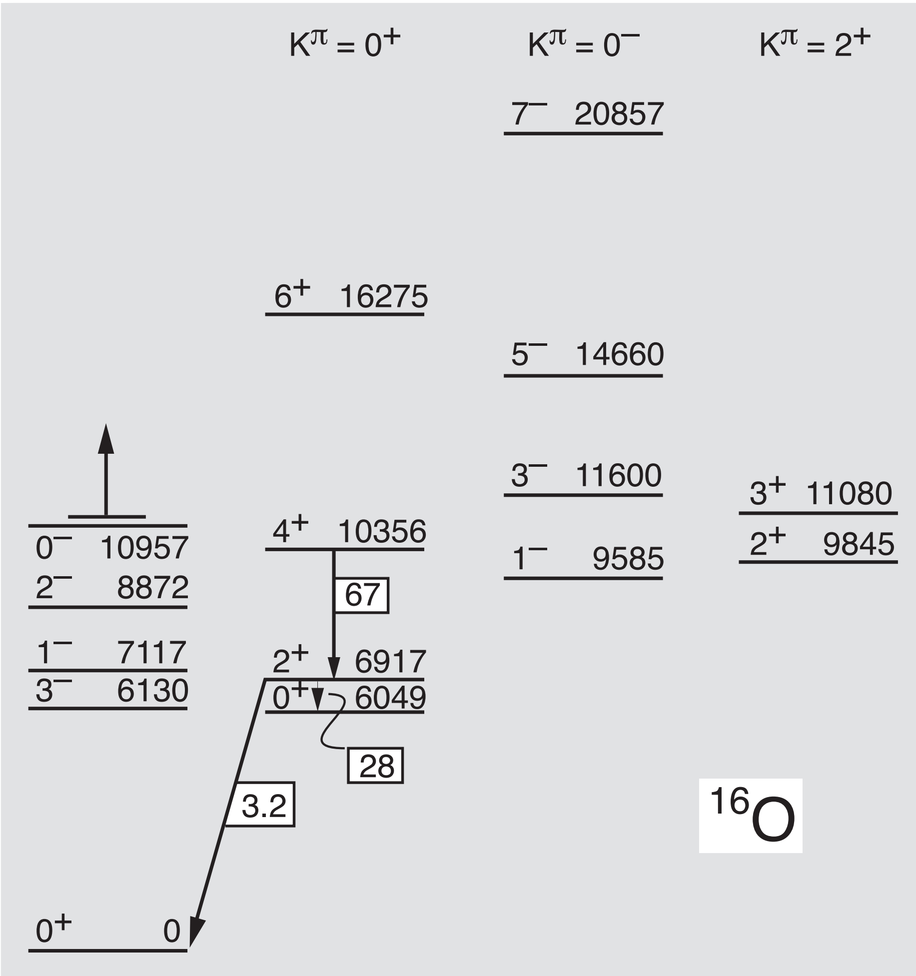


Figure from Rowe & Wood

Energies of states are given in keV.

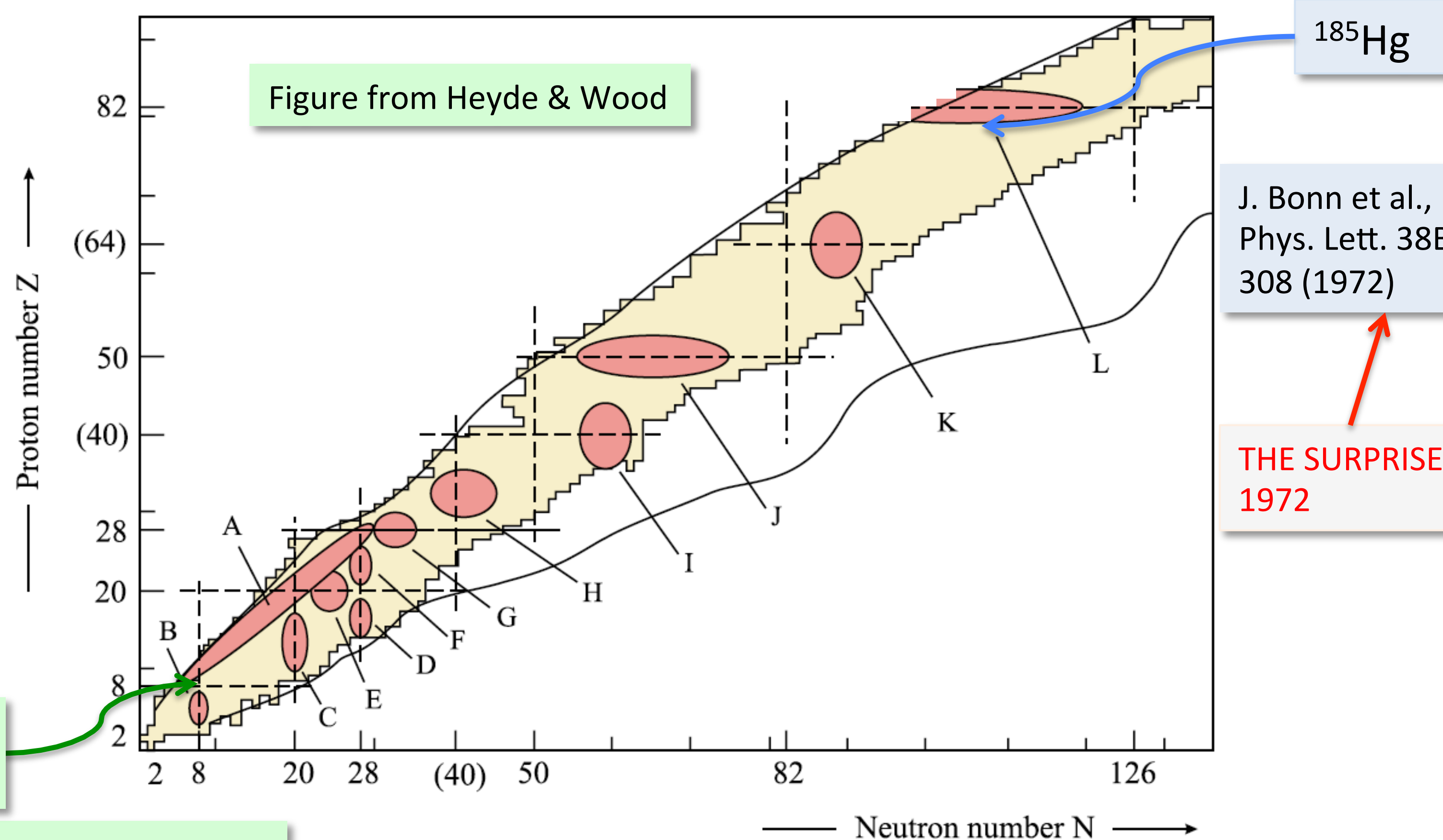
B(E2) values are given in W.u.

States on the far left are spherical.

The beginnings of three deformed bands, with K = 0, 0, 2, are shown.

--Morinaga-san was right!

Coexistence: where we have been



J. Bonn et al., Phys. Lett. 38B, 308 (1972)

THE SURPRISE: 1972

H. Morinaga, Phys. Rev. 101, 254 (1956)

THE BEGINNING: 1956

Coexistence: Synopsis of this talk

- An overview of the Pt – Pb (Z = 82) region:

  ★ the region with by far the most widely characterized manifestation of shape coexistence in nuclei

  ★ a region that demanded development of techniques for rare isotope studies

  ★ a region where deformed states "intrude" below the expected spherical states

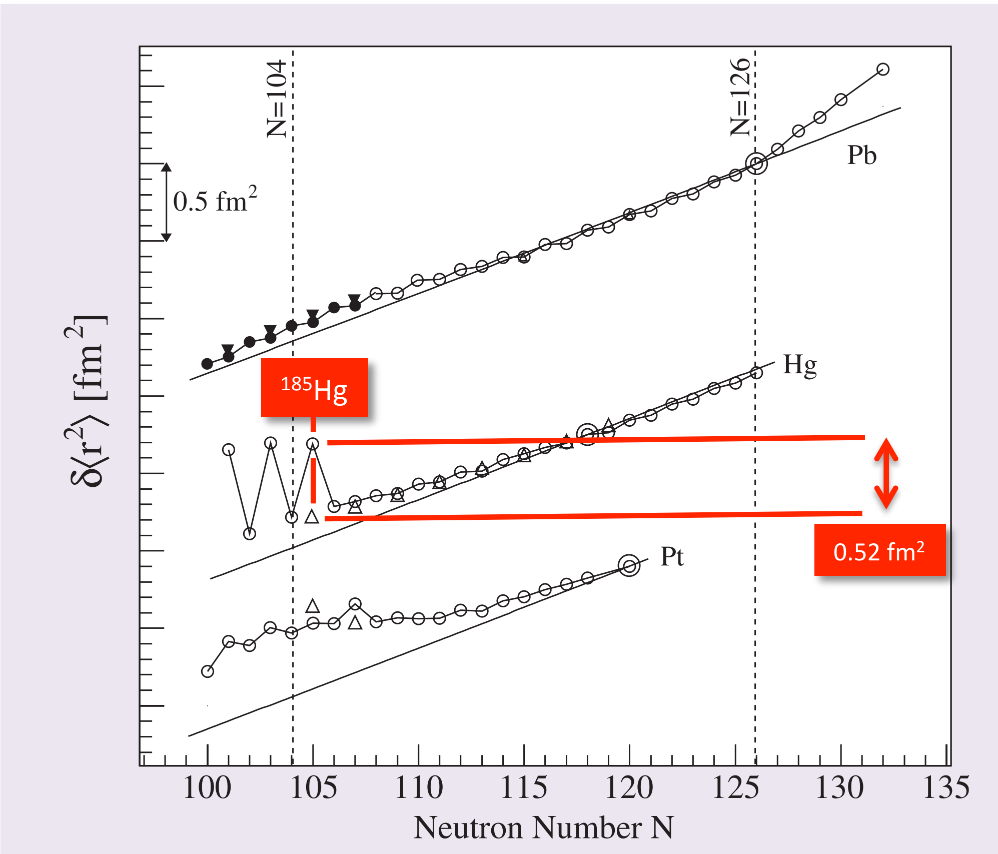
- A view of the ^{32}Mg – ^{48}Ca (N, Z = 20) region:

  is the spherical shell at N = 20 really breaking down?

- A brief view of the ^{100}Zr region:

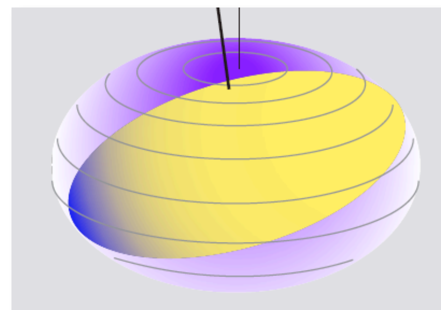
  when do subshells produce coexistence?

Isotope shifts in the Pb, Hg, and Pt isotopes and the ^{185}Hg isomer shift



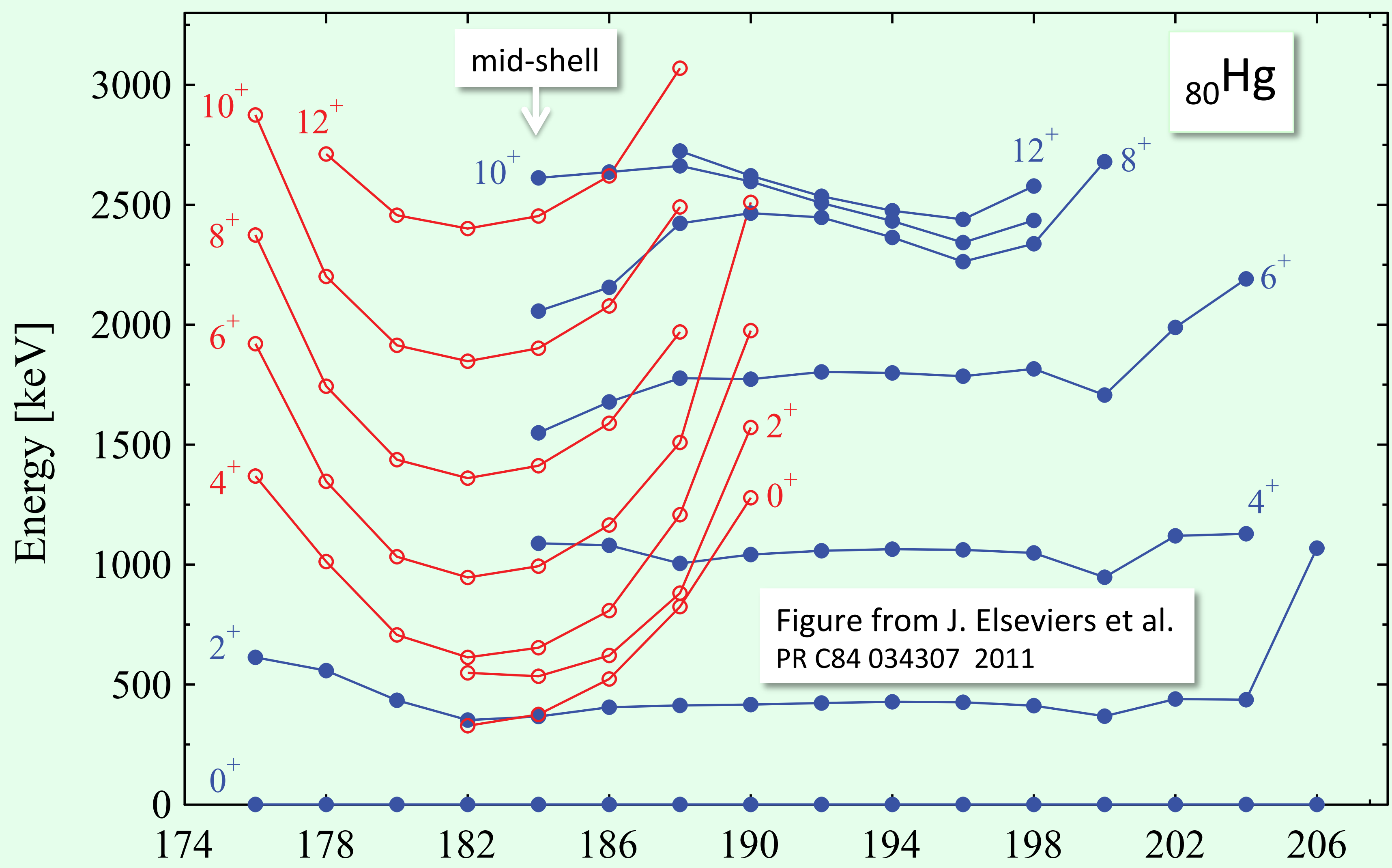
^{185}Hg / ^{186}Hg isotope shift
J. Bonn et al., Phys. Lett. B 38, 308 (1972)

^{185}Hg^m / ^{185}Hg^g isomer shift
P. Dabkiewicz et al., Phys. Lett. B 82, 199 (1979)

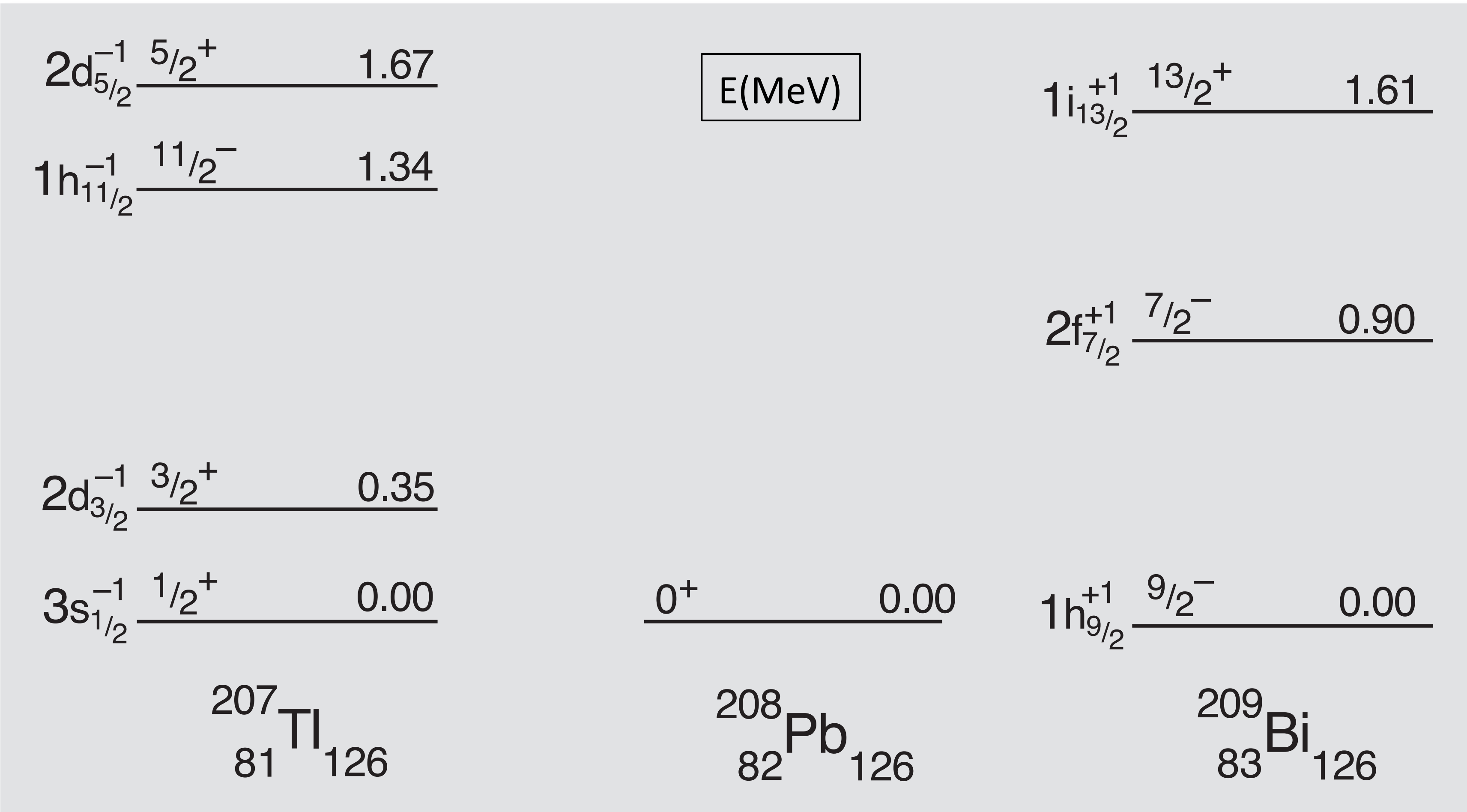


Shape coexistence in the even-Hg isotopes:

NOTE characteristic *parabolic energy* trend

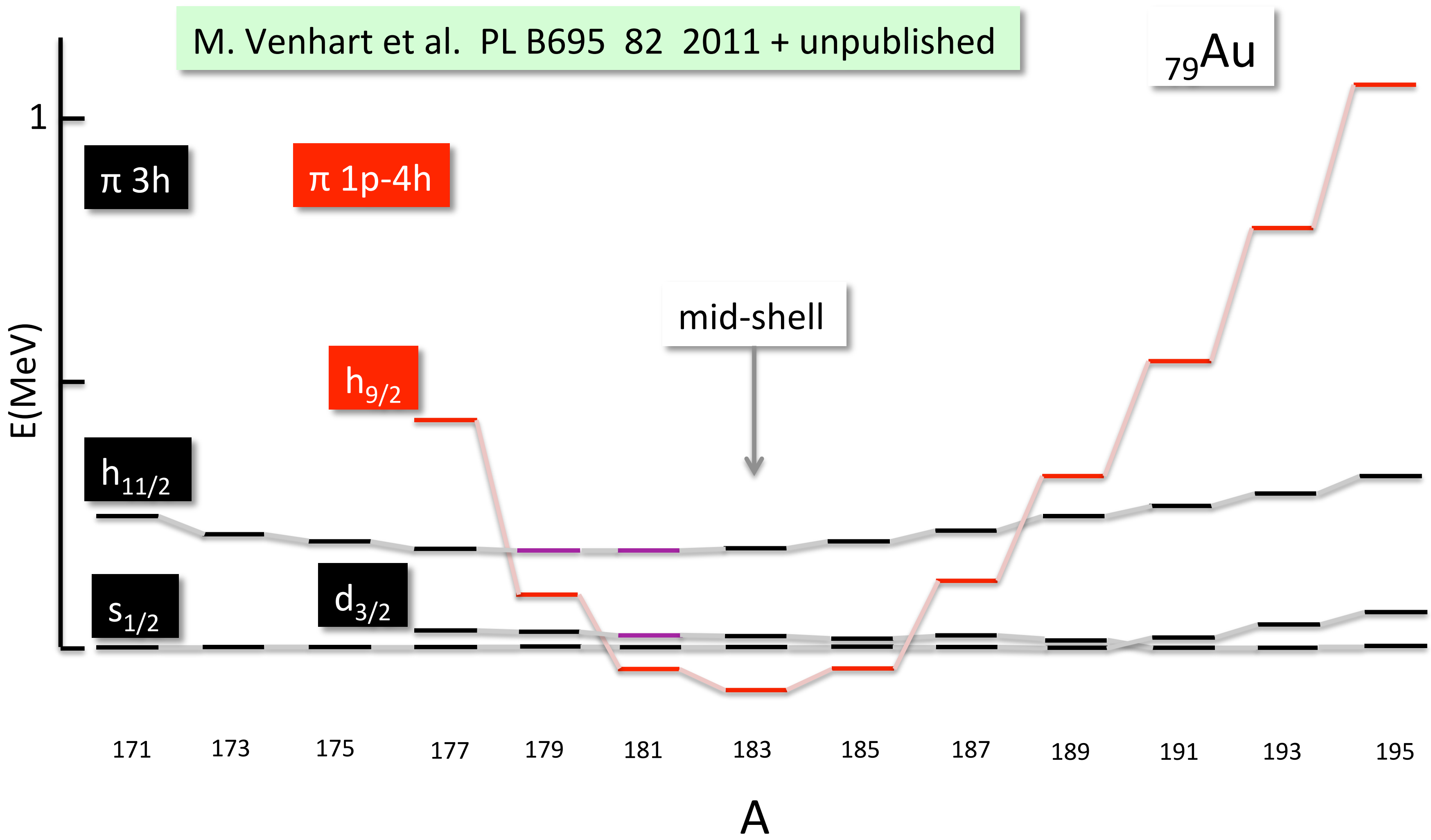


Proton single-hole / particle states near Z = 82



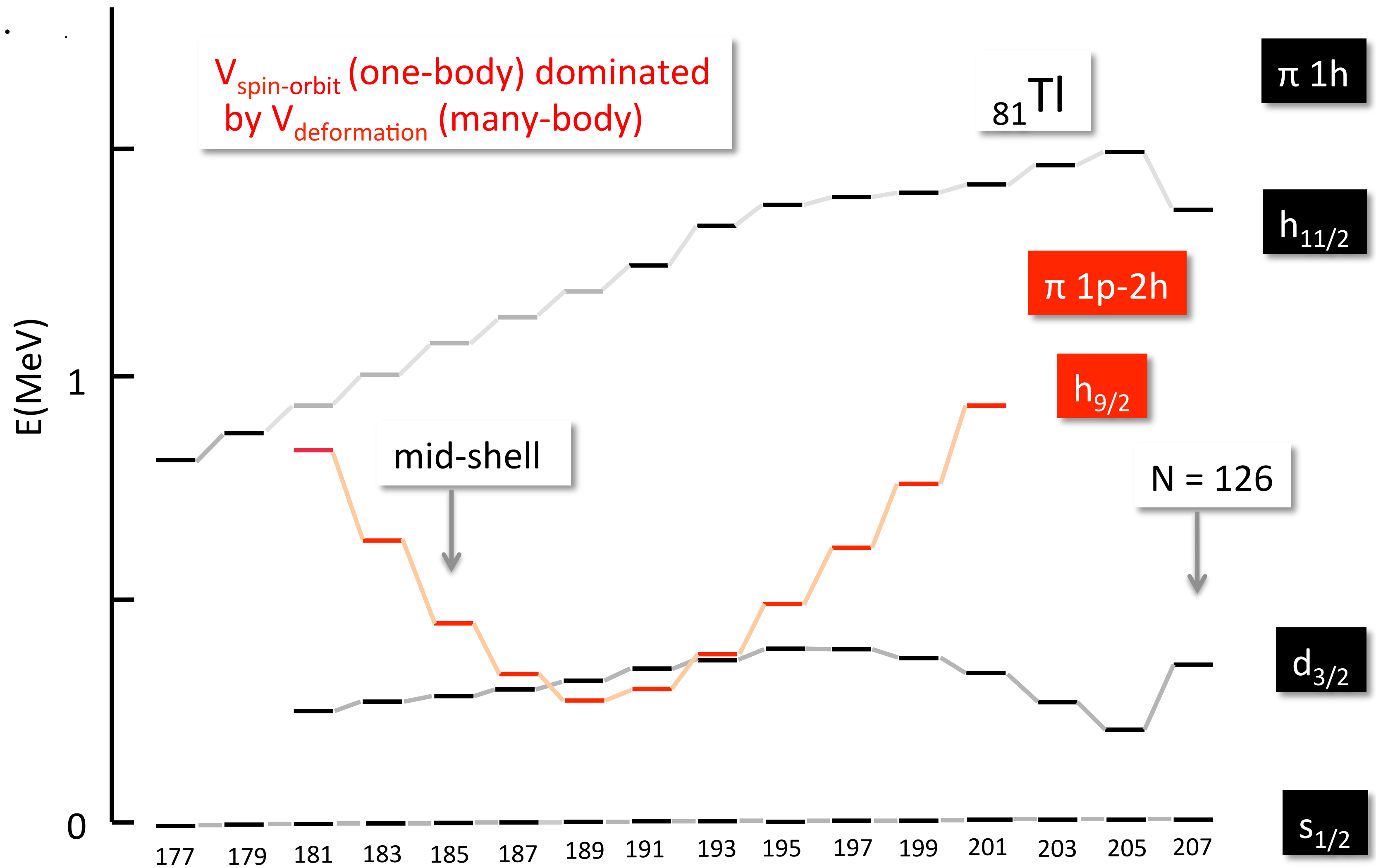
Odd-Au isotopes: $h_{9/2}$ "intruder" state

NOTE characteristic *parabolic energy* trend



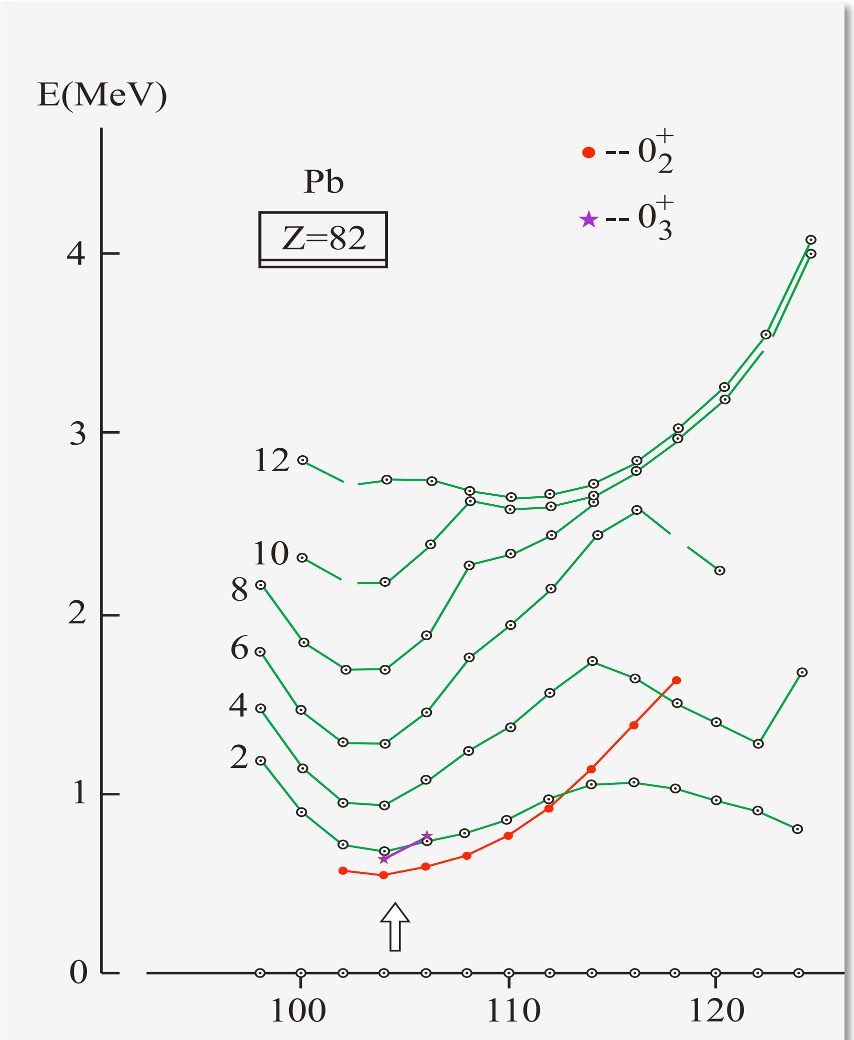
Odd-Tl isotopes:

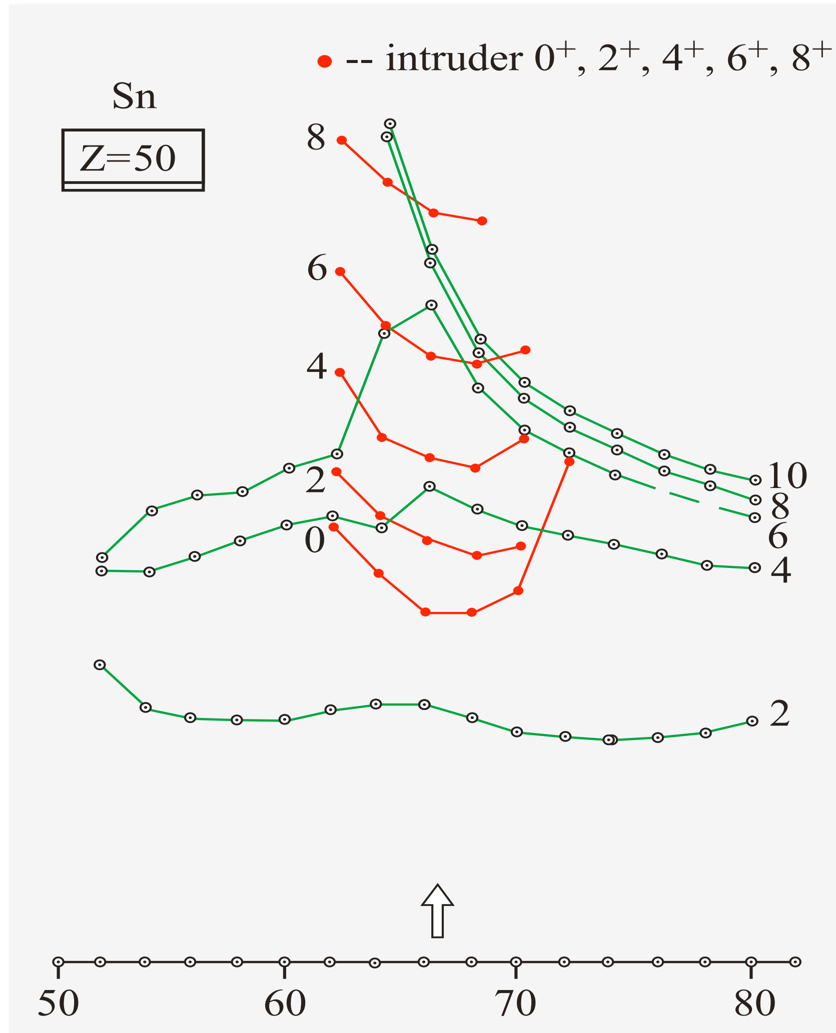
NOTE the $h_{9/2}$ state lies *below* the $h_{11/2}$ state



Even Pb and Sn isotopes:

green—yrast states (easily seen); red—non-yrast states (seen with difficulty)





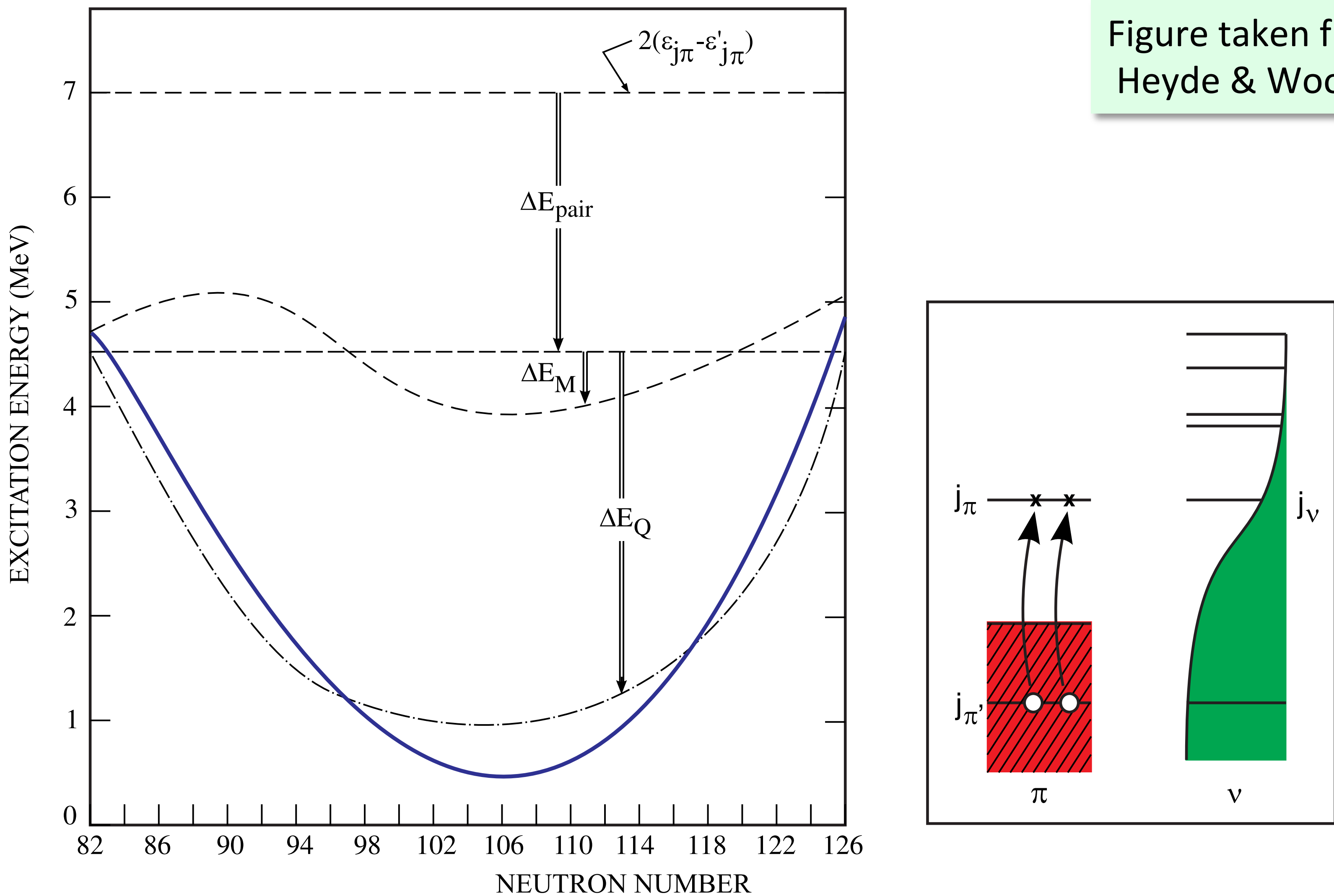
mid shell

neutron number

mid shell

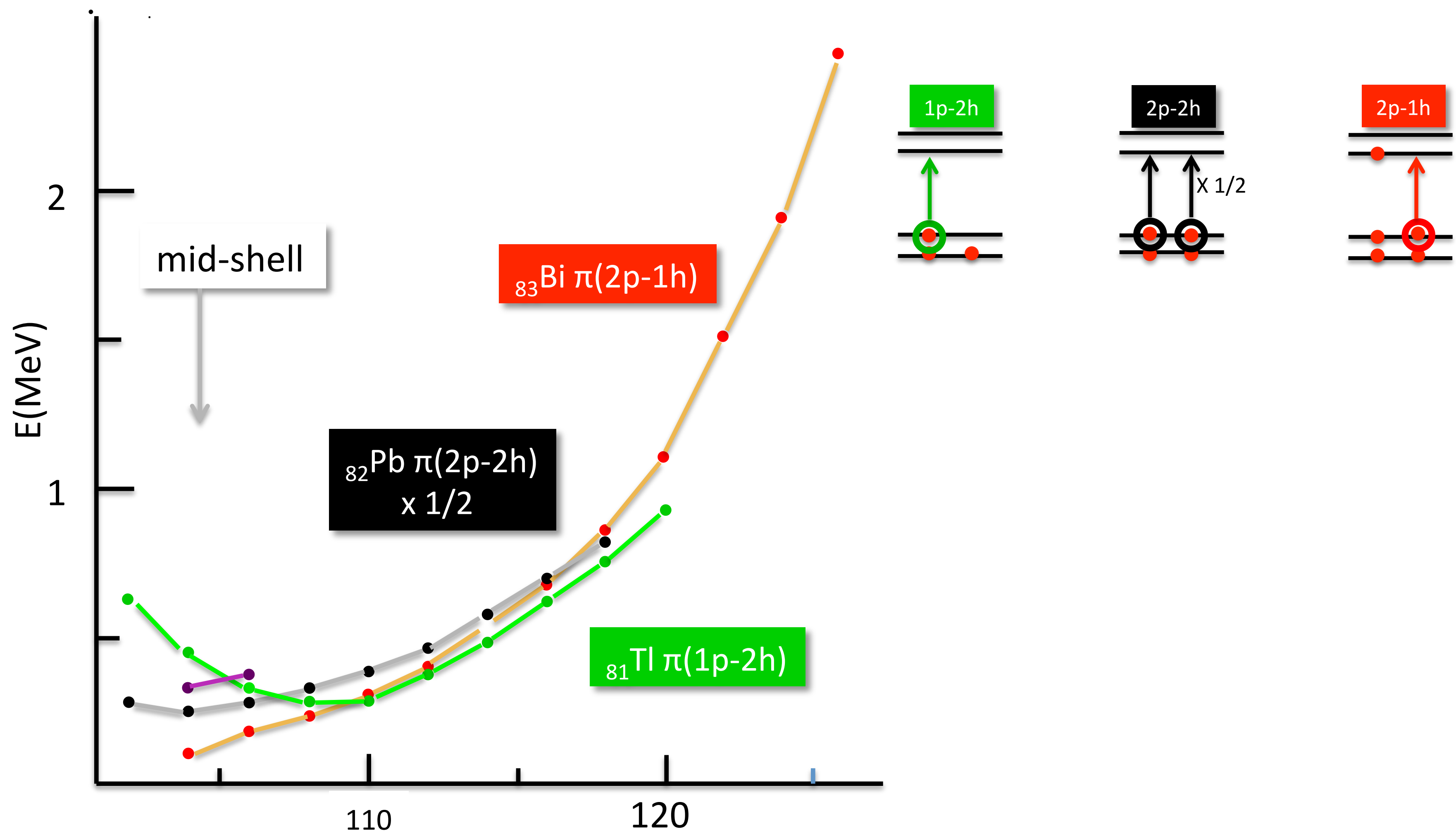
Energy contributions to a π(2p-2h) intruder state in the Pb isotopes

Figure taken from:
Heyde & Wood



Relationship between energies of intruder states in odd-mass nuclei and coexistence in even-mass nuclei

Unpaired nucleons are not the "drivers" of deformation



From heavy to light nuclei:
intruder states and coexistence at N,Z = 20

- "We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances. Therefore, to the same natural effects we must, so far as possible, assign the same causes."

  --Isaac Newton

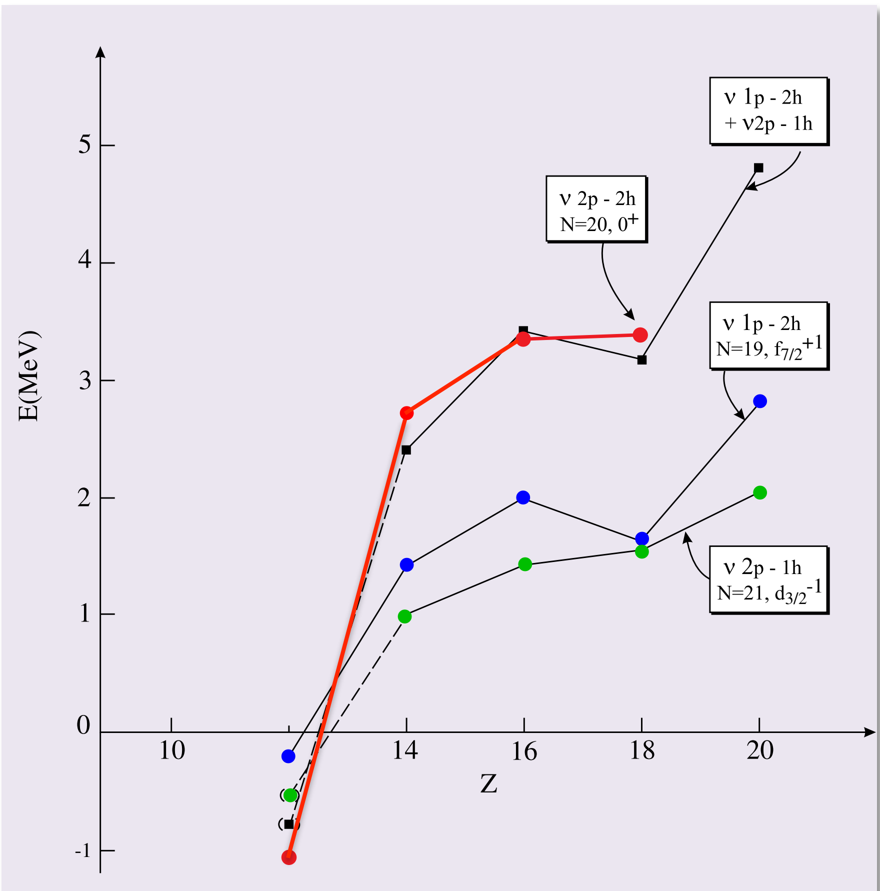
- "Everything should be made as simple as possible, but not simpler."

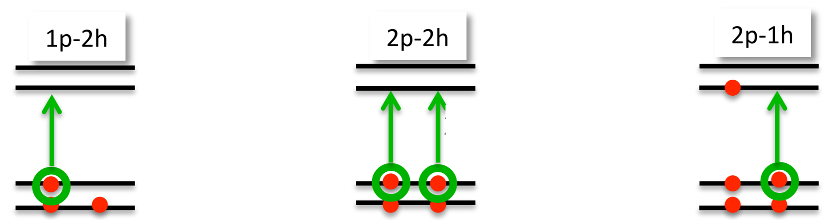
  -- Albert Einstein

0^{+} ν(2p-2h) intruder state energies @ N=20:

estimates from ν (1p-2h) + ν (2p-1h) energies

Figure adapted from Heyde & Wood





N = 19

$f_{7/2}^{+1}$ x Cooper hole pair

N = 20

Cooper particle pair x Cooper hole pair

N = 21

$d_{3/2}^{-1}$ x Cooper particle pair

Expt. ● ν 1p-2h

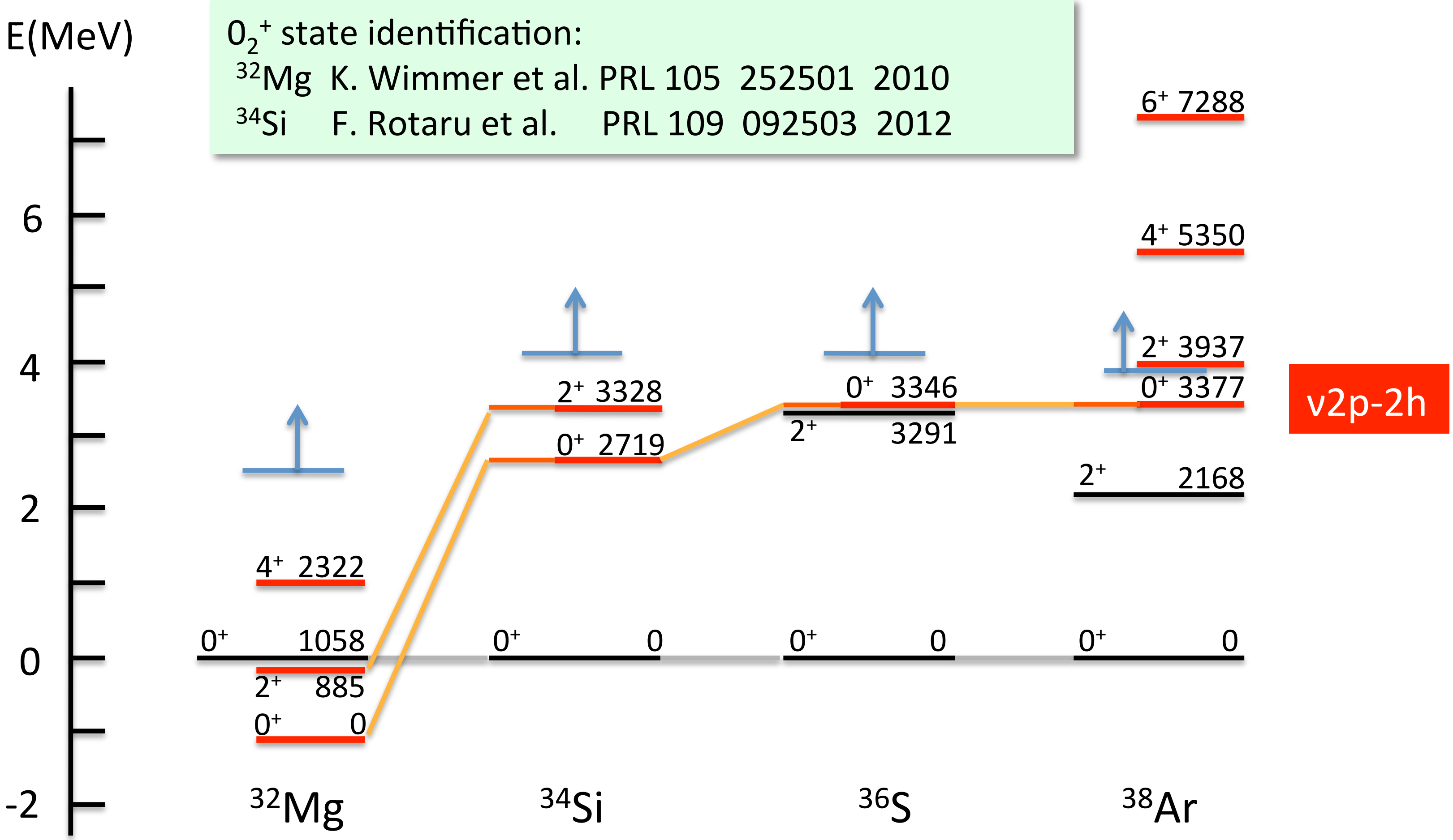
Expt. ● ν 2p-2h

Expt. ● ν 2p-1h

Est. ■ ν 2p-2h

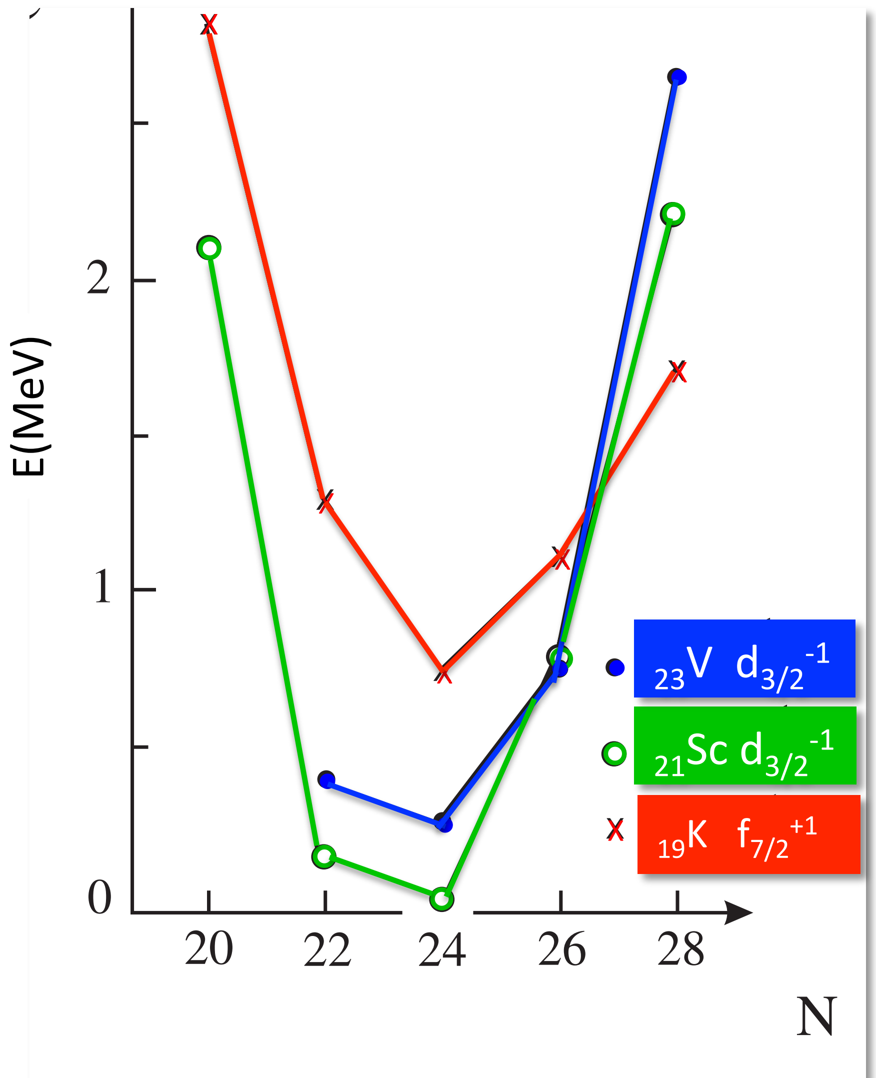
Intruder states or the “island of inversion” @ N=20

0_2^+ state identification:
^{32}Mg K. Wimmer et al. PRL 105 252501 2010
^{34}Si F. Rotaru et al. PRL 109 092503 2012



Coexistence in the odd K, Sc, and V isotopes:

deformed intruder states exhibit a characteristic parabolic energy trend



NOTE:

★ Parabolas sharper in light nuclei than in heavy nuclei because shells more confining.

★ Ground state of $^{45}Sc_{24}$: almost an "island of inversion".

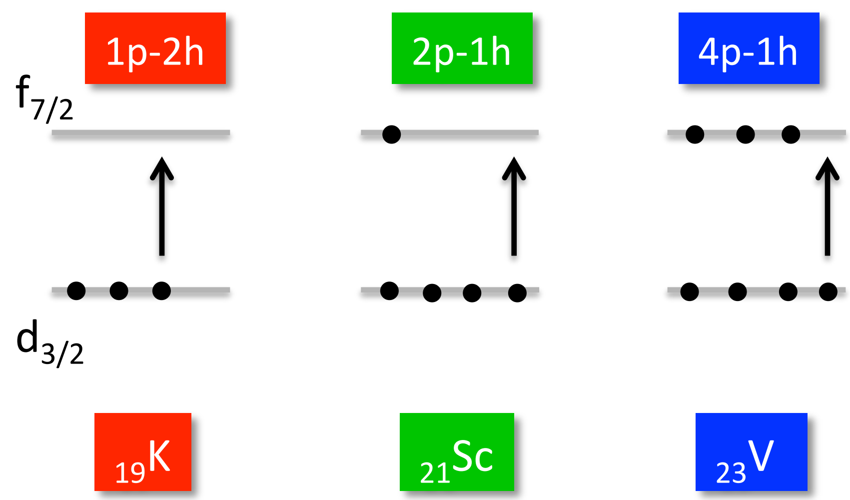
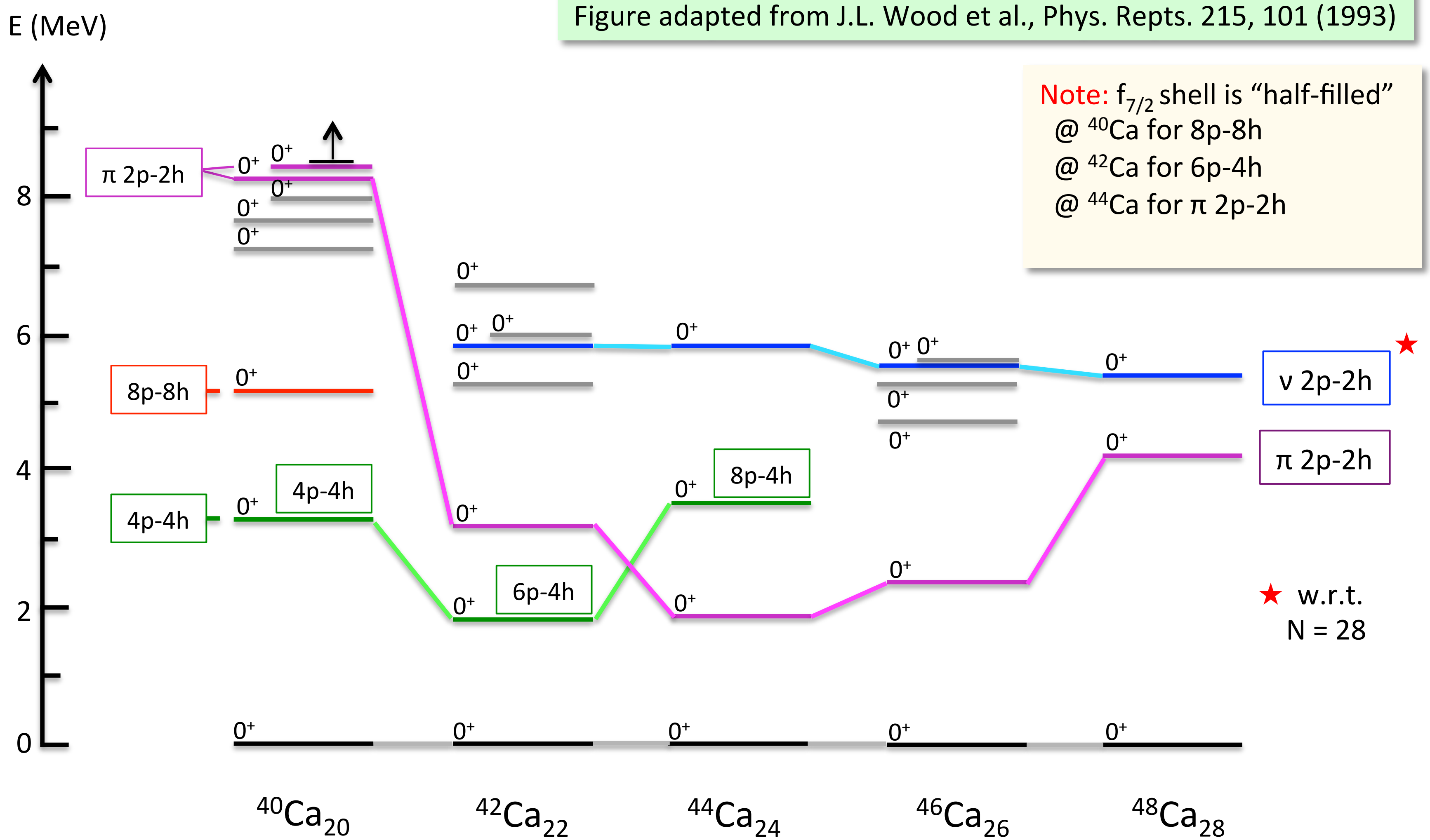


Figure taken from Heyde & Wood

Excited 0^+ states in the Ca isotopes:

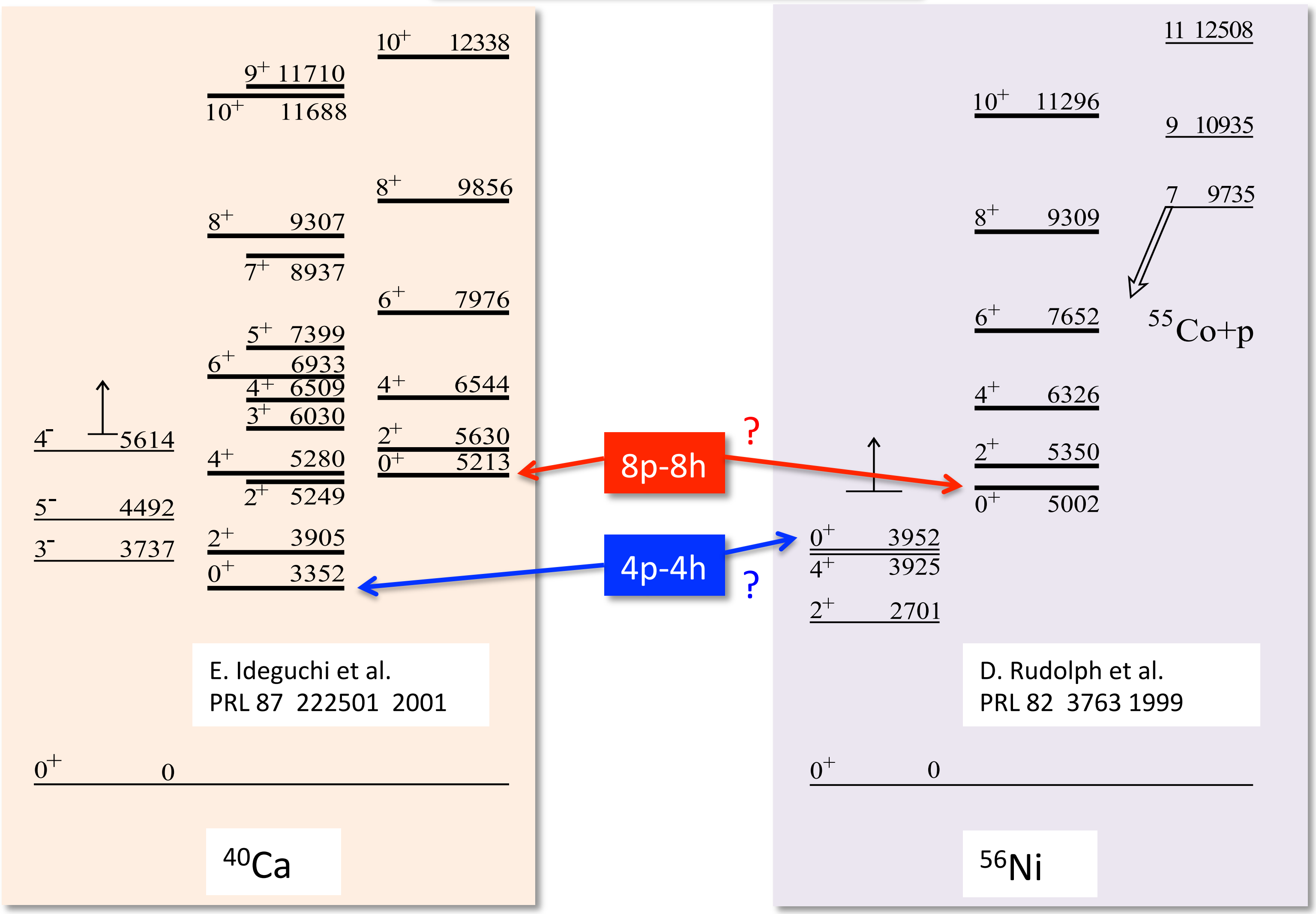
multi-particle-multi-hole states, and…?

Figure adapted from J.L. Wood et al., Phys. Repts. 215, 101 (1993)



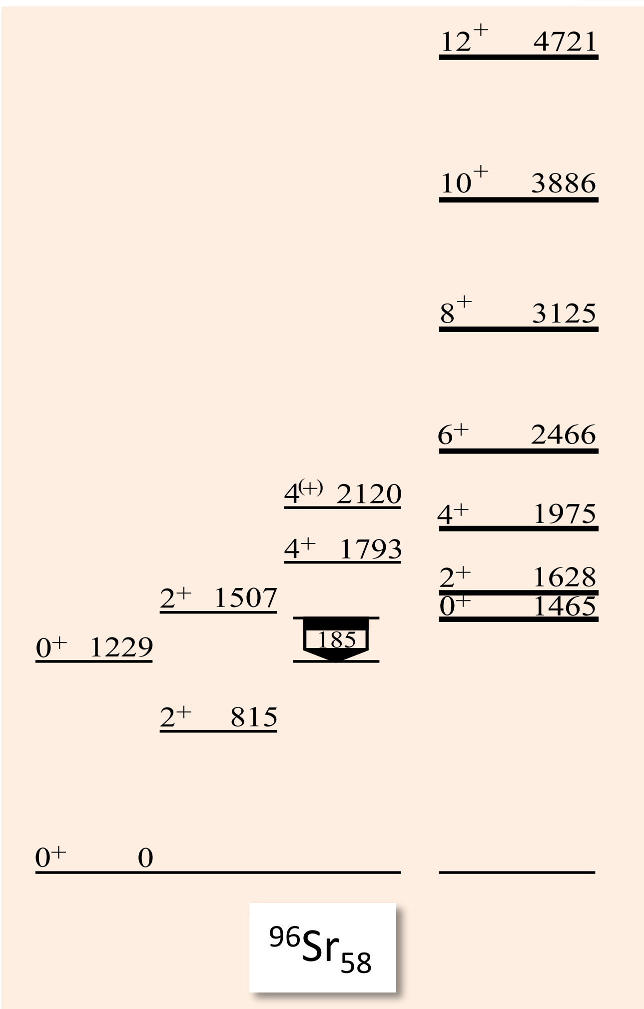
Shape coexistence in the double-closed shell nuclei ^{40}Ca and ^{56}Ni

Figure from Heyde & Wood



Shape coexistence and subshells: ^{96}Sr and ^{98}Zr

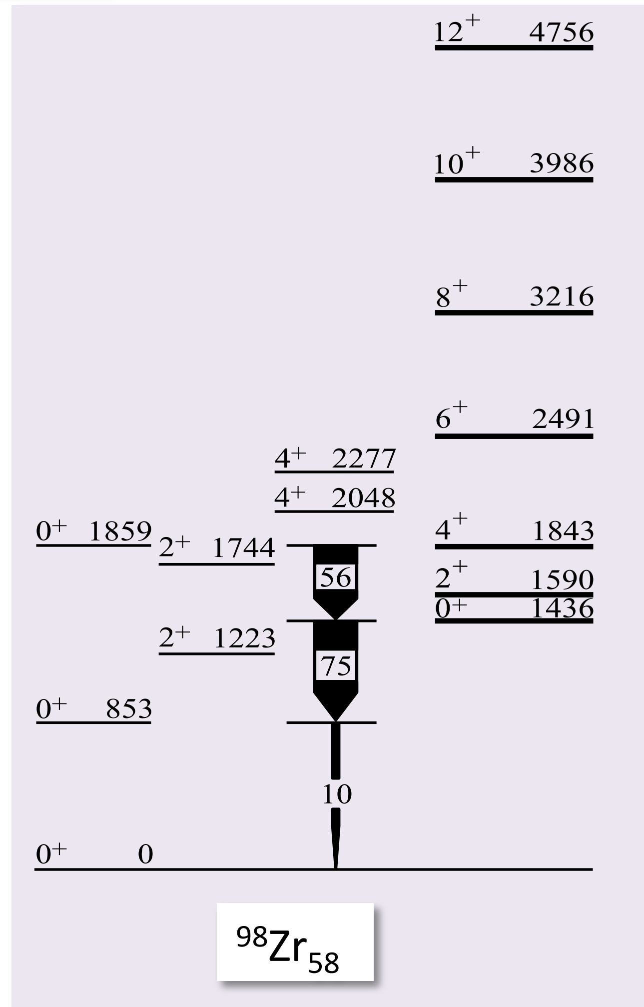
Figure: Heyde & Wood



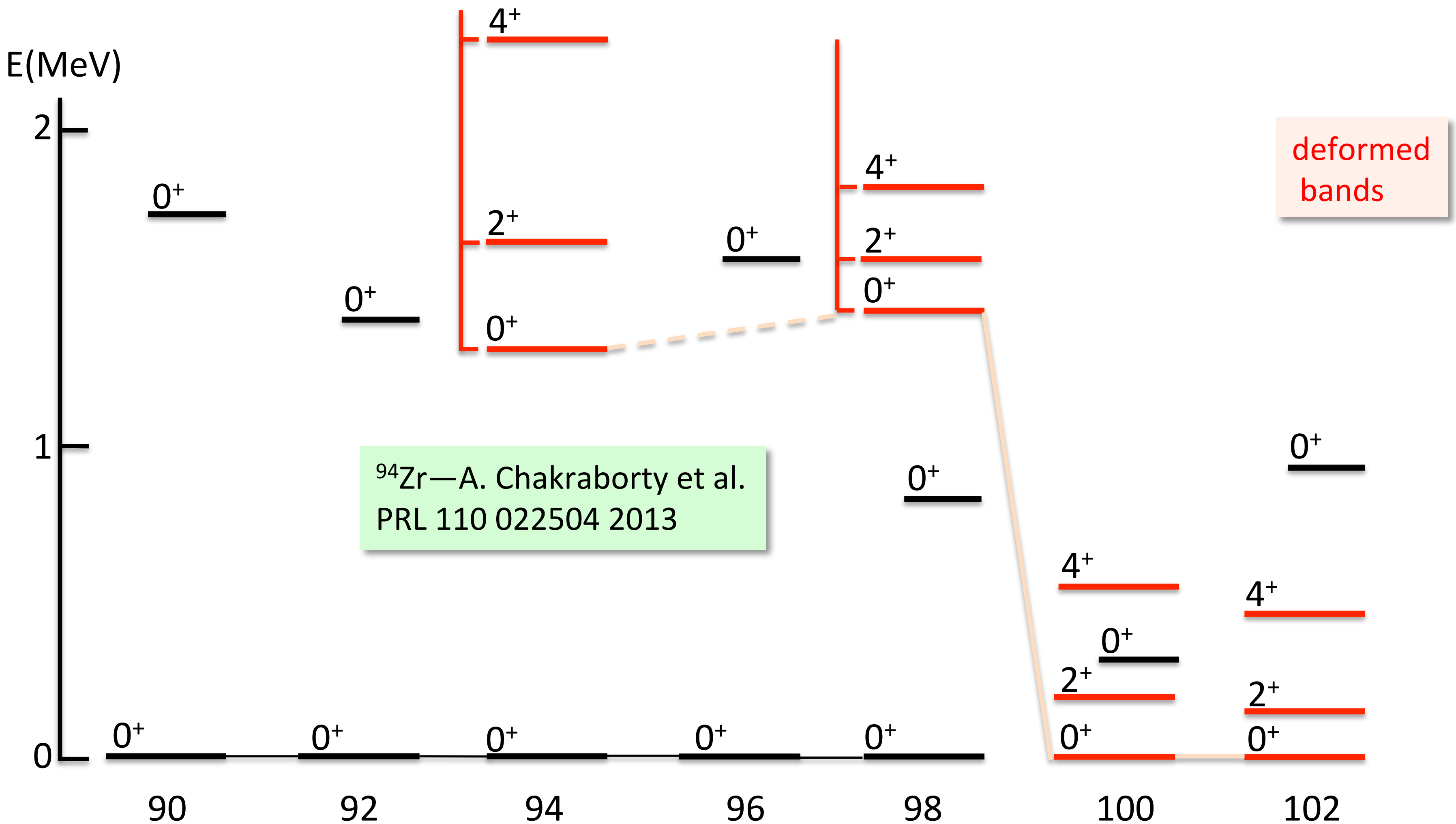
E0 transitions
$\rho^2(E0) \bullet 10^3$ values

G. Lhersonneau et al.
PR C49 1379 1994

C.Y. Wu et al.
PR C70 064312 2004



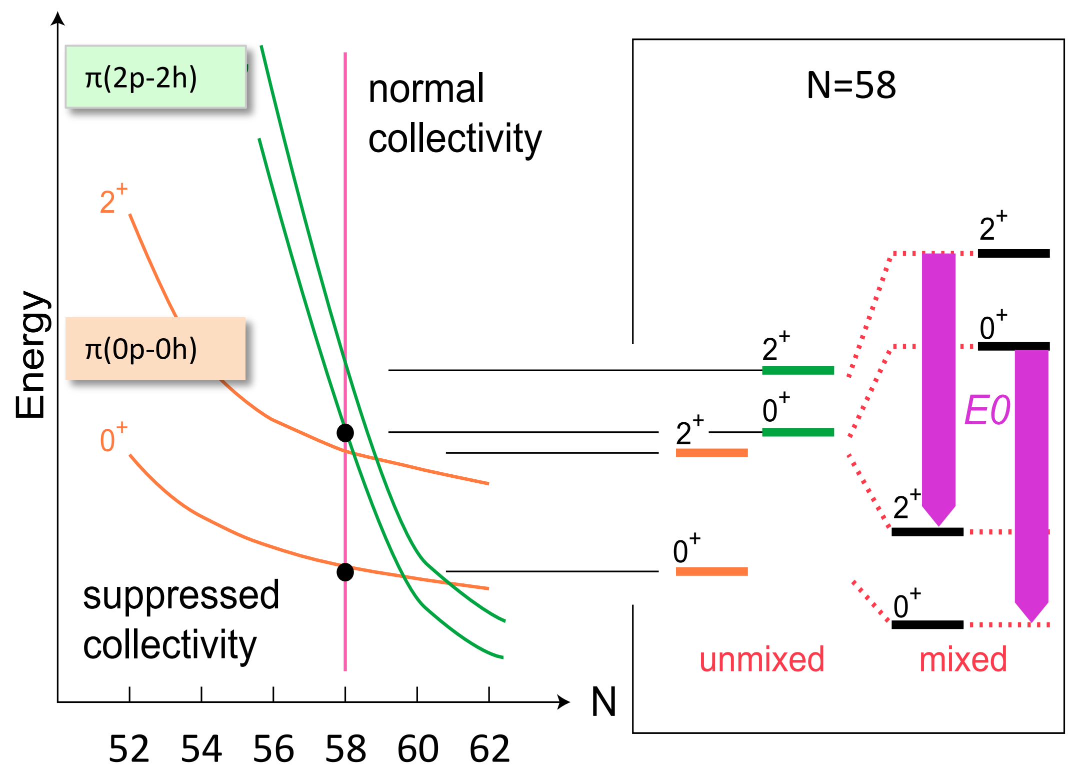
Deformation in Zr isotopes, 50 ≤ N ≤ 62



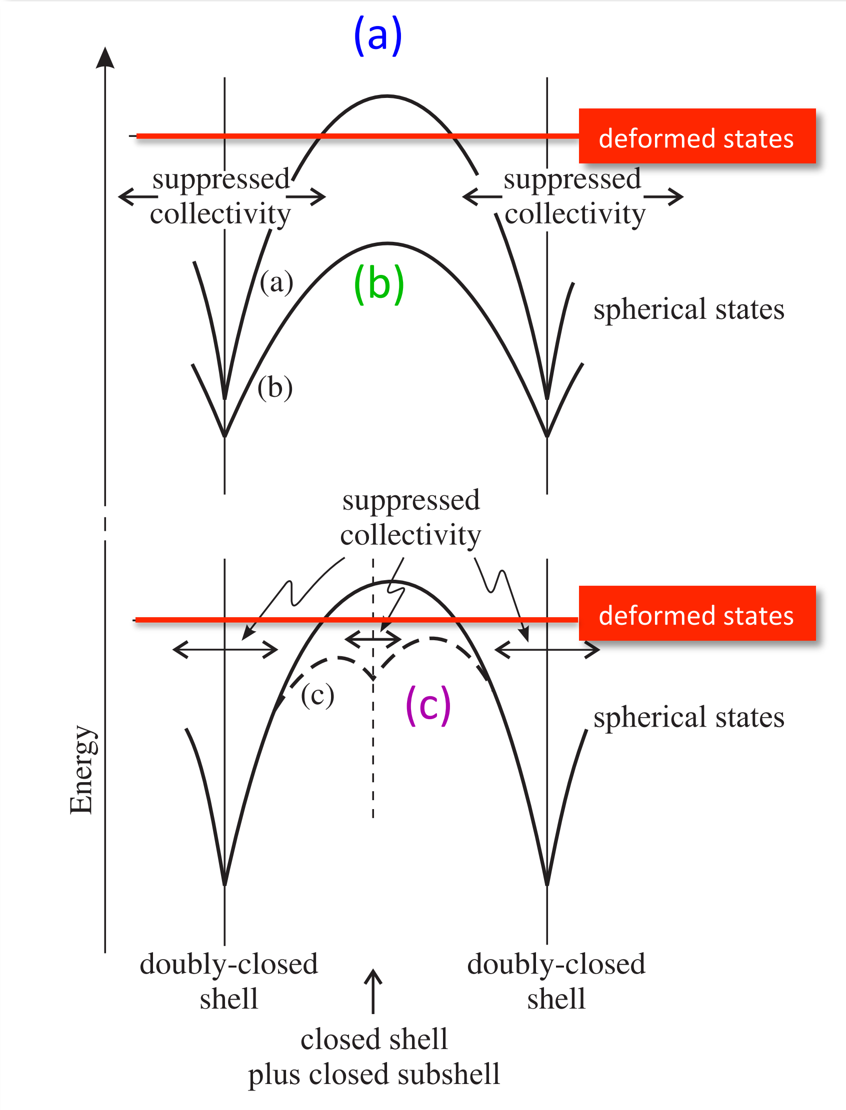
A deformed structure can intrude to become a ground state

Nuclei are manifestations of coexisting structures
that may invert by addition of a few nucleons, and may mix.

Proton pair excitations with respect to the Z = 40 subshell



Shape coexistence at shell and subshell gaps: the suppression of collectivity—THE MESSAGE



Shape coexistence in regions such as:

(a) ^{32}Mg

(b) $^{180\text{-}196}Pb$

(c) $^{90\text{-}98}Zr$

Figure from Heyde & Wood

Shape coexistence: Conclusions

- ★ Shape coexistence probably occurs in all nuclei.
- ★ Shape coexistence can occur at low energy in the regions of shell energy gaps and subshell energy gaps.
- ★ In order to move towards a unified (and complete) view of the collective model of the nucleus, experimental and theoretical work on shape coexistence is essential.
- ★ CONTENTION: deformation is the universal norm of all nuclei (sphericity is a special case of "deformation").

This program is in collaboration with:

Mitch Allmond (ORNL), Paul Garrett (U. Guelph), Kris Heyde (RU Gent), David Rowe (U. Toronto), Martin Venhart (Slovak Academy of Sciences), Steve Yates (U. Kentucky), Ed Zganjar (LSU)

physicists ponder
what is the revelation
shape coexistence
(with apologies to Arima-san)

Odd-mass intruder states and their association with low-energy excited 0^+ states

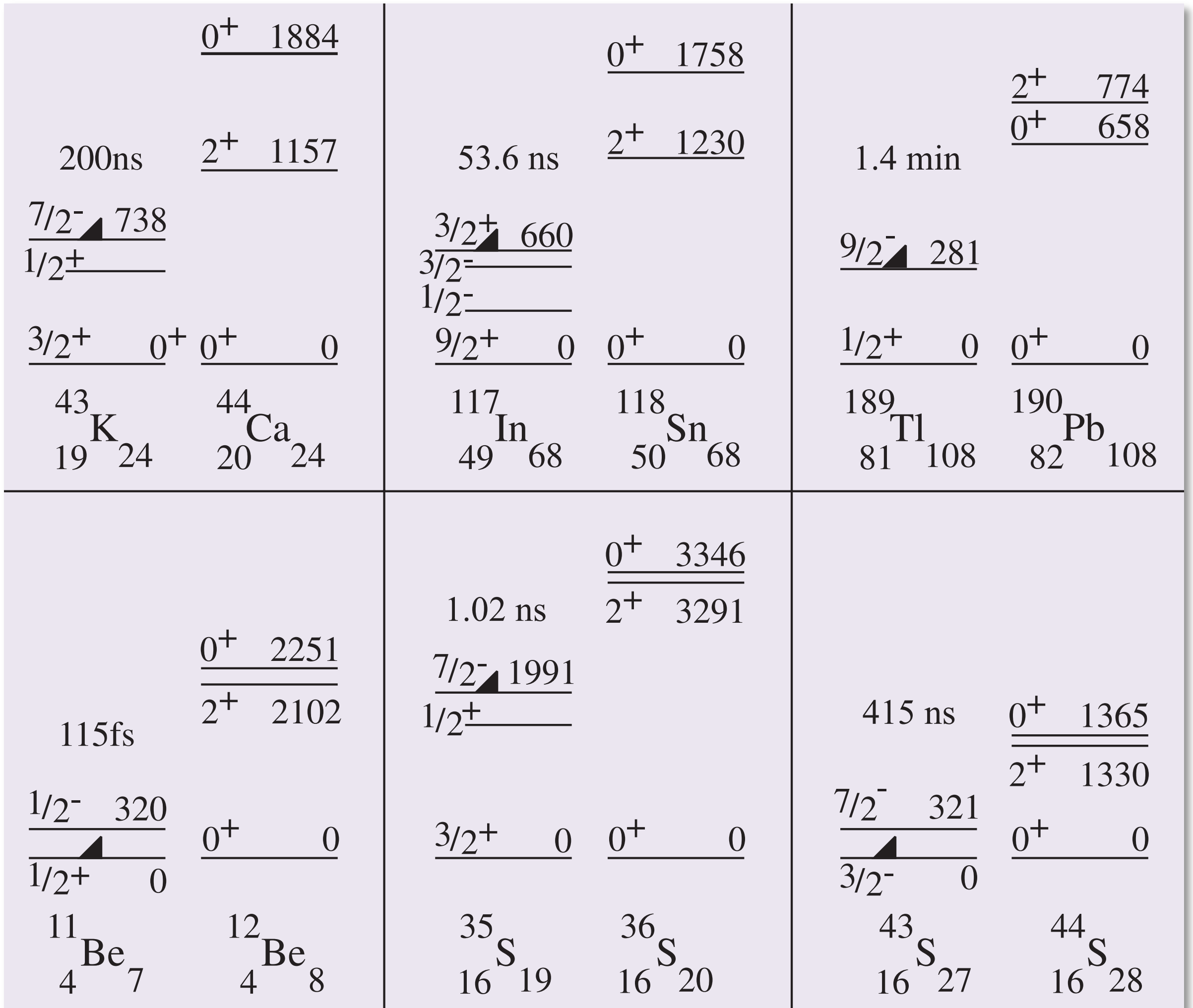
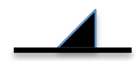


Figure:Heyde & Wood

$T_{1/2}$ isomeric state



intruder state