LECTURE 3.
How well do we understand excited 0^+ states in nuclei?

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

John L. Wood, J. Phys. Conf. Ser. 403 012011 2012

J.L. Wood, Nucl. Phys. A 421 43c 1984 [Suzhou Conf. 1983]

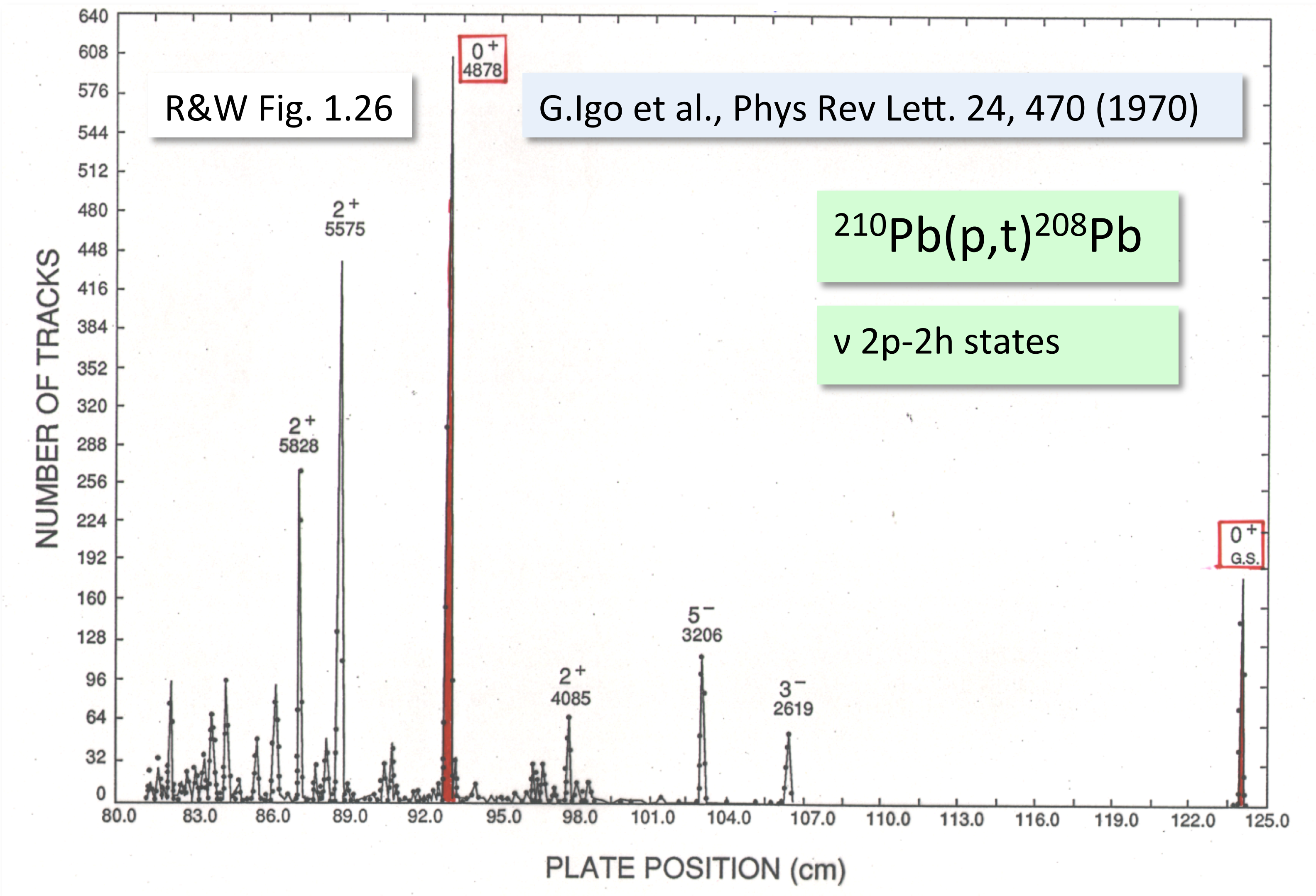
First excited 0^+ states in nuclei: number of theories slightly less than the number of states that are experimentally well categorized

"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

- Pair excitations across closed shells
- Shape coexistence (intruder states)
- Symplectic shell model
- Elliott SU(3) model
- Pairing vibrations in spherical nuclei
- Pairing isomers in deformed nuclei
- Dynamic deformation theory
- Beta vibrations in deformed nuclei
- Two-phonon quadrupole vibrations in spherical nuclei
- Wilets-Jean model seniority-three states
- Critical-point symmetry models
- Boson expansion theory models
- Interacting boson models: coupling of d bosons to J = 0

Excited 0^+ states at closed shells: neutron "pairing vibration" in ^{208}Pb



Excited 0^+ states at closed shells: shape coexistence in ^{16}O

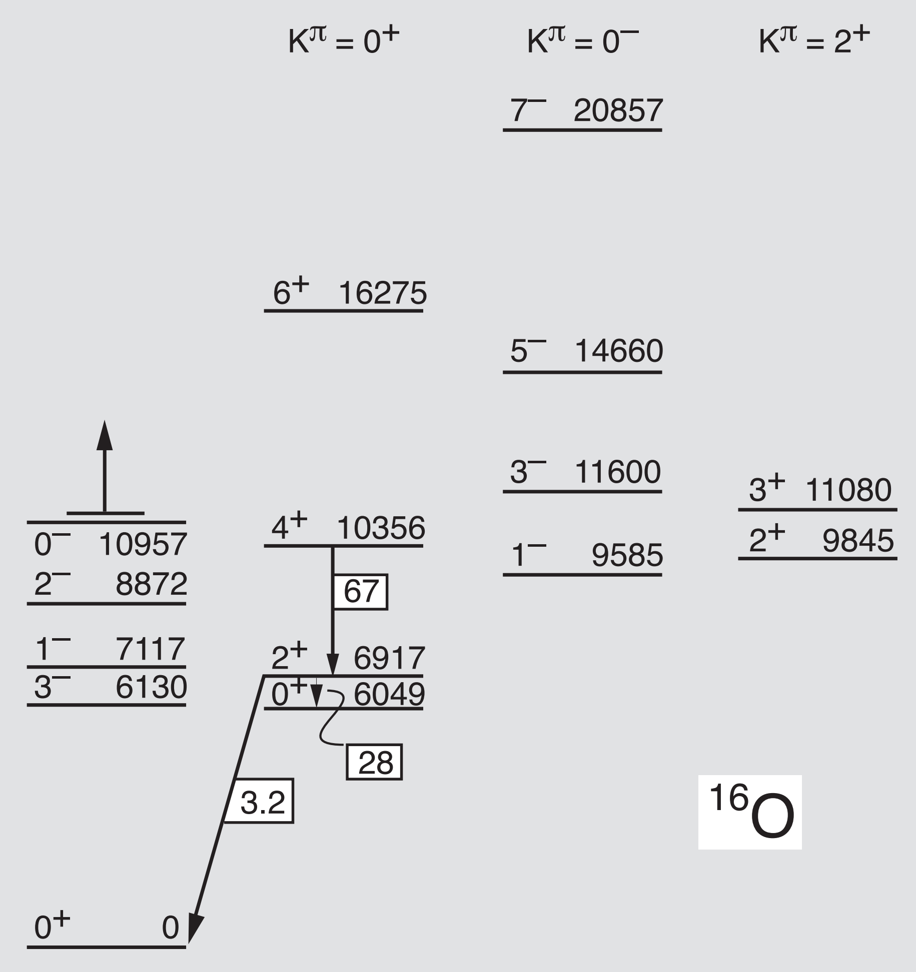


Figure from Rowe & Wood

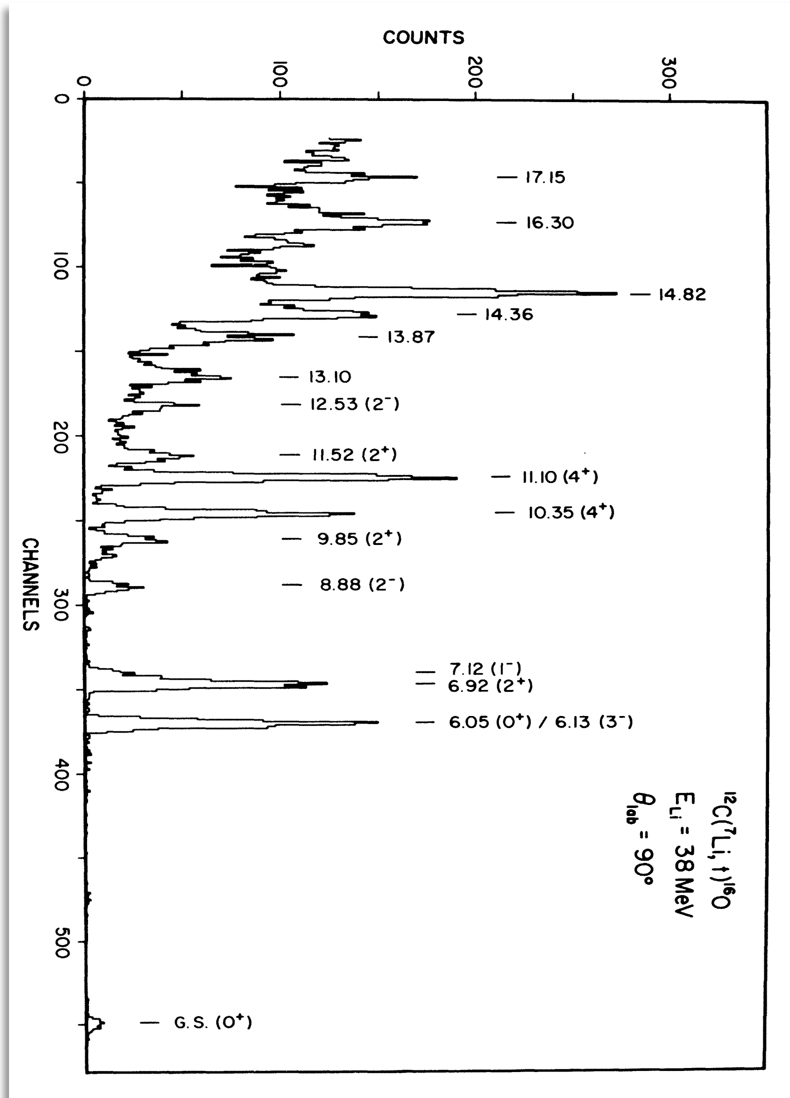
Energies of states are given in keV.

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

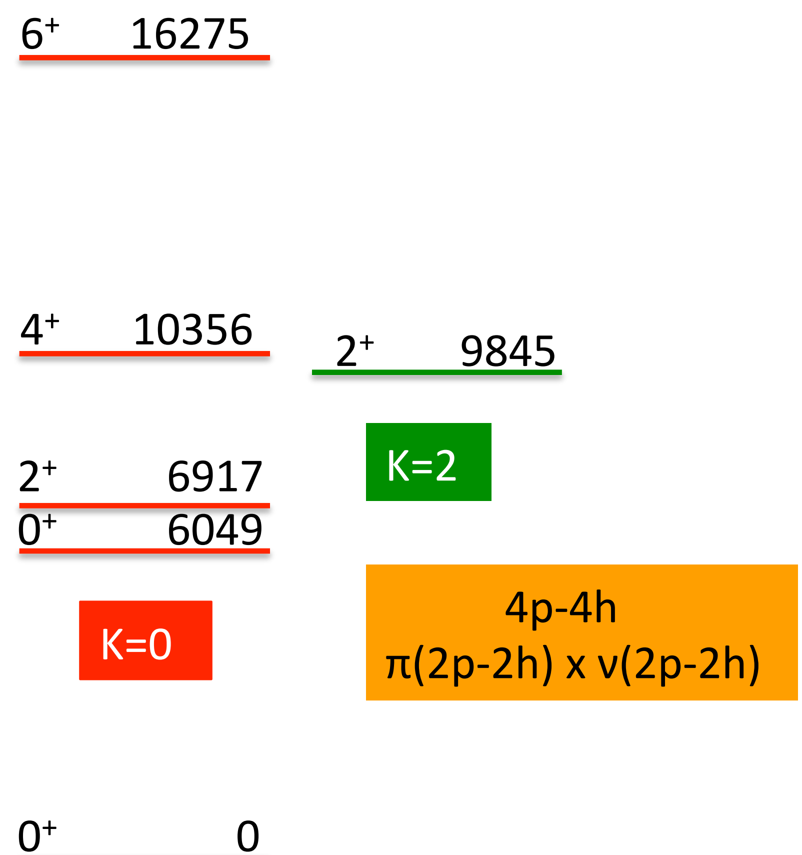
States on the far left are spherical.

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

^{16}O: population of deformed states by alpha stripping reactions

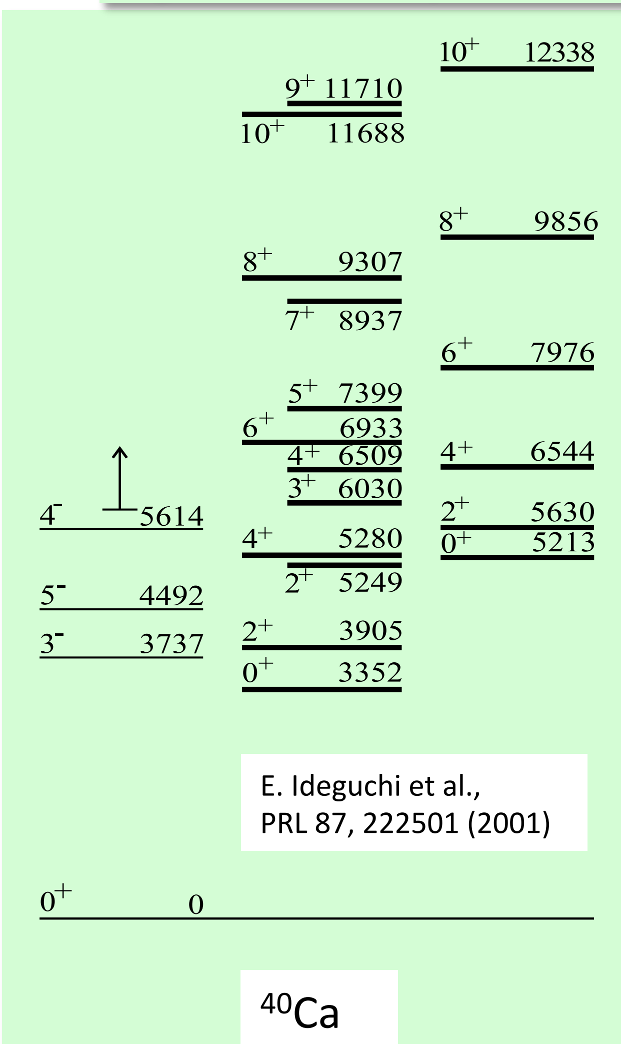


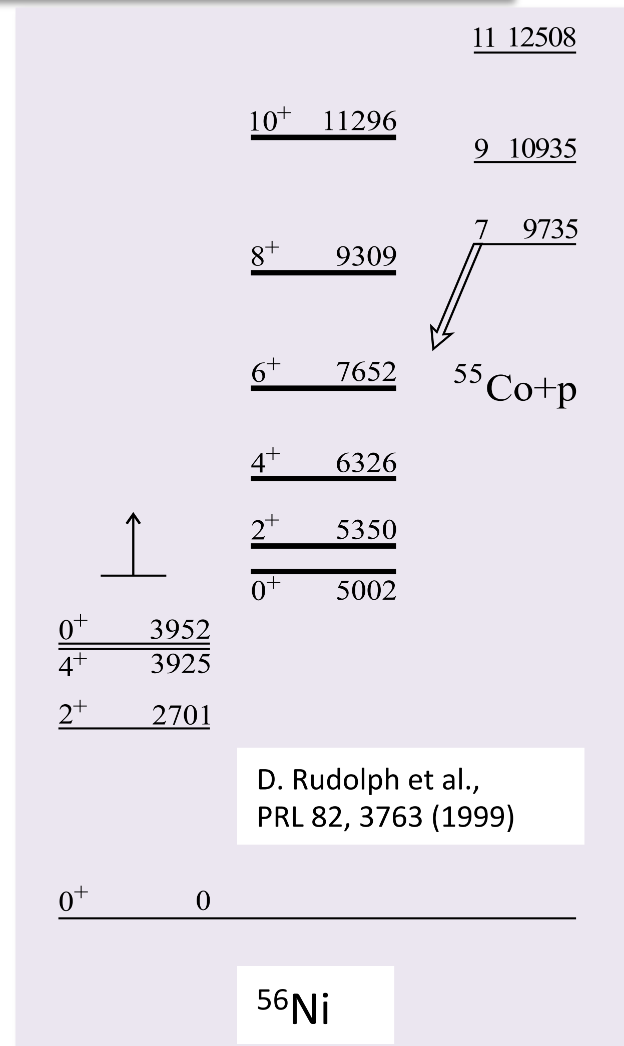
(^{7}Li,t) spectrum from M.E. Cobern et al., PR C14, 491 (1976)



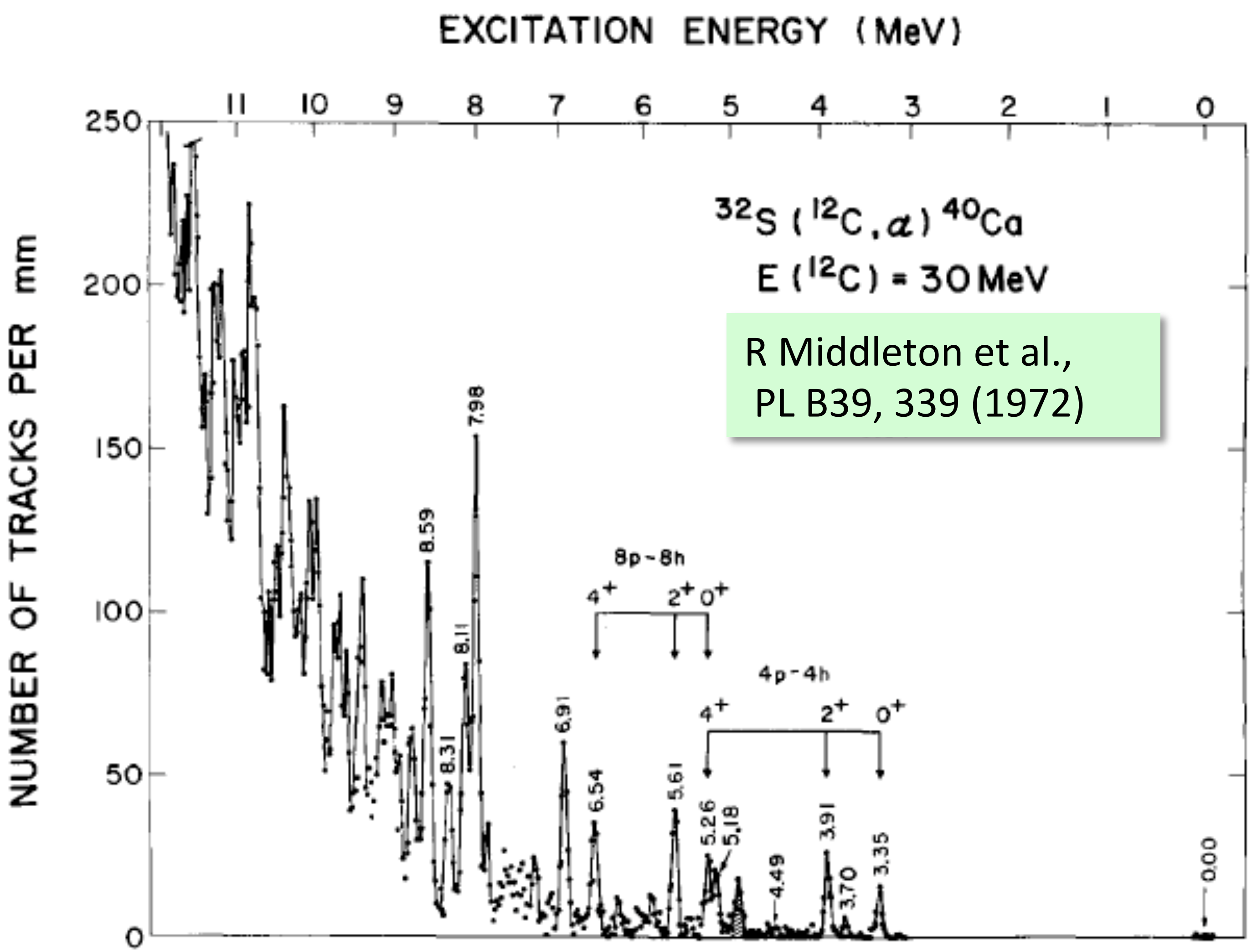
Excited 0^+ states at closed shells: shape coexistence in the double-closed shell nuclei ^{40}Ca and ^{56}Ni

Figure from K. Heyde and J.L. Wood, Rev. Mod. Phys. 83, 1467 (2011)





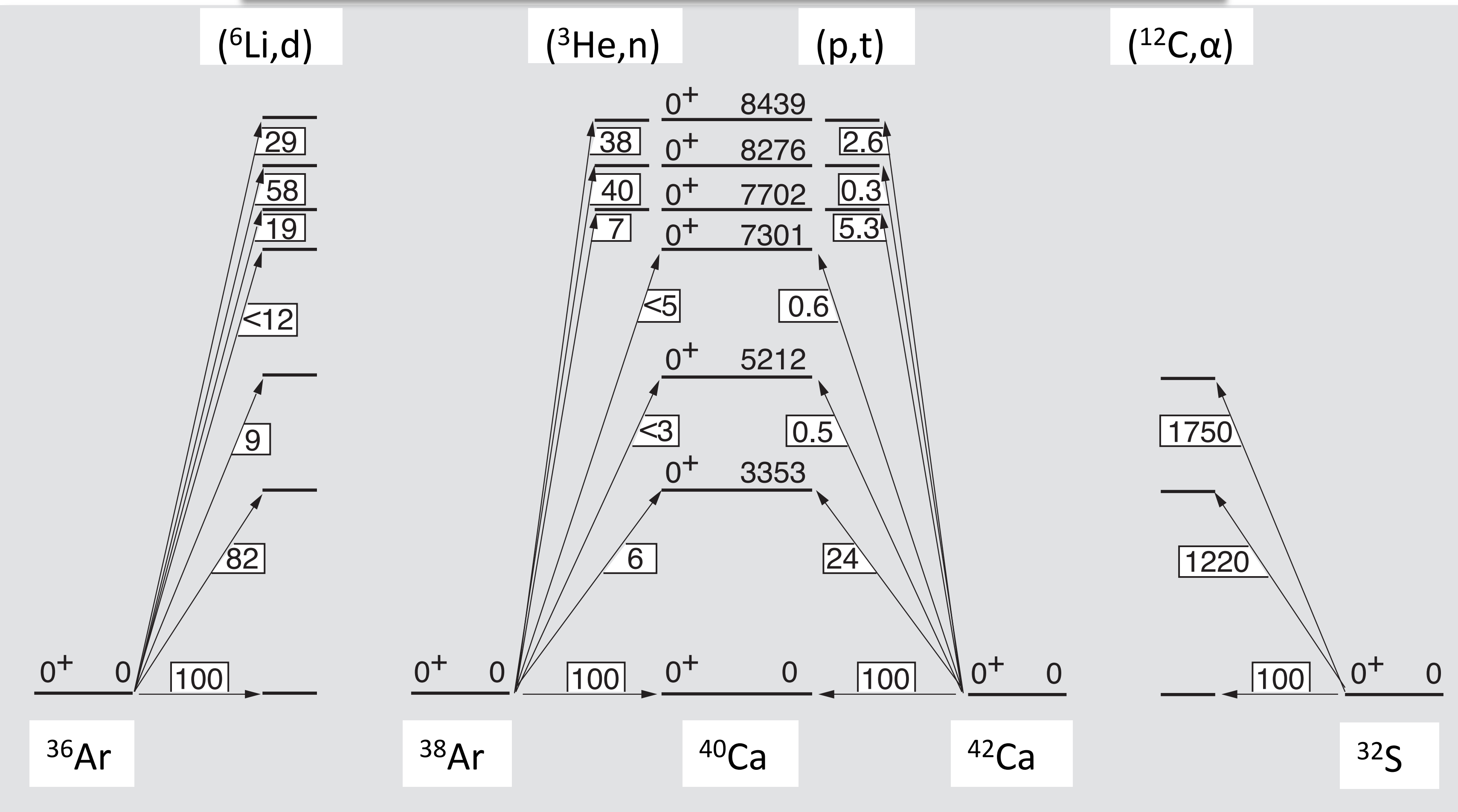
^{40}Ca: population of highly deformed bands by (^{12}C,α)



R Middleton et al., PL B39, 339 (1972)

Excited 0^+ states at closed shells: population in ^{40}Ca by multi-nucleon transfer reactions

Figure from J.L.Wood et al., Phys. Repts. 215, 101 (1992)

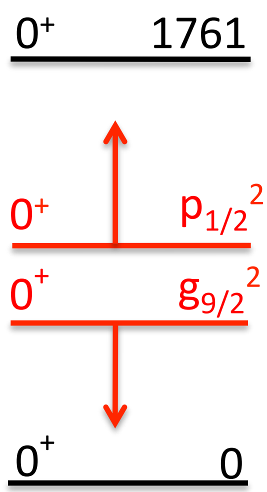


0^+ spherical states at closed shells: v = 0,2 (seniority) states @ N = 50

N=50: $g_{9/2}$ seniority structure

J = ½ orbitals can only contribute to v = 0 states, at low energy

^{90}Zr E(2_1^+) is high: suggests a closed subshell, but is due to *depression* of the ground-state energy



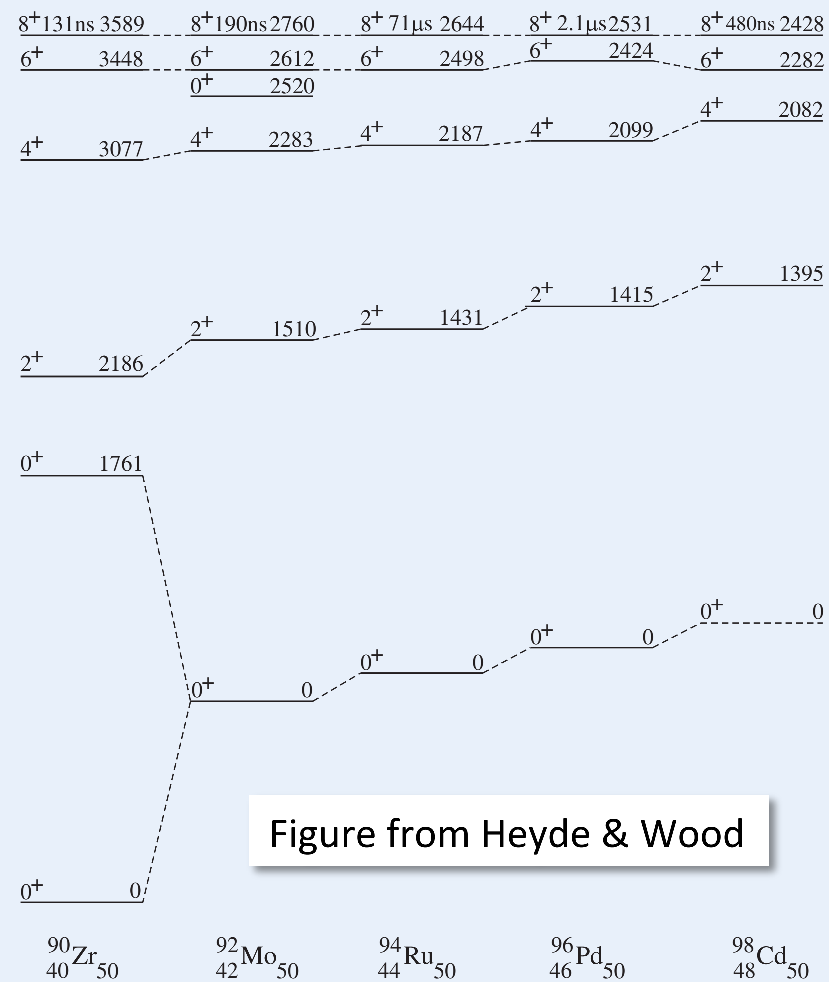
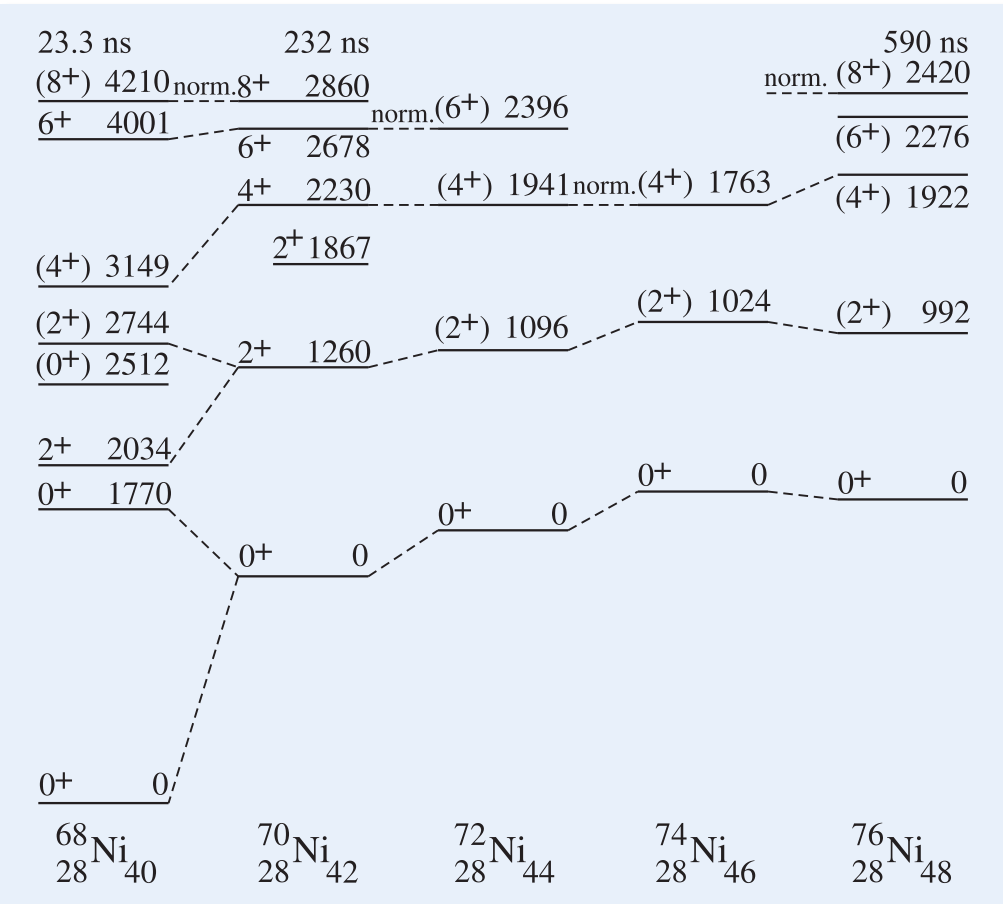


Figure from Heyde & Wood

0^+ states in ^{68}Ni: seniority structure and …?



The relatively high $E(2_1^+)$ value in ^{68}Ni is probably not indicative of a closed subshell

0^+ states @ 1770, 2512 keV: spherical, deformed?

Figure from Heyde & Wood

0^+ states in ^{68}Ni:

0_2^+ v=0 state? 0_3^+ π 2p-2h deformed state?

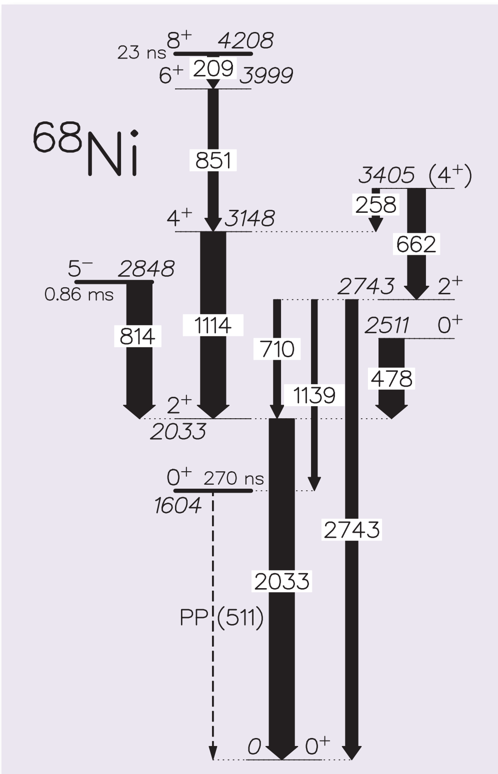
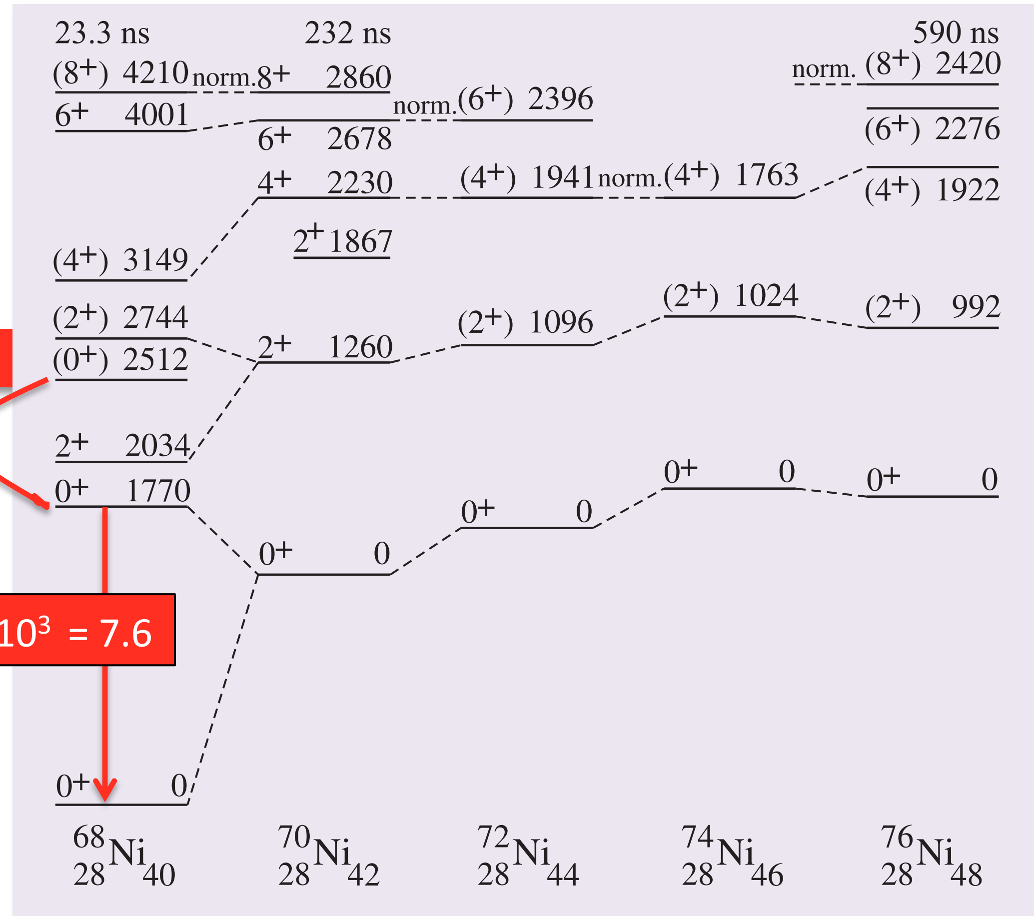


Figure taken from F. Recchia et al., PR C88 041302 2013

π(2p-2h)?

MIX

$\rho^2(E0)\bullet 10^3 = 7.6$



S. Suchyta et al., PR C89 021301 2014

See also: D. Pauwels et al., PR C82 027304 2010

0^+ states in ^{68}Ni:

0_2^+ ν=0 state? 0_3^+ π 2p-2h deformed state?

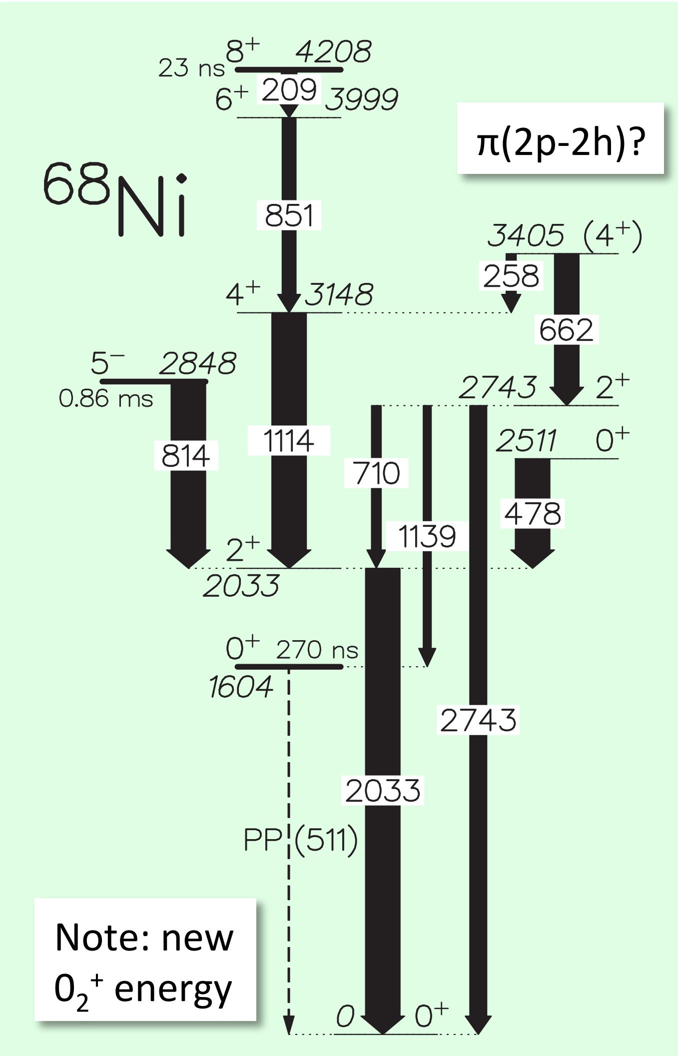


Figure taken from F. Recchia et al., Phys. Rev. C88, 041302 (2013)

OPEN QUESTIONS:

What are the intensities of—

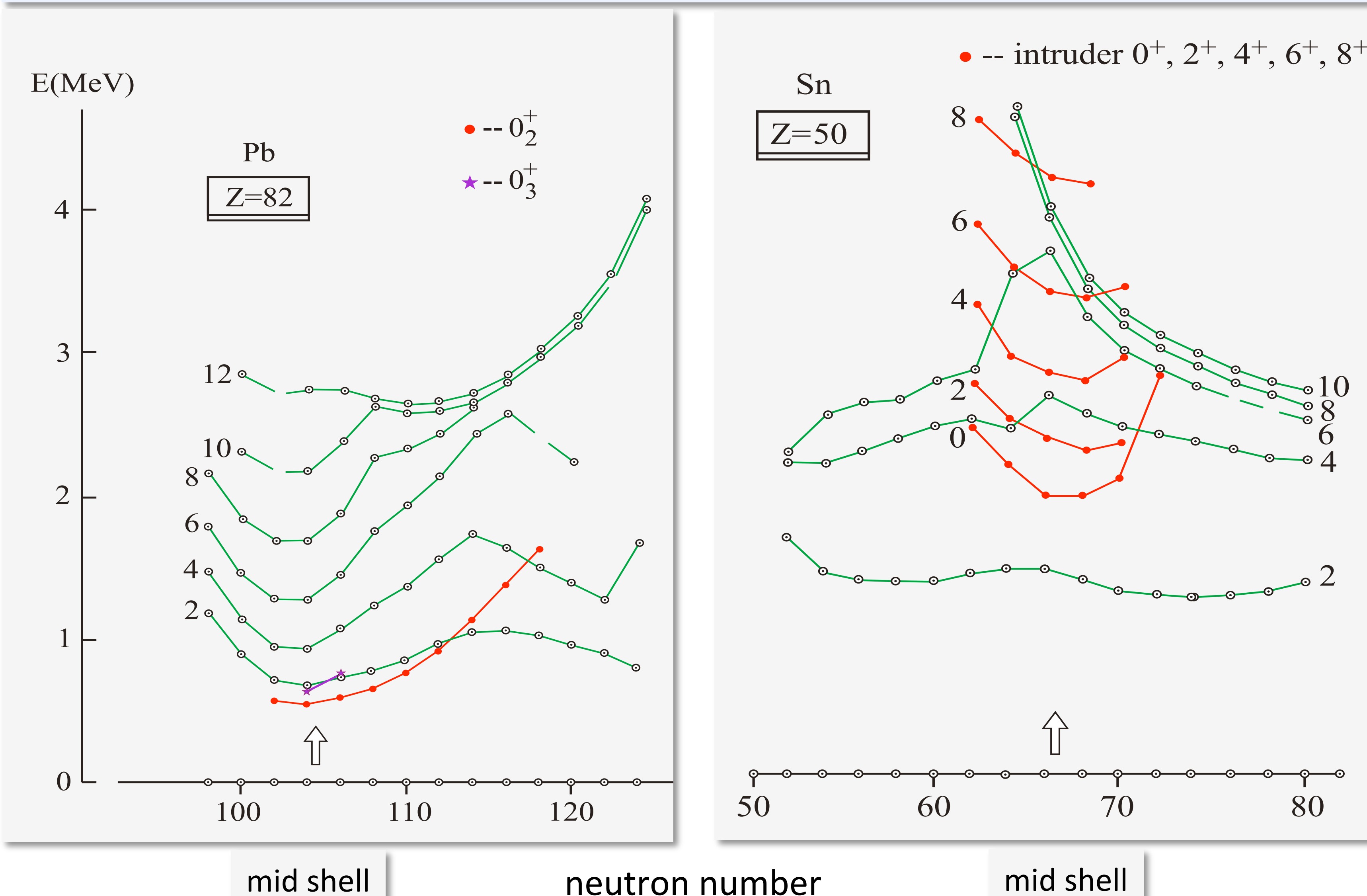
- **the 232 keV transition between the 2743 and 2511 keV levels?**
- **the 429 keV transition between the 2033 and 1604 keV leveks?**

What are the lifetimes of—

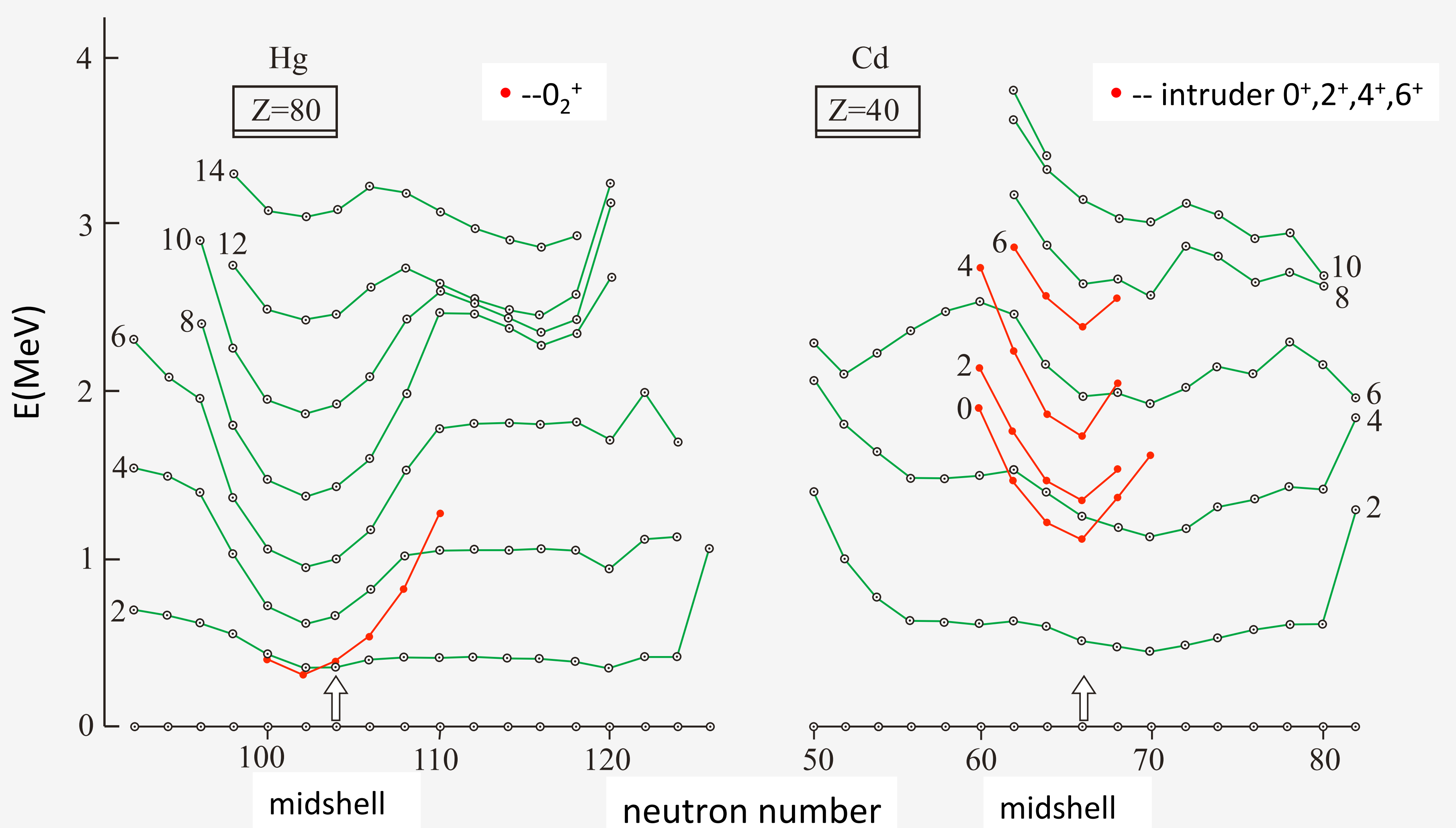
- **the 2743 keV state?**
- **the 2033 keV state?**

See also: D. Pauwels et al., Phys. Rev. C82, 027304 (2010)

Excited 0^+ states at closed shells: intruder states in the Pb and Sn isotopes

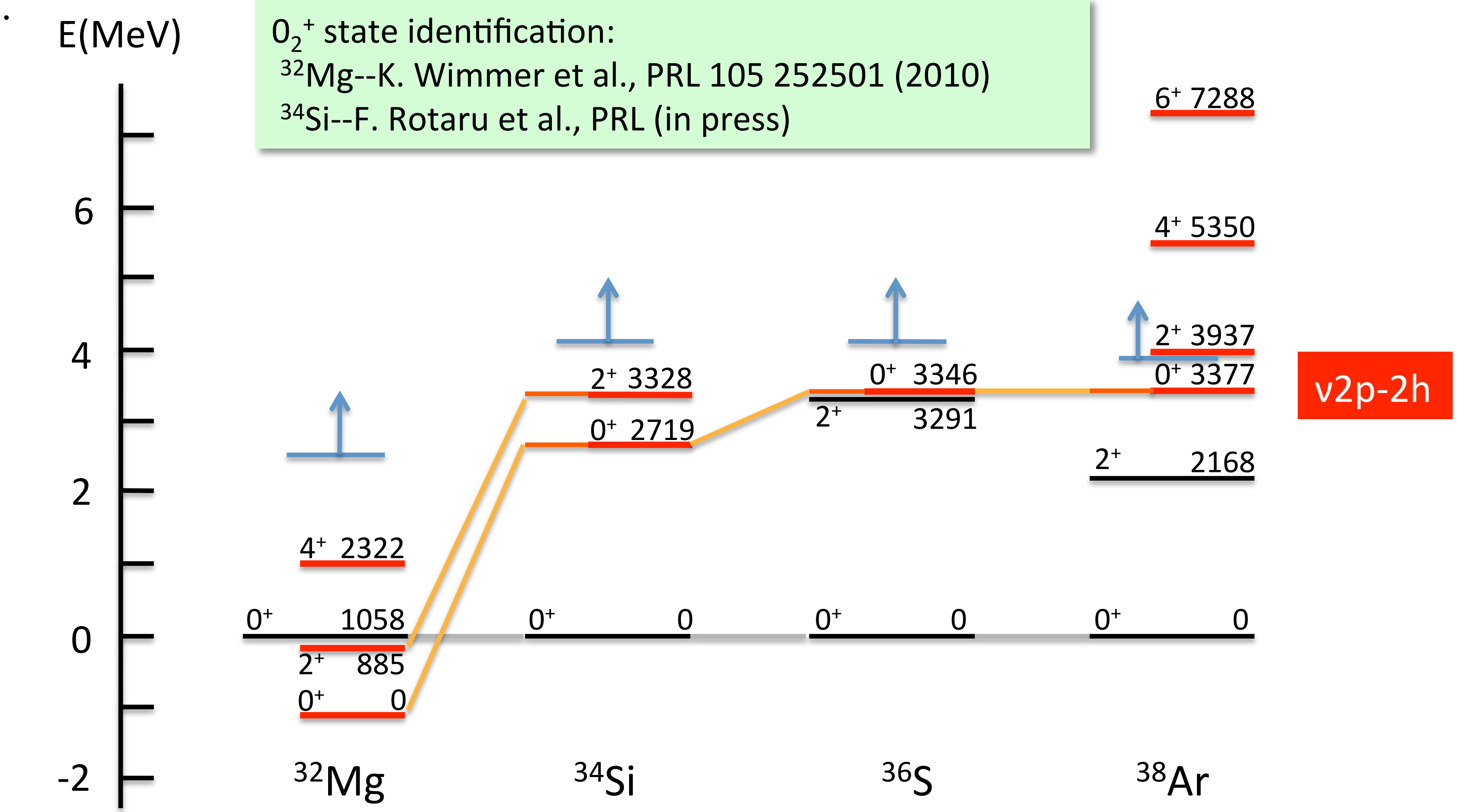


Excited 0^+ states adjacent to closed shells: intruder states in the Hg and Cd isotopes

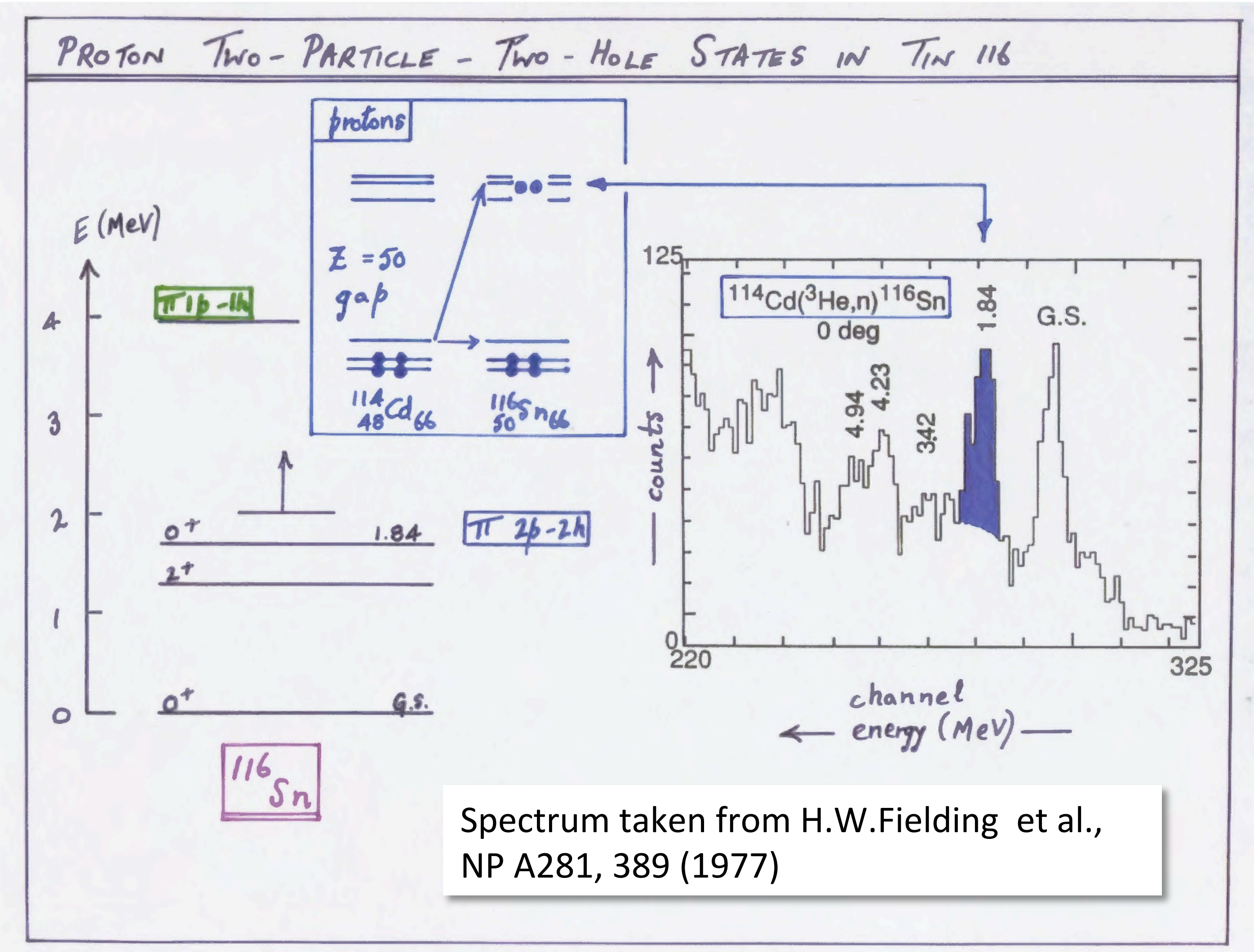


Intruder states or the "island of inversion" @ N=20

0_2^+ state identification:
^{32}Mg--K. Wimmer et al., PRL 105 252501 (2010)
^{34}Si--F. Rotaru et al., PRL (in press)



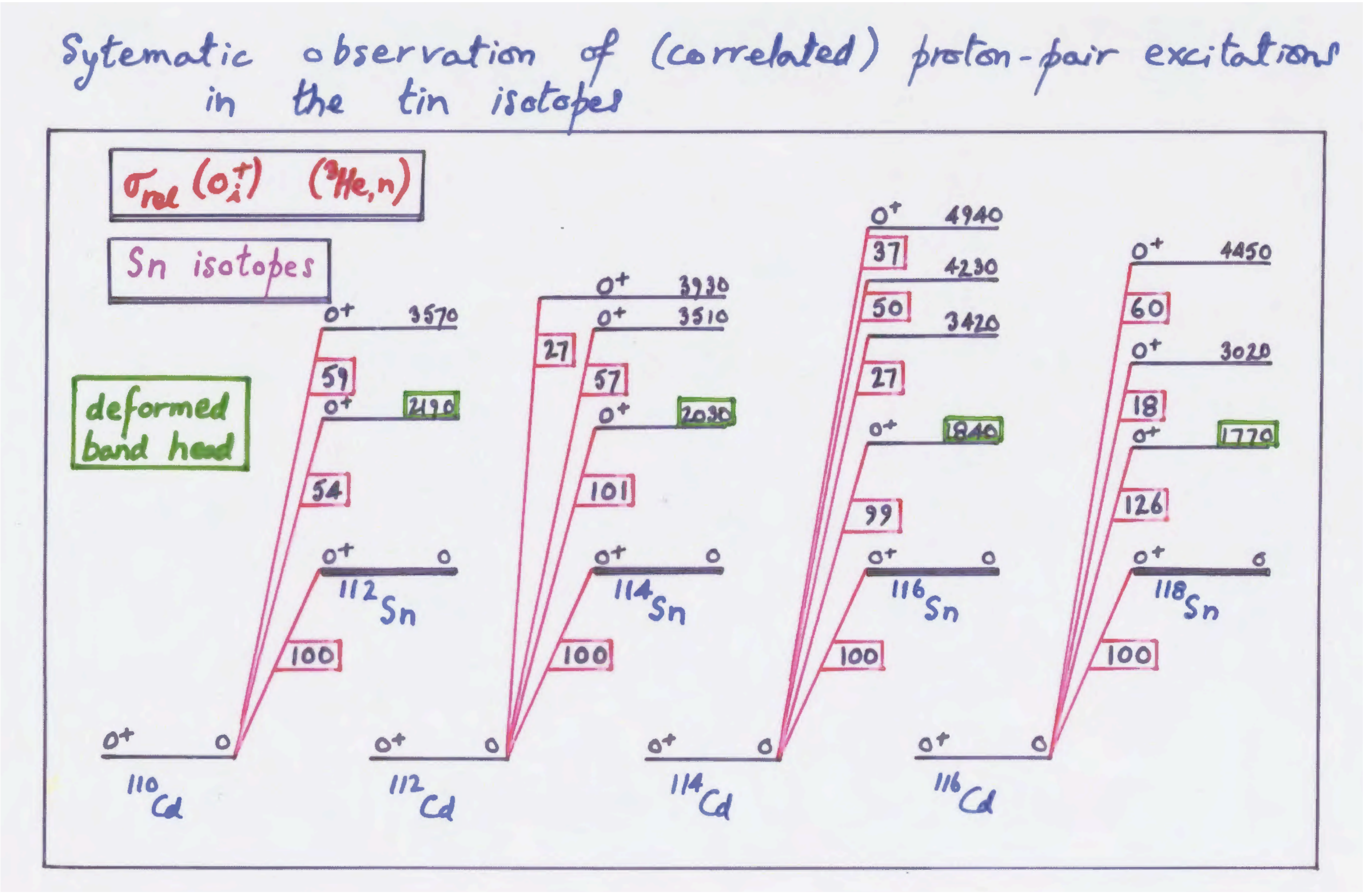
The 0^+ intruder state in ^{116}Sn revealed by (^{3}He,n) transfer reaction spectroscopy



Spectrum taken from H.W.Fielding et al., NP A281, 389 (1977)

Excited 0$^+$ states in the tin isotopes with strong population in two-proton stripping reactions

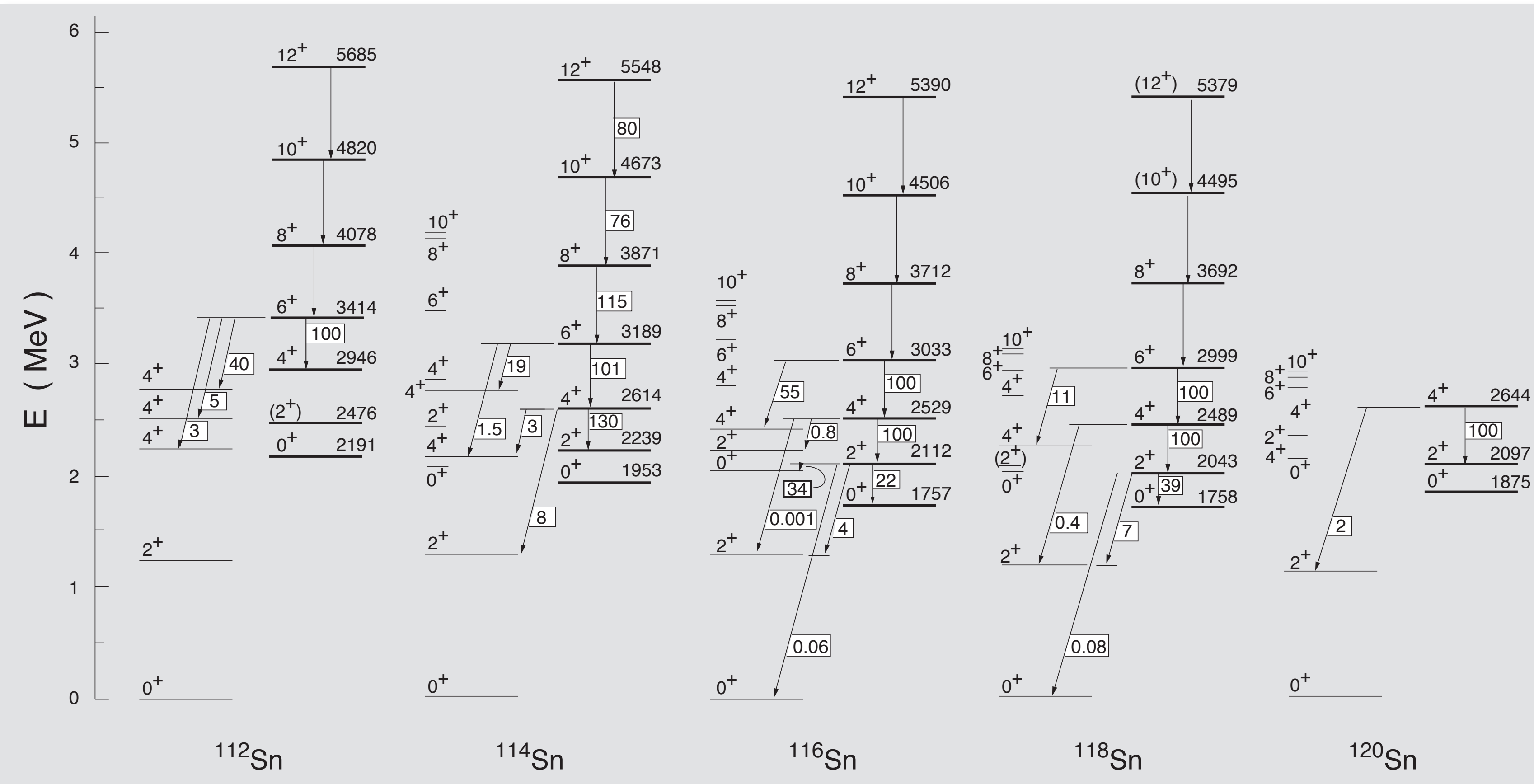
Data taken from H.W.Fielding et al., NP A281, 389 (1977)



Deformed bands in $^{112-120}$Sn built on the first excited 0^+ states

Figure from Rowe & Wood

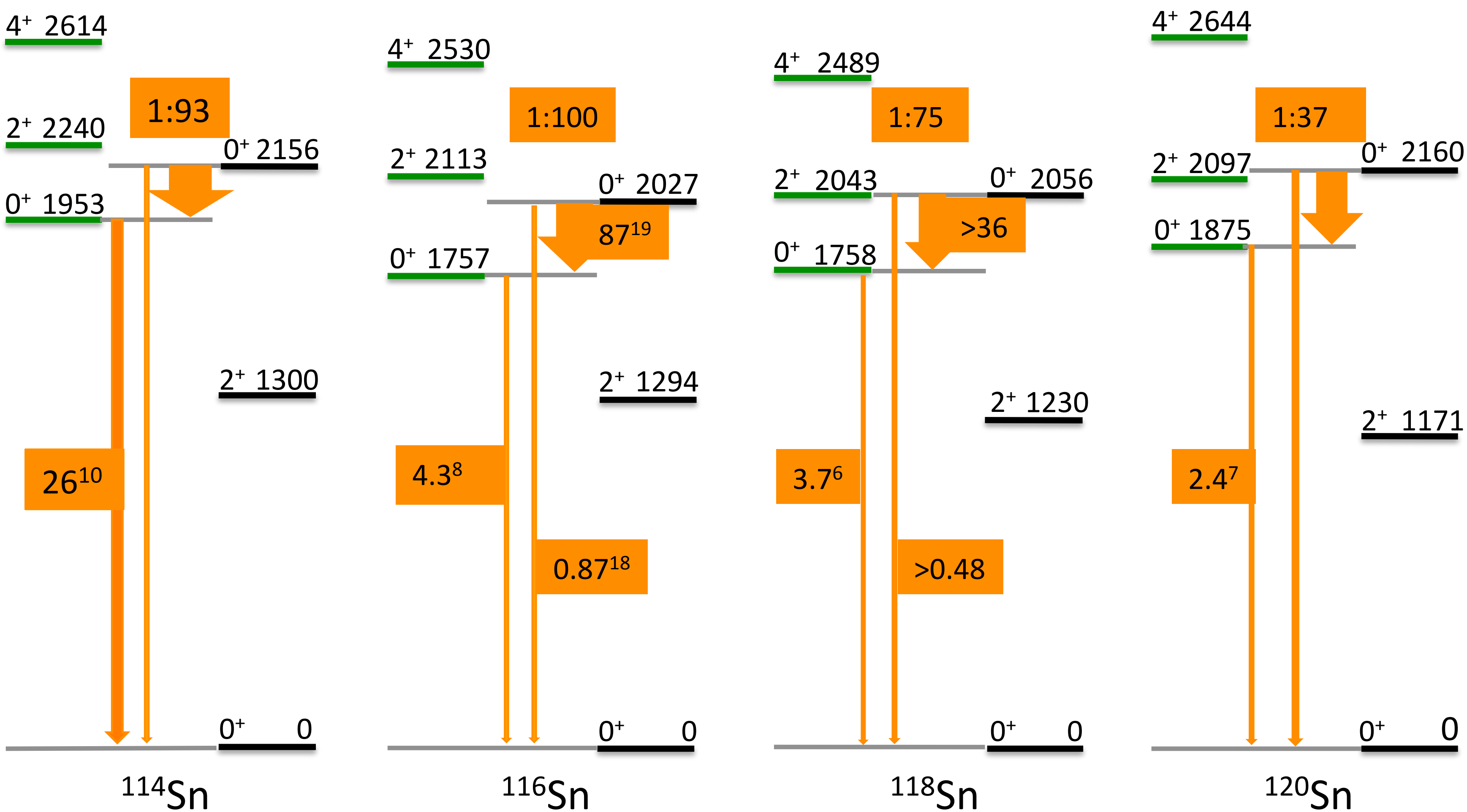
B(E2)'s in W.u. [100 = rel. value]



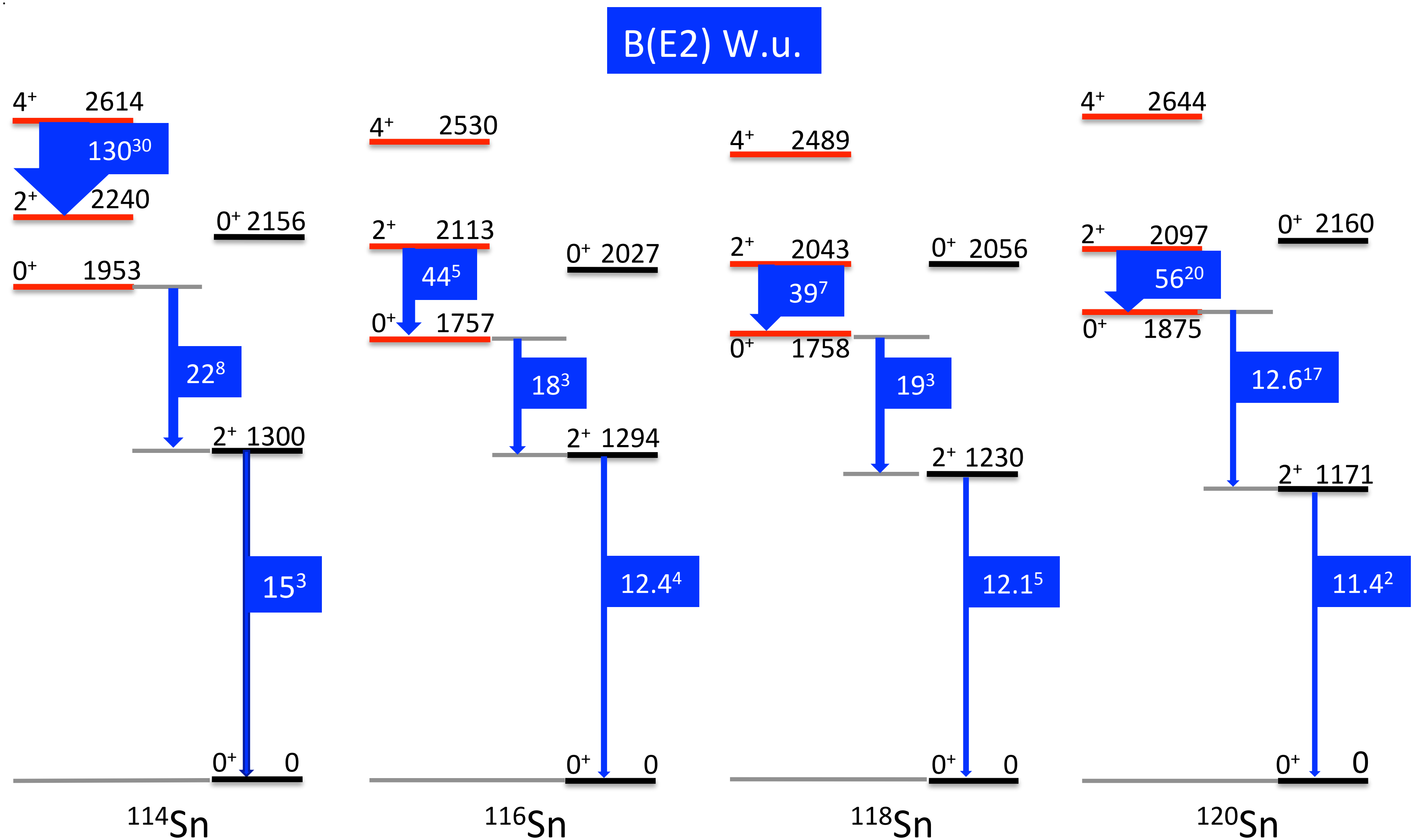
E0 transitions associated with shape coexistence in $^{114-120}Sn$

J. Kantele et al., ZP A289, 157 (1979)   T. Kibedi and R.H. Spear, ADNDT 89, 277 (2005)

$\rho^2(E0)\cdot 10^3$

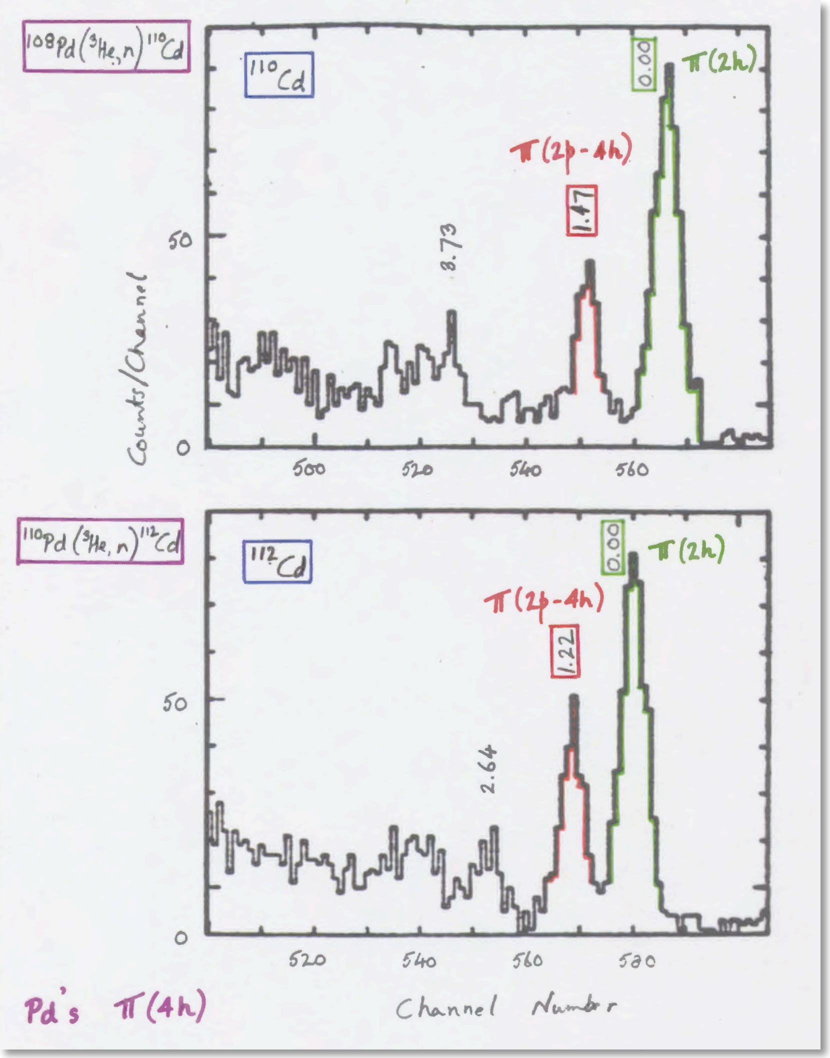


E2 transitions associated with shape coexistence in $^{114-120}Sn$



The 0^+ intruder states in ^{108,110}Cd revealed by (^{3}He,n) reaction spectroscopy

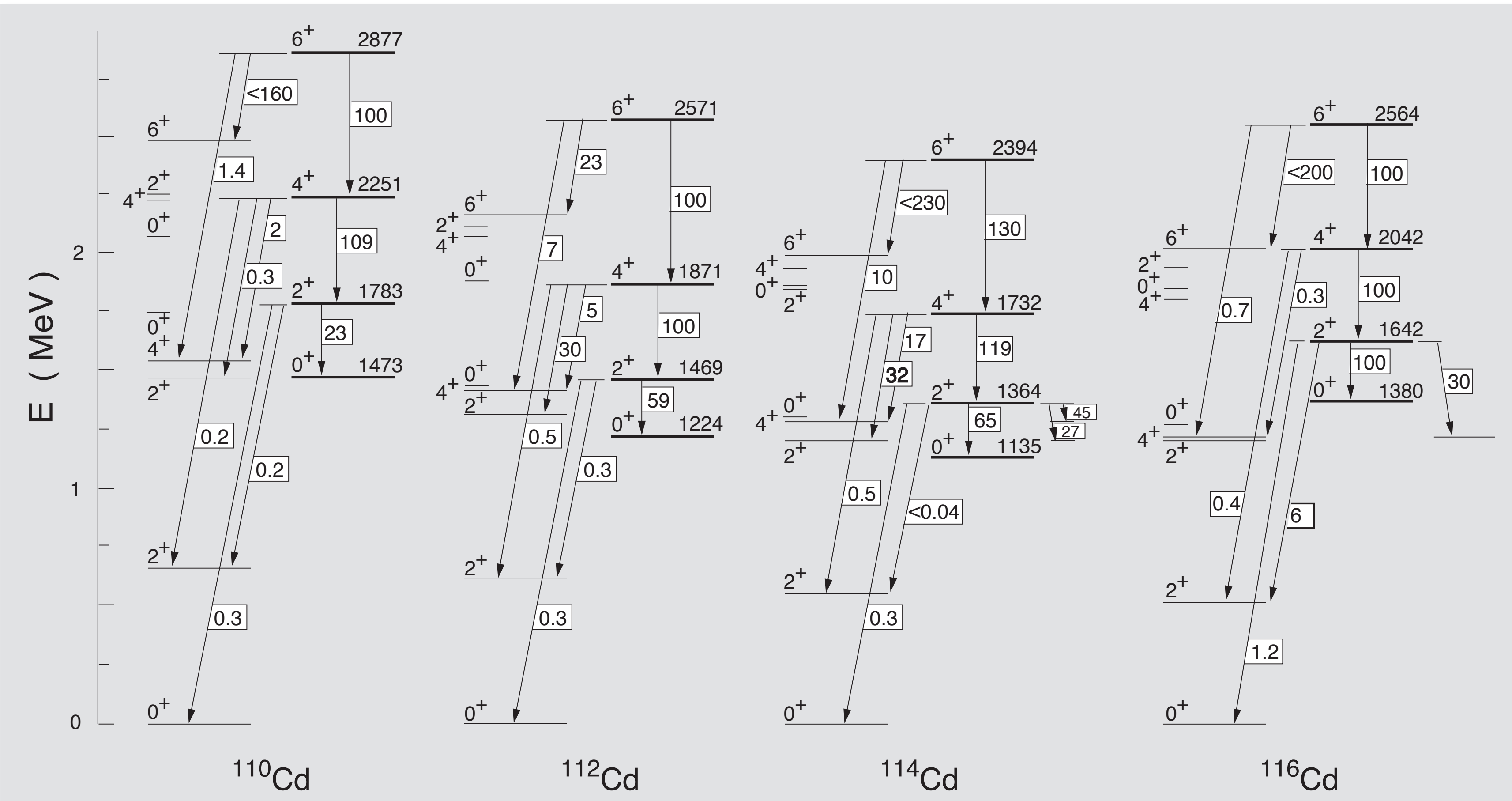
Spectra taken from H.W. Fielding et al., NP A281, 389 (1977)



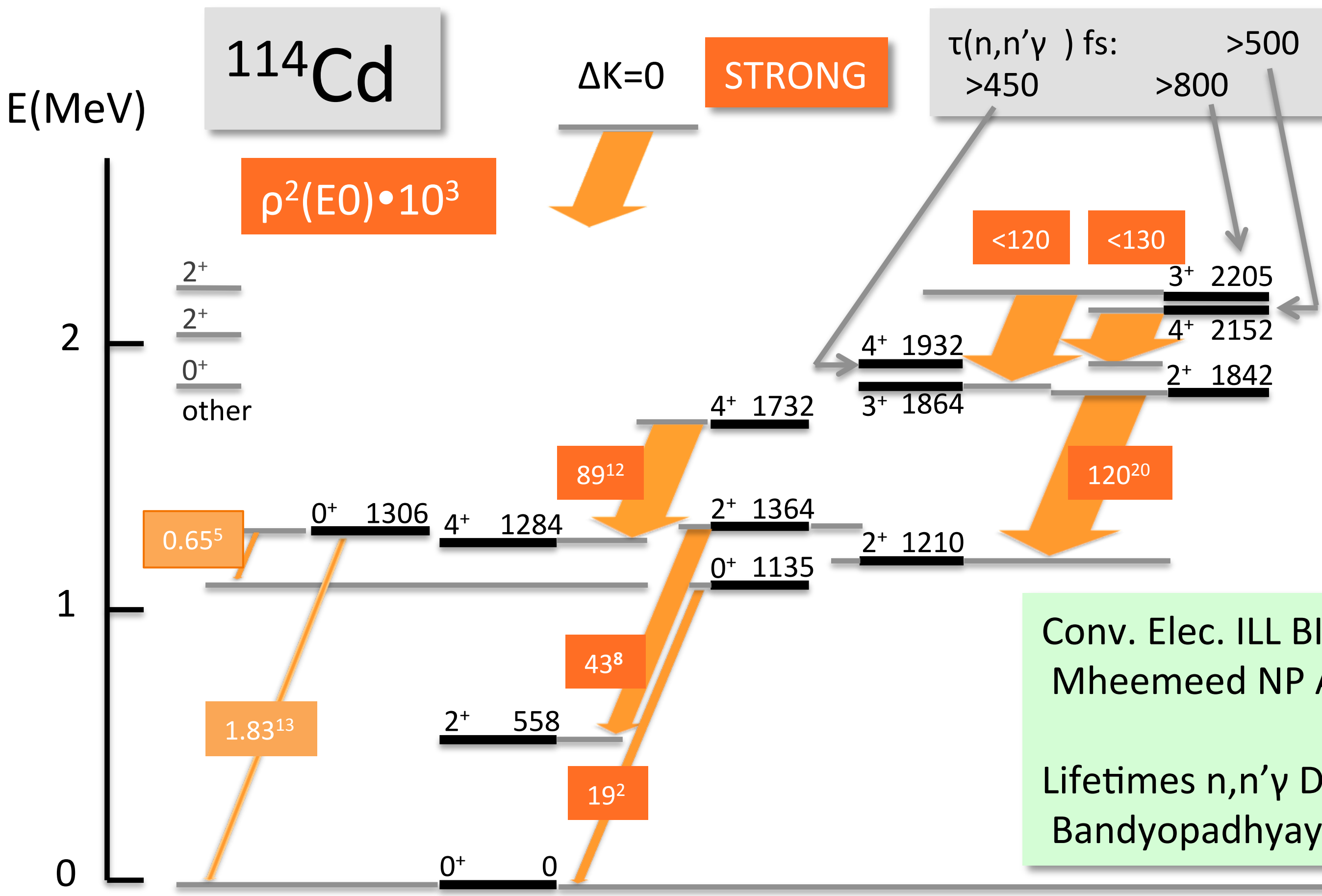
Deformed bands in $^{110\text{-}116}$Cd

Figure from Rowe & Wood

B(E2)'s in W.u. [100 = rel. value]



E0 transition strengths in ^{114}Cd support the existence of good K quantum numbers



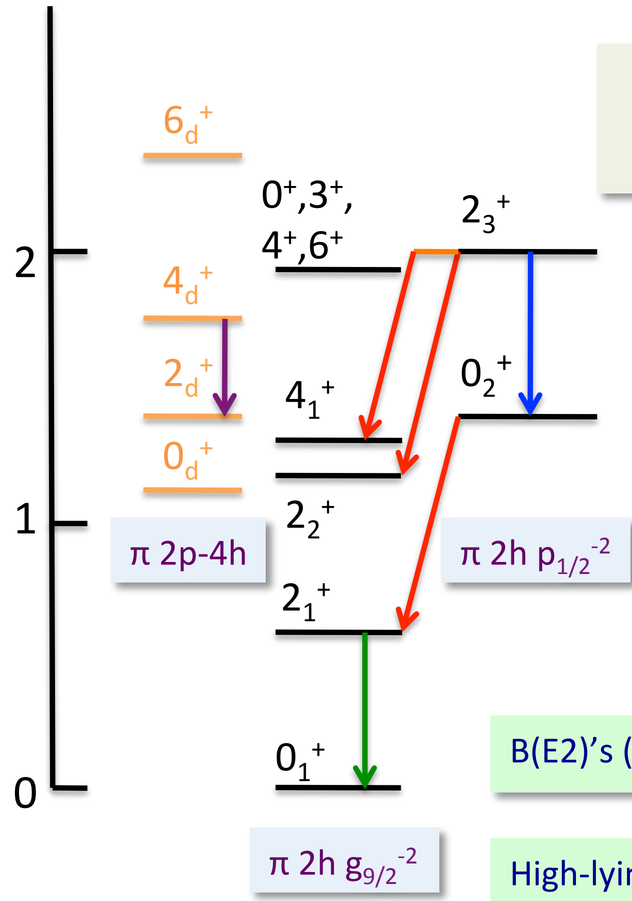
Conv. Elec. ILL BILL/GAMS
Mheemeed NP A412 113 1984

Lifetimes n,n'γ Doppler U. Kentucky
Bandyopadhyay PR C76 054308 2007

Demise of quadrupole vibrations in $^{110-116}$Cd:

low-energy 0^+ states are shell and subshell excitations

P.E. Garrett and J.L. Wood, J.Phys. G37, 064028 (2010)



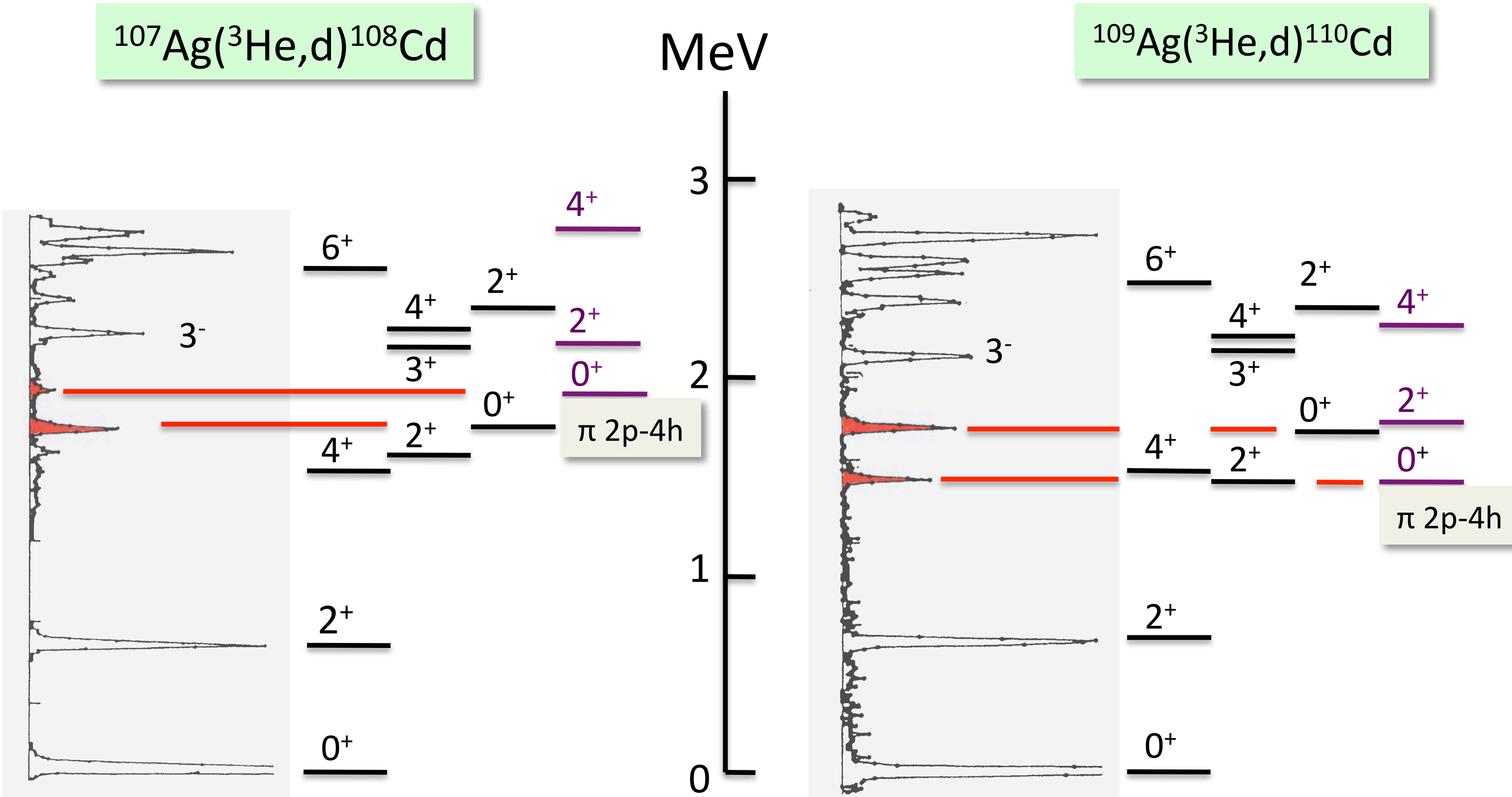
trans.	^{110}Cd	^{112}Cd	^{114}Cd	^{116}Cd	harm. vib.
4_d2_d	116^{35}		119^{12}		
2_30_2	24^{2}	27^{8}	17^{5}	35^{10}	42
2_34_1	< 5	< 0.4	< 0.3	< 7	31
2_32_2	< 4.5	< 2	2.8^{4}	2.0^{6}	17
0_22_1	< 7.9	0.0099^{44}	0.0026^{4}	0.55^{4}	60
2_10_1	27	30	31	34	30 (norm)

B(E2)'s (W.u.) from lifetime measurements @ Univ. of Kentucky using (n,n'γ).

High-lying, low-energy transitions are difficult to observe: used 8Pi array @ TRIUMF-ISAC and ultrahigh statistics β-decay scheme studies.

Population of 0^+ states in ^{108,110}Cd by one-proton stripping reactions

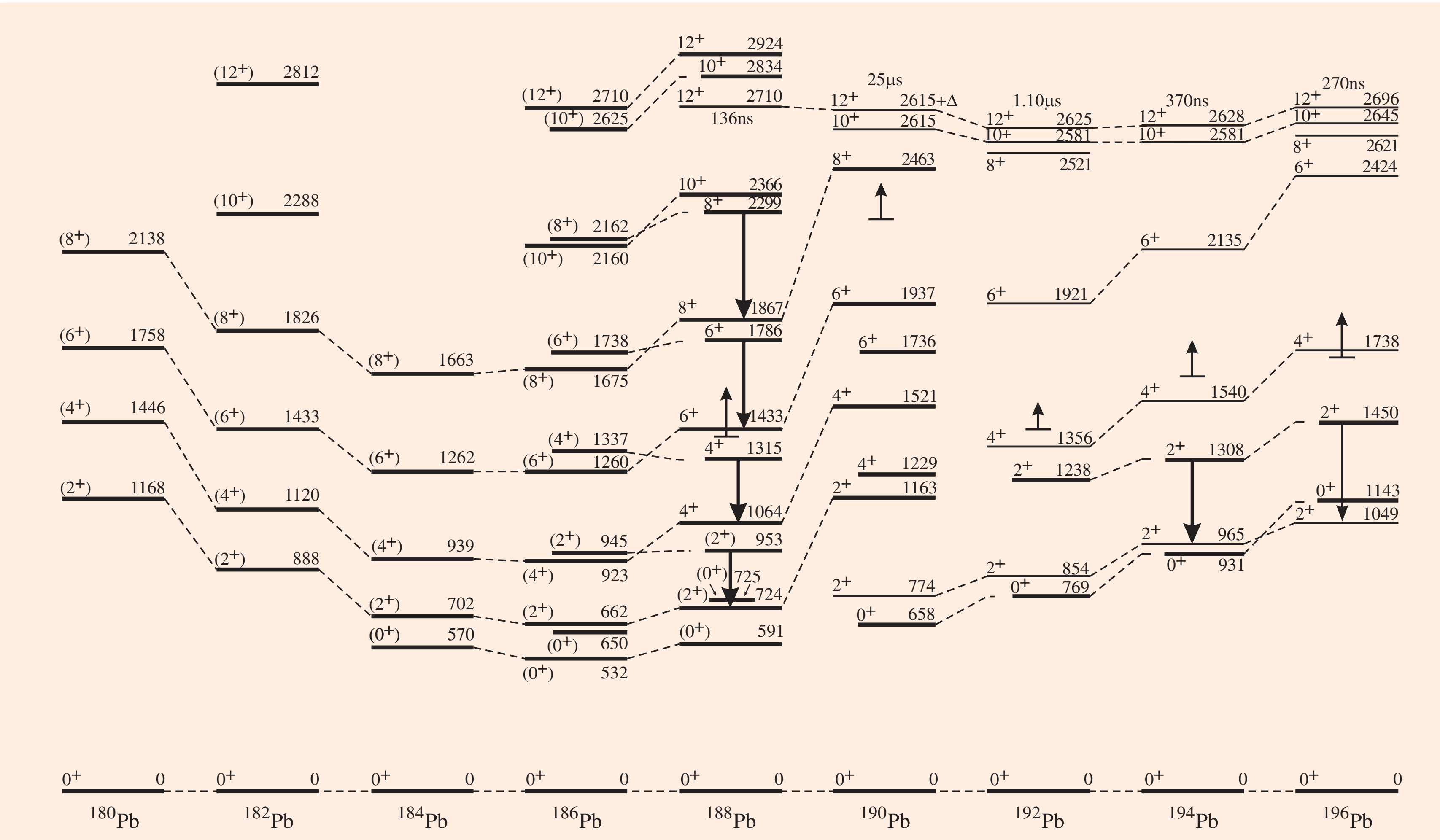
R.L. Auble et al., Phys. Rev. C6 2223 (1972)



Shape coexistence in singly closed-shell nuclei: the even-mass Pb isotopes

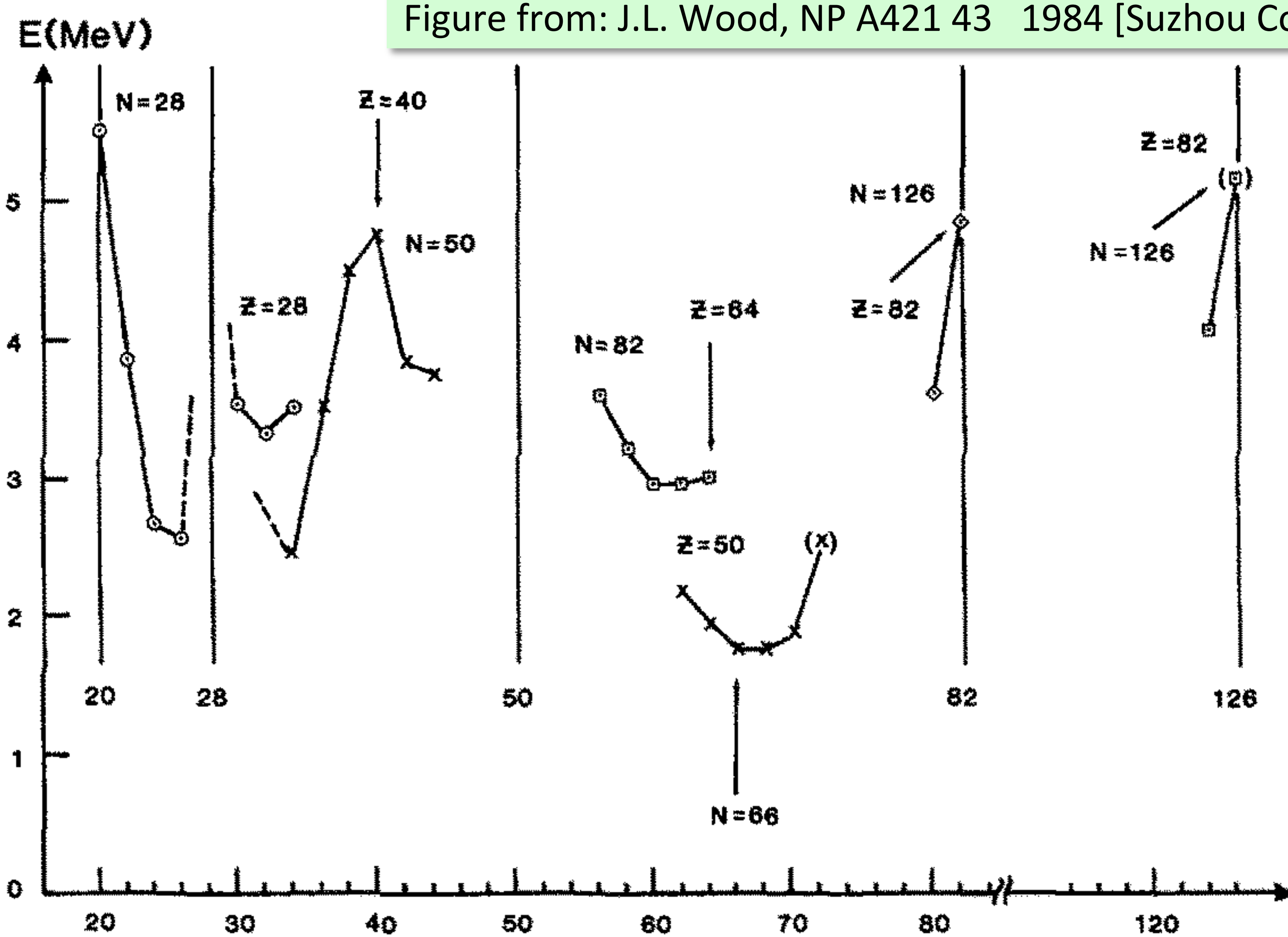
Figure from Heyde & Wood

Heavy arrows indicate E0+M1+E2 transitions



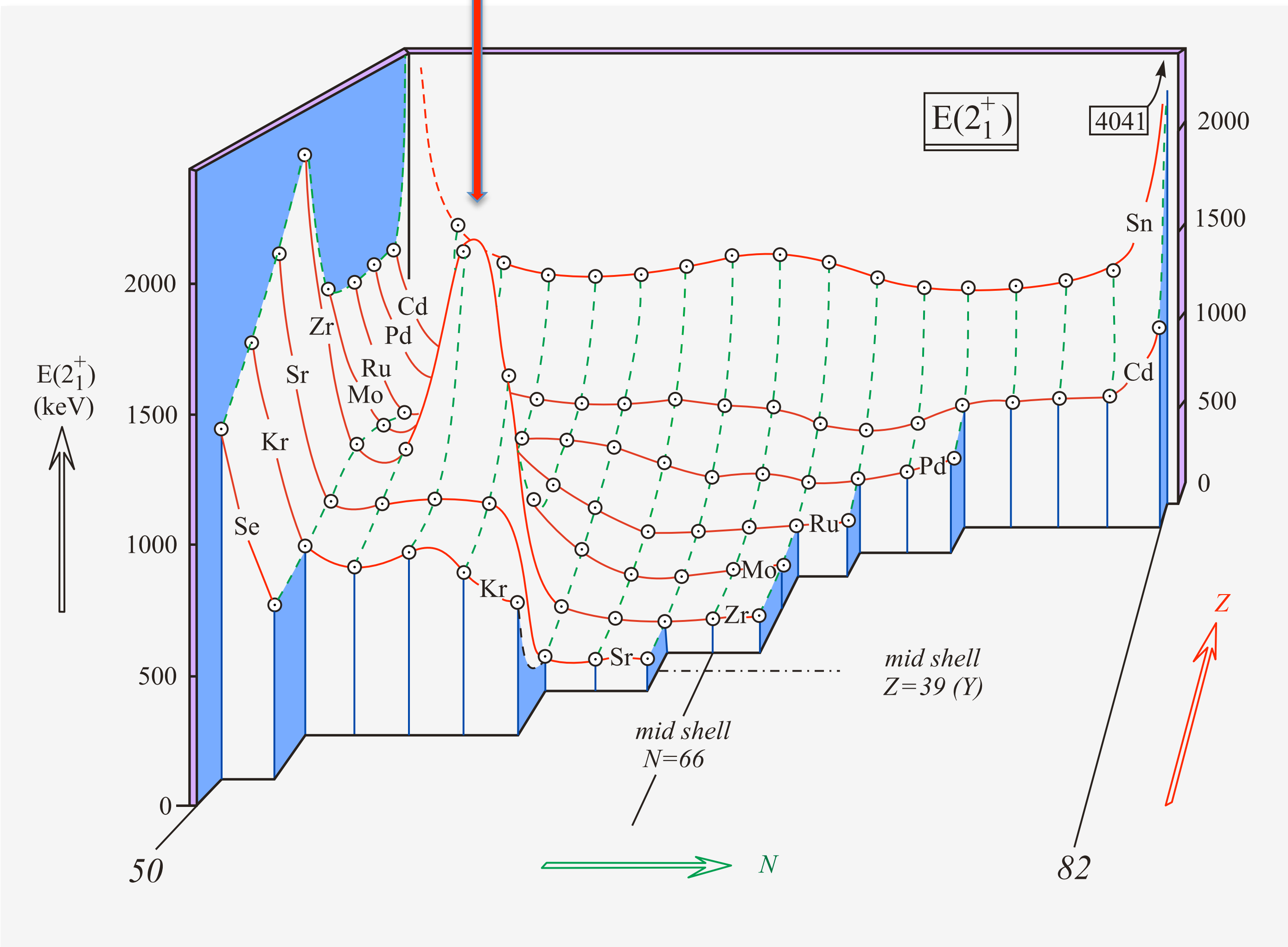
Pair excitations across closed shells

Figure from: J.L. Wood, NP A421 43 1984 [Suzhou Conf.]



Systematic of $E(2_1^+)$ for $N \geq 50$, $Z \leq 50$:

^{96}Zr is a double-closed subshell

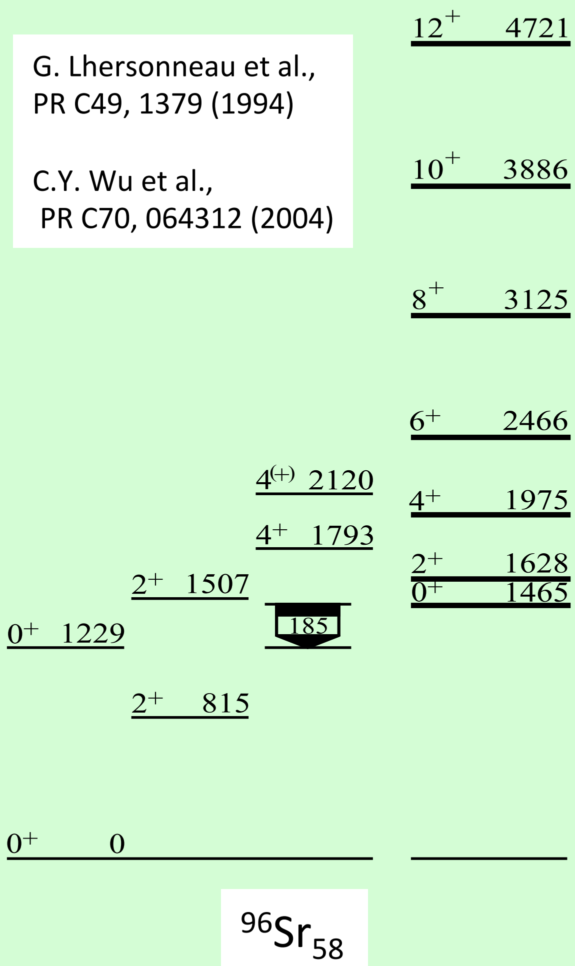


Shape coexistence at and near closed subshells: the nuclei ^{96}Sr and ^{98}Zr

Figure from K. Heyde and J.L. Wood, Rev. Mod. Phys. 83, 1467 (2011)

G. Lhersonneau et al., PR C49, 1379 (1994)

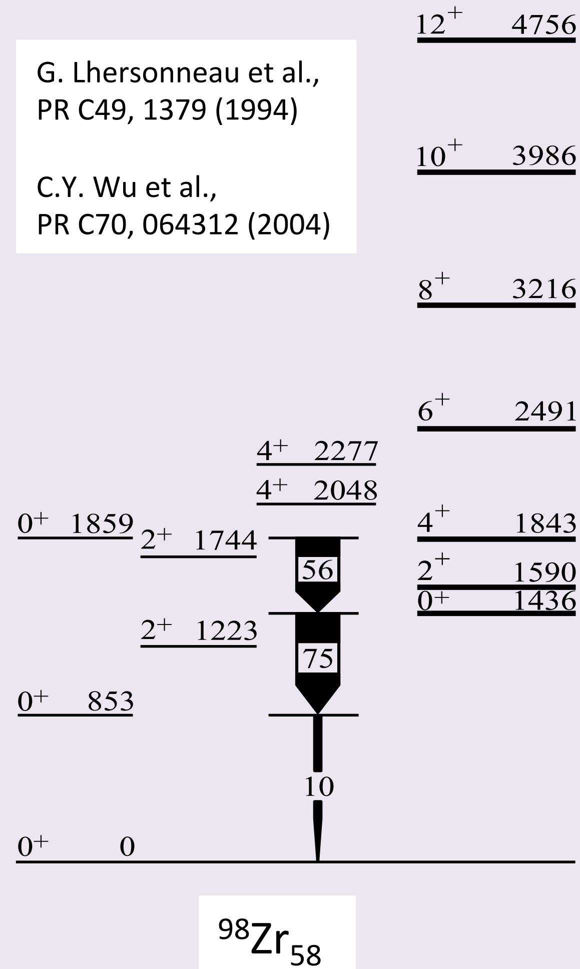
C.Y. Wu et al., PR C70, 064312 (2004)



E0 transitions: $\rho^2(E0)\bullet10^3$ values are shown

G. Lhersonneau et al., PR C49, 1379 (1994)

C.Y. Wu et al., PR C70, 064312 (2004)



^{96}Zr: a nucleus that deserves detailed study using multiple spectroscopic techniques

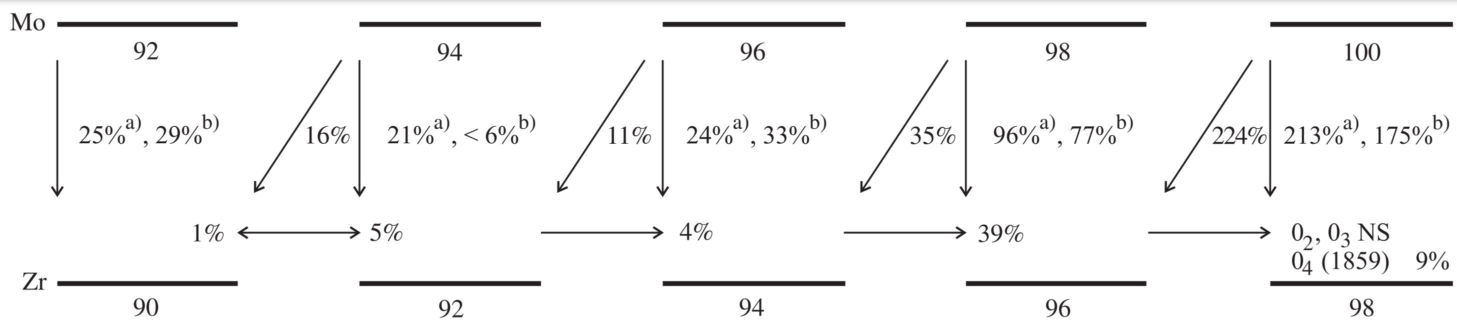


FIG. 29. Two-nucleon and multinucleon transfer strengths to 0_2^+ states in the Zr isotopes, given relative to 100% for 0_1^+ states. The strengths marked a) are from (^{6}Li, ^{8}B) reactions, and b) are from (^{14}C, ^{16}O) reactions. The data are from references given in Nuclear Data Sheets.

Figure from K. Heyde and J.L. Wood, Rev. Mod. Phys. 83, 1467 (2011)

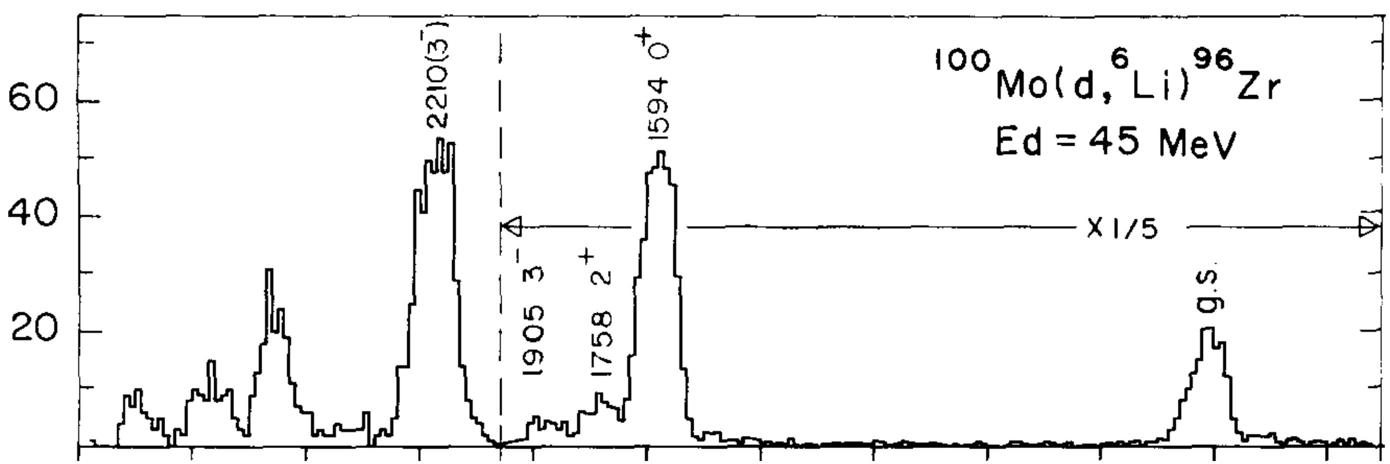
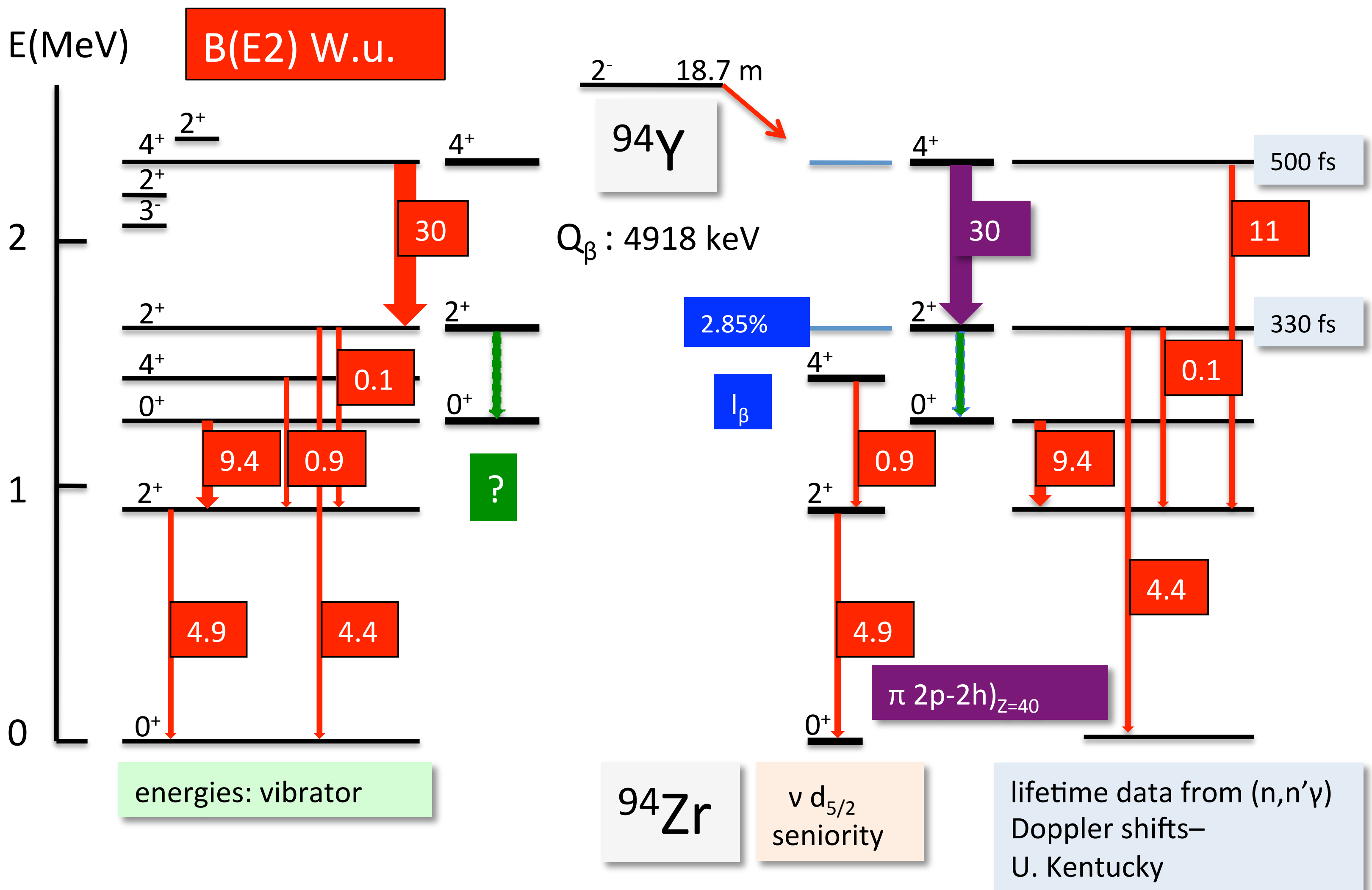


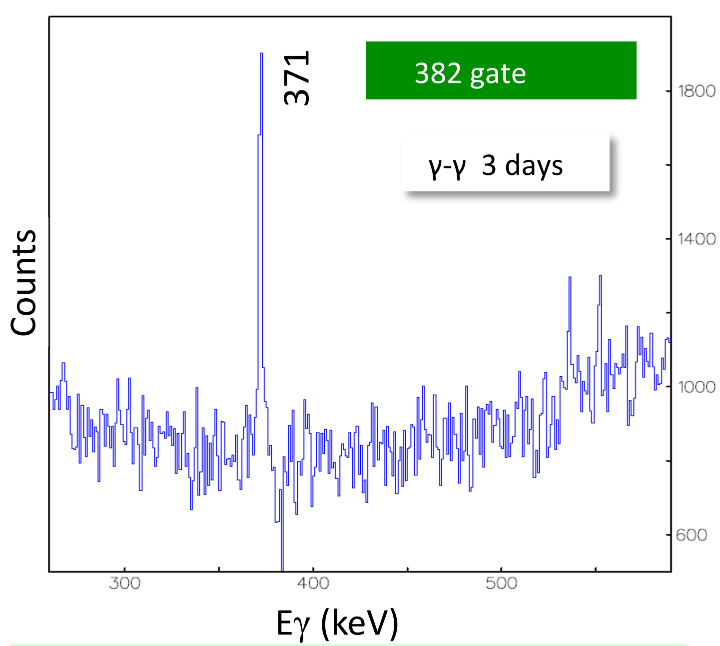
Figure from A. Saha et al., Phys. Lett. 82B, 209 (1979)

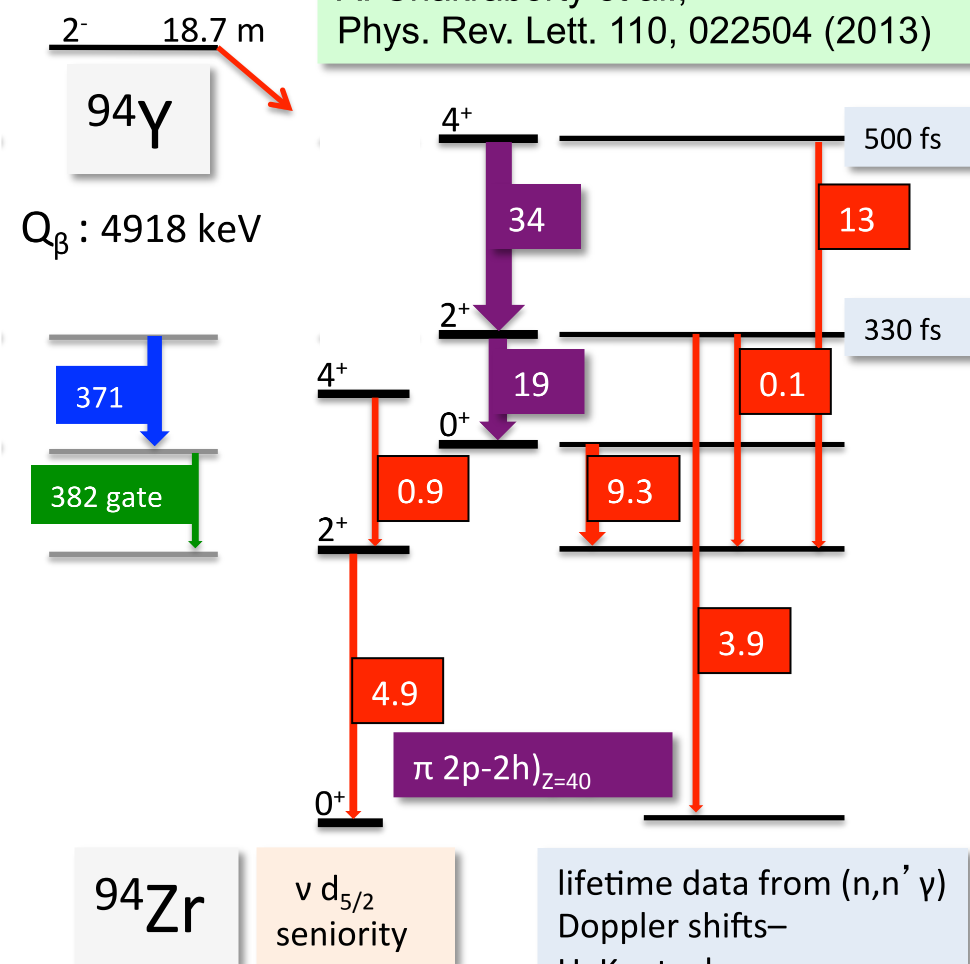
^{94}Zr from two structural perspectives: vibrator OR coexisting seniority and deformed structures



^{94}Zr from two structural perspectives: vibrator OR coexisting seniority and deformed structures

A. Chakraborty et al.,
Phys. Rev. Lett. 110, 022504 (2013)





lifetime data from (n,n’ γ) Doppler shifts–
U. Kentucky

gamma branches from the 2^+ 2p-2h state to:

0_1^+ state 58

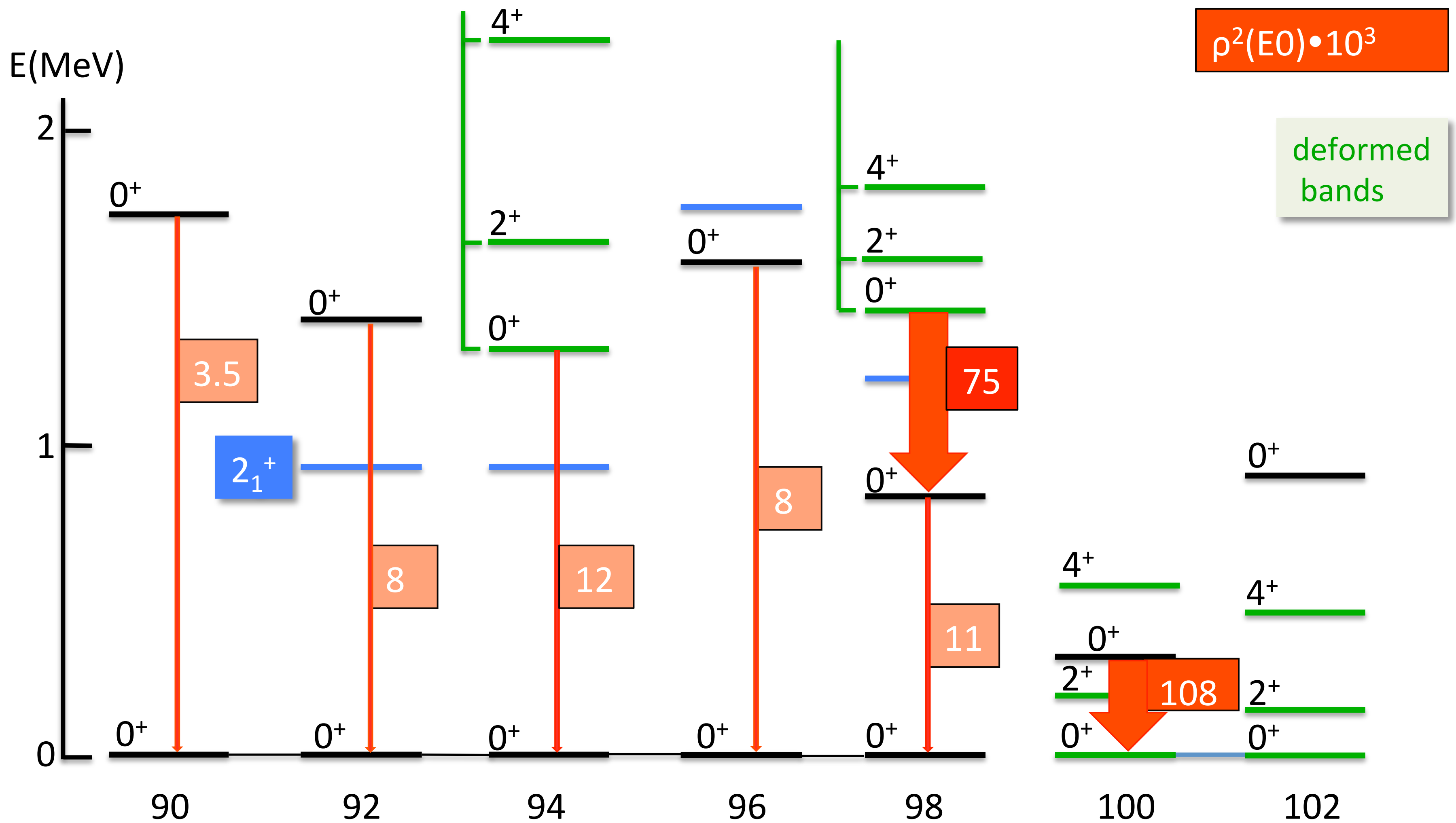
2_1^+ state 42 (δ = 0.02: 0.04% E2)

0^+ 2p-2h state 0.15

E. Elhami et al., PR C78, 054303 (2008)

8Pi expt.: S.W. Yates et al.,S1286 (5 days)

0_2^+ states and deformation in Zr isotopes, $50 \leq N \leq 62$:
electric monopole transition strengths

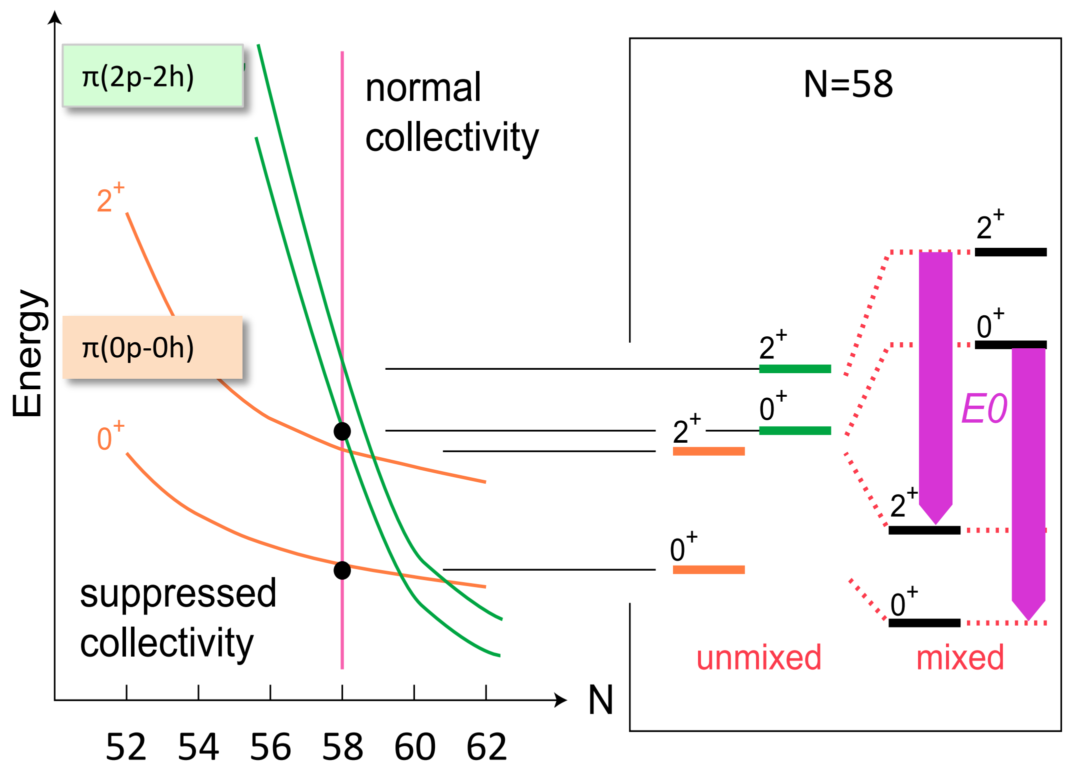


A deformed structure can intrude to become a ground state:

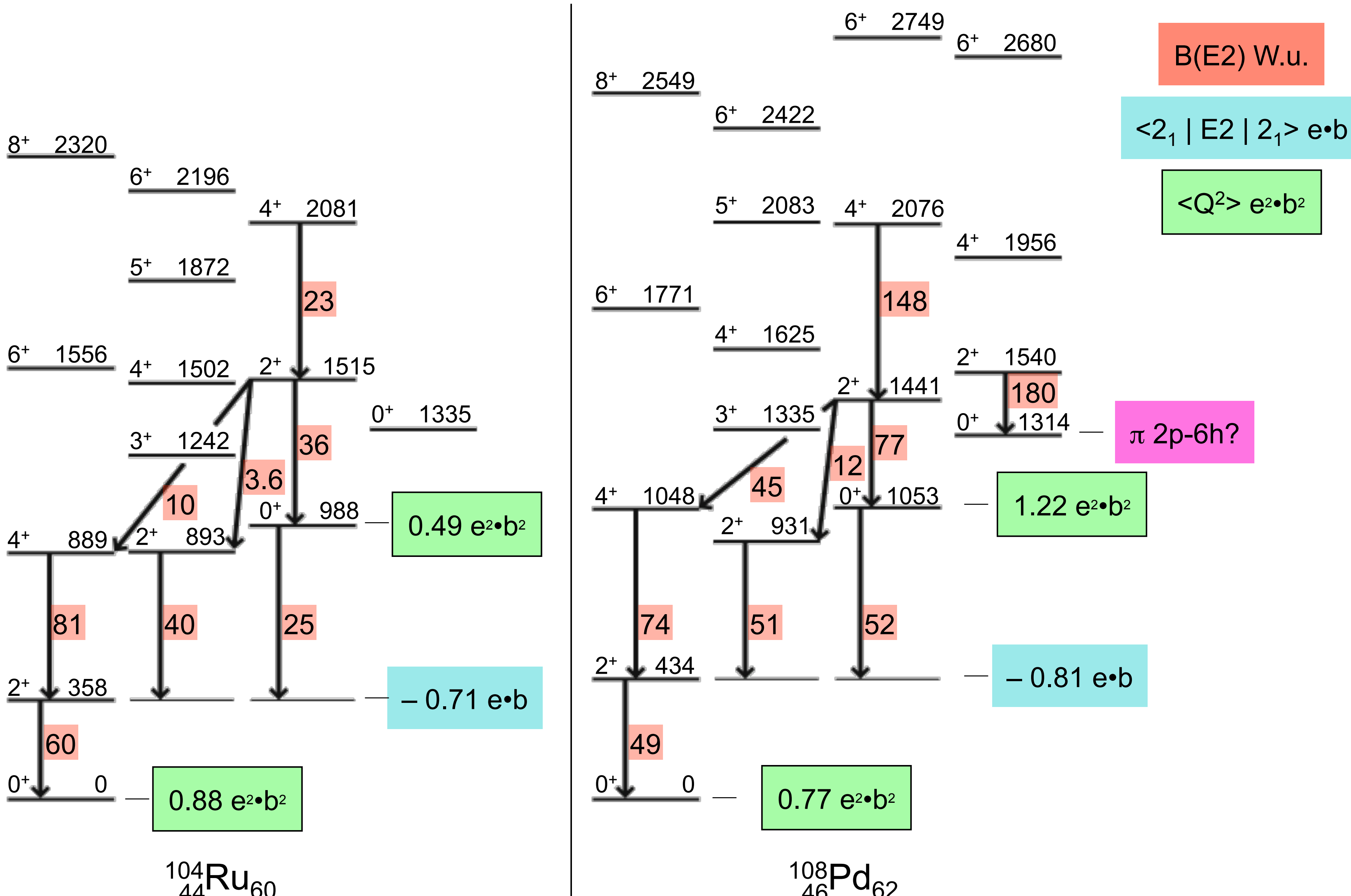
appears to produce a “collective phase change”

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



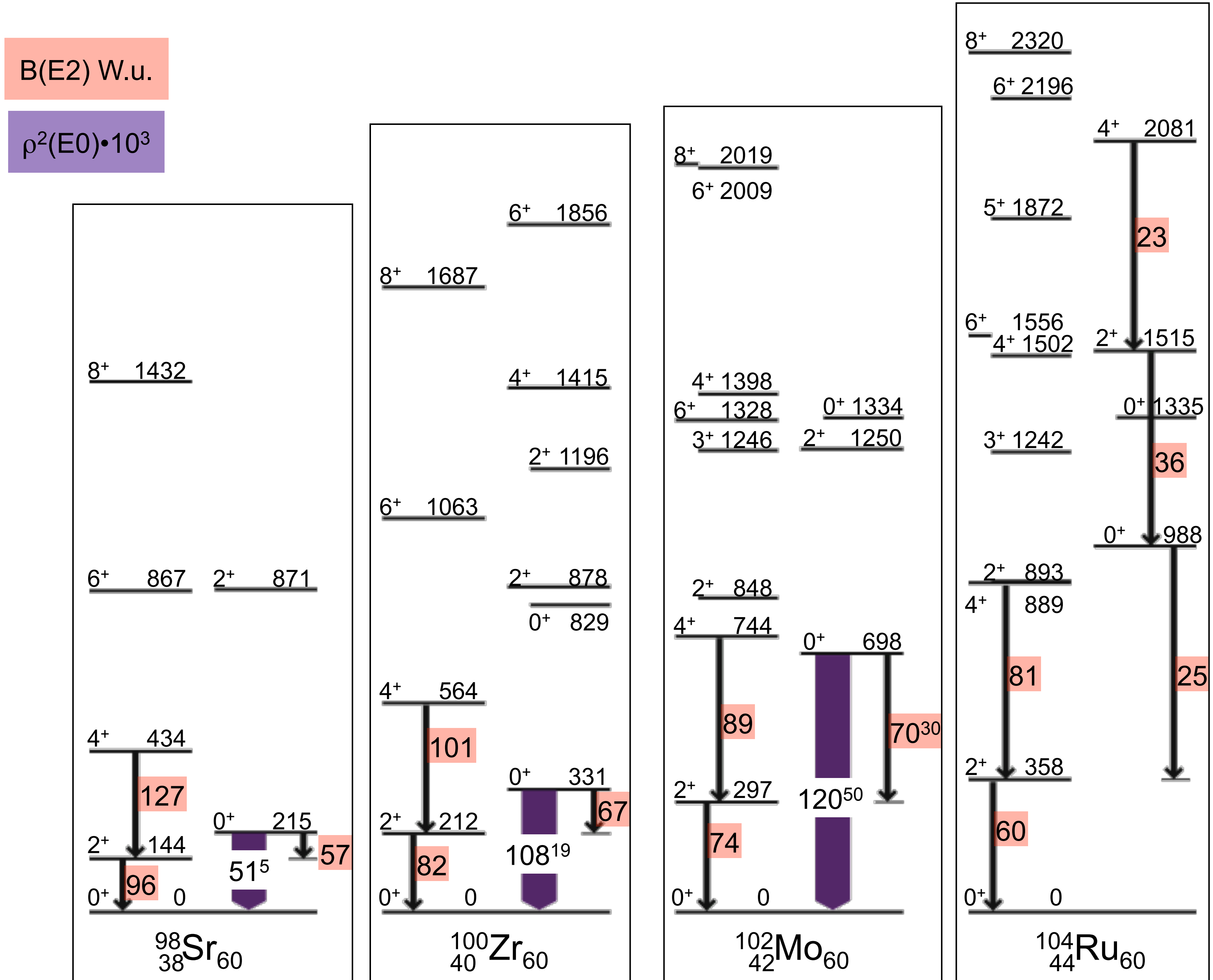
Collective states in ^{104}Ru and ^{108}Pd from multi-Coulex



J. Srebrny et al.
Nucl. Phys. **A766**, 25(2006)

L. E. Svensson et al.
Nucl. Phys. **A584**, 547(1995)

Systematics of low-lying collective states in N=60 isotones

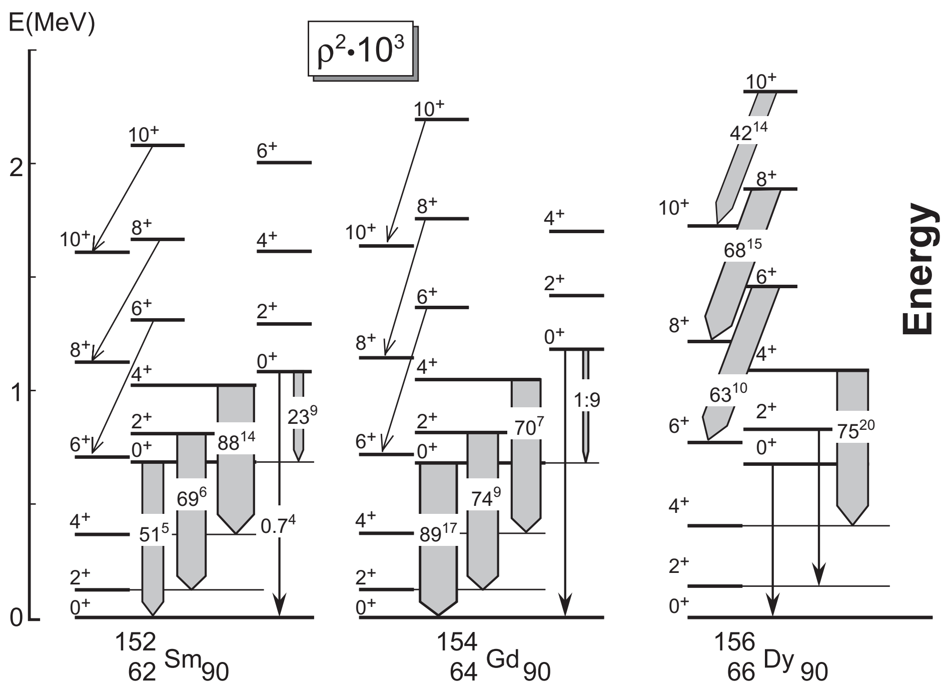


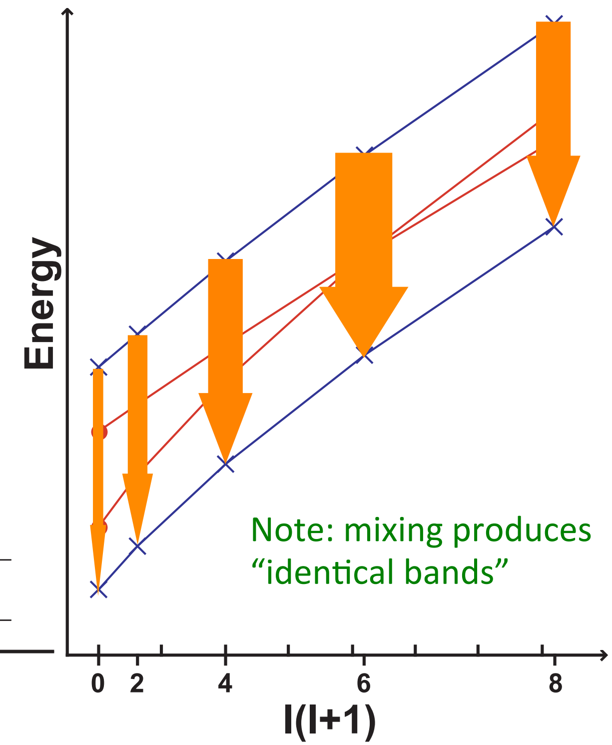
Shape coexistence in the N = 90 isotones:

revealed by E0 transition strengths

Strong mixing of coexisting shapes produces strong electric monopole (E0) transitions and identical bands.

Data from Heyde and Wood (2011)





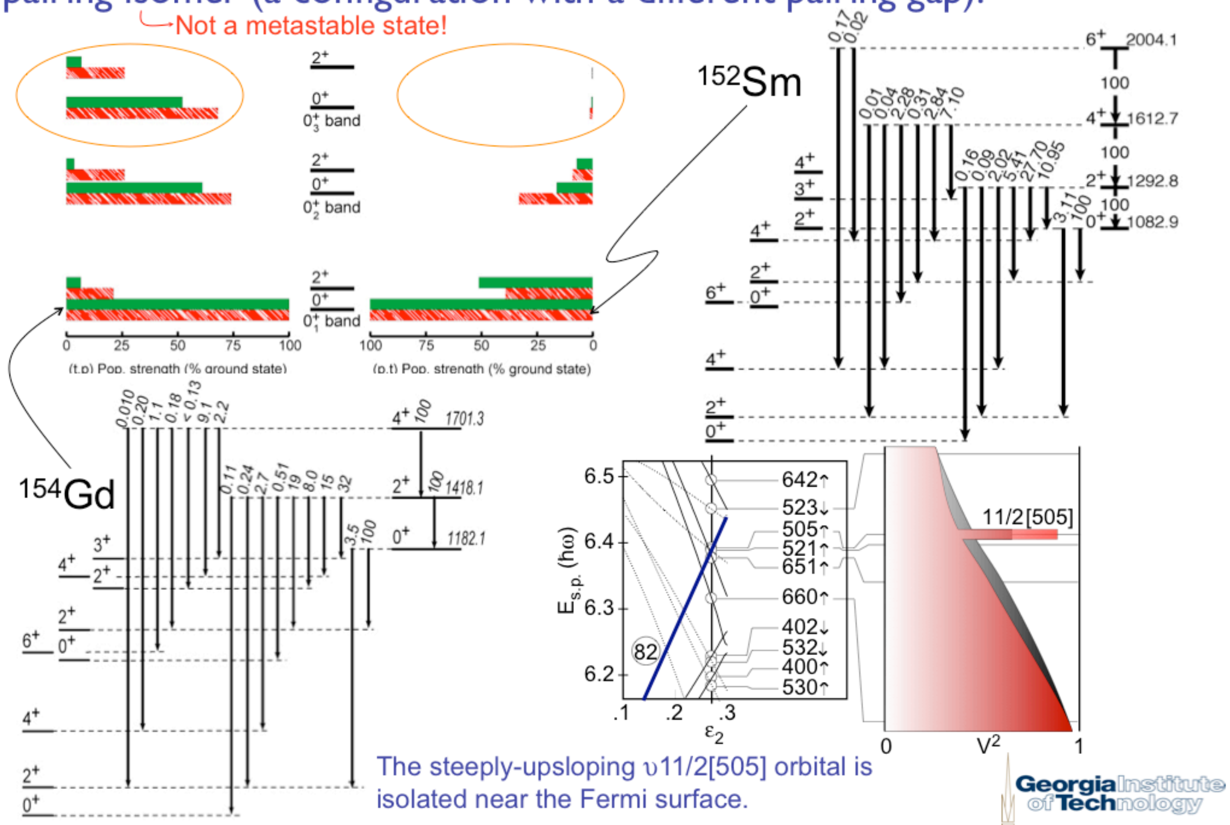
$$\rho^2 \cdot 10^3 = \alpha^2\beta^2 \left(\Delta\langle r^2\rangle\right)^2 \cdot 10^3 \frac{Z^2}{R_0^4}$$

$$R_0 = 1.2A^{1/3} \text{ fm}$$

E0 strength is a function of mixing.

Pairing isomers in the N = 90 isotones: ^{152}Sm and ^{154}Gd

Two-neutron transfer reactions reveal that the 0+3 state is a pairing isomer (a configuration with a different pairing gap).



W.D. Kulp et al., Phys. Rev. Lett. 91, 102501 (2003)

Nilsson intruders in the rare-earth region: possible origin of pairing isomers

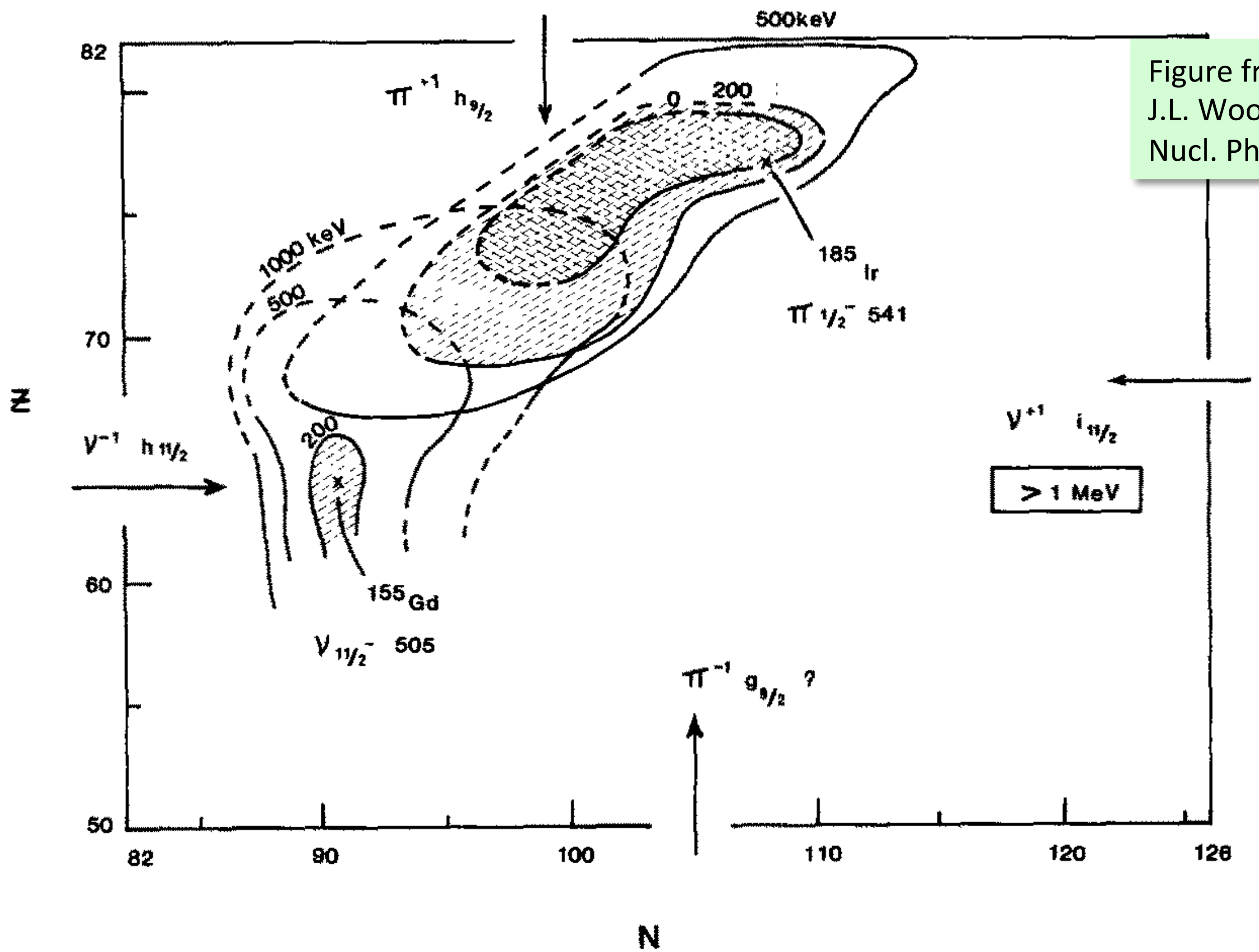


Figure from:
J.L. Wood,
Nucl. Phys. A421 43c 1984

Nilsson intruders in the actinide region: possible origin of pairing isomers

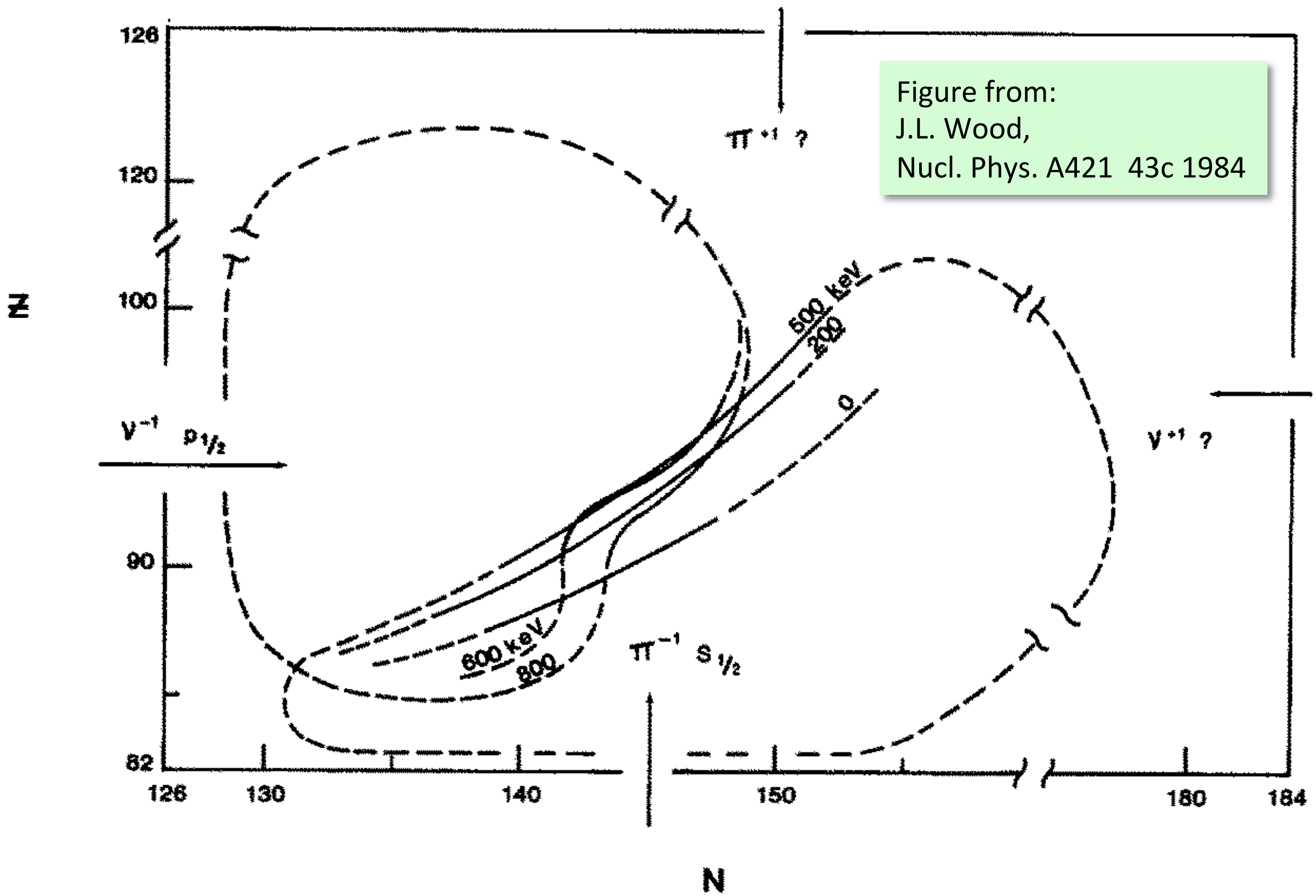
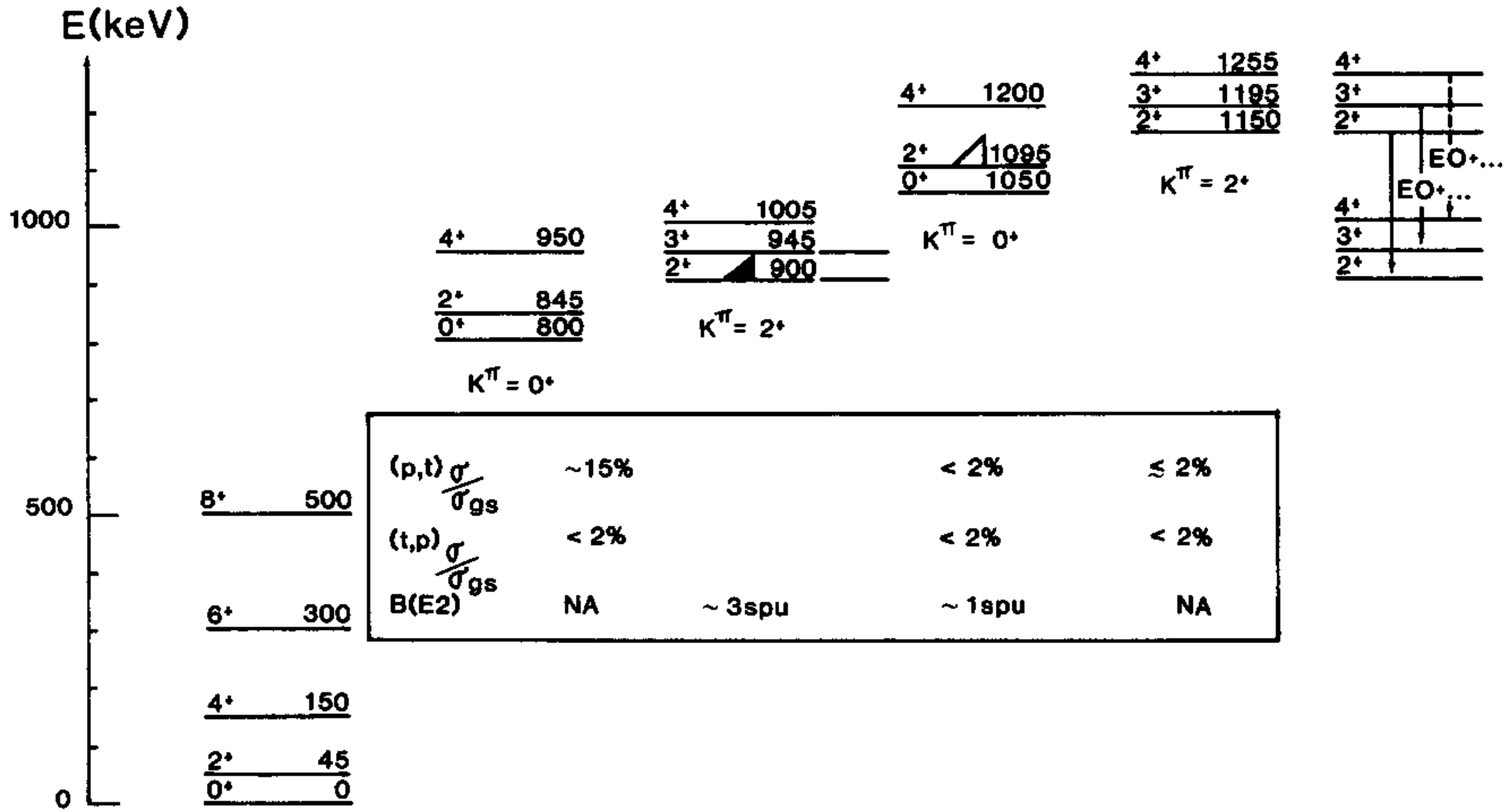


Figure from:
J.L. Wood,
Nucl. Phys. A421 43c 1984

Collective excitations in the actinides: a typical set of bands (e.g., ^{234}U)

Figure from; J.L. Wood, Nucl. Phys. A421 43c 1984 [Suzhou Conf. 1983]



Pairing isomers in the actinide region:

strong L = 0 transfer to excited states in (p,t)

PHYSICAL REVIEW C VOLUME 9, NUMBER 2 FEBRUARY 1974

Further studies of pairing excitations in actinide nuclei: ^{233}U, ^{237}Pu, ^{235}Np, ^{241}Am, ^{224}Ra, and ^{238}Pu†

A. M. Friedman and K. Katori*
Chemistry Division, Argonne National Laboratory, Argonne, Illinois 60439

D. Albright and J. P. Schiffer
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439,
and University of Chicago, Chicago, Illinois 60637

(Received 30 October 1973)

The behavior of a pairing excitation, previously reported in even actinide nuclei, has been explored with two odd-neutron (^{235}U and ^{239}Pu) and two odd-proton (^{237}Np and ^{243}Am) targets as well as the even-even targets ^{226}Ra and ^{240}Pu. It is found that this behavior is similar to that previously found in even-even actinide nuclei.

[NUCLEAR REACTIONS ^{226}Ra, ^{235}U, ^{237}Np, ^{239}Pu, ^{243}Am, ^{240}Pu(p,t) measured $\sigma(\theta)$, deduced excitations and cross sections of pairing excited states.]

Pairing isomers in the actinide region:

strong L = 0 transfer to excited states in (d,^{6}Li)

PHYSICAL REVIEW C VOLUME 23, NUMBER 1 JANUARY 1981

Selective excitations in actinide nuclei via alpha pickup

J. Jänecke
Department of Physics, University of Michigan, Ann Arbor, Michigan 48109
and Kernfysisch Versneller Instituut der Rijksuniversiteit, 9747 AA Groningen, The Netherlands

F. D. Becchetti and D. Overway
Department of Physics, University of Michigan, Ann Arbor, Michigan 48109

J. D. Cossairt*
Cyclotron Institute, Texas A&M University, College Station, Texas 77843

R. L. Spross
Department of Physics, University of Southwestern Louisiana, Lafayette, Louisiana 70504
(Received 16 July 1980)

The α-cluster pickup reaction $(d,^6\mathrm{Li})$ has been studied at $E_d = 55$ MeV on targets of ^{232}Th and ^{238}U. Members of the ground-state rotational bands in ^{228}Ra and ^{234}Th are excited and absolute reduced α widths obtained from finite-range distorted-wave analysis are in good agreement with values deduced from α decay. In addition three excited groups of states are very strongly populated in both nuclei with spectroscopic strength per group comparable with those of the respective ground state bands. These groups are apparently excited rotational bands with band heads at $E_x = 700\pm40$, 1070 ± 60, and 1390 ± 60 keV in ^{228}Ra and $E_x = 810\pm30$, 1150 ± 40, and 1470 ± 40 keV in ^{234}Th. The selective and strong excitation in this particular multi-nucleon transfer reaction of several excited bands is not predicted by existing theoretical models. An attempt has been made to describe the systematics of excited 0^+ states in the actinide region with the interacting boson model. Excitation energies are reasonably well described but intruder states are present and transfer strengths are not reproduced properly. The observation of strong α-cluster pickup to excited rotational bands suggests coherent contributions from both neutron *and* proton pair excitations which can lead to strong four-body correlations and/or to new types of collective excitations which favor quartet structure. It is found that about 25% of the nuclear charge (matter) at $r\simeq10.6$ fm must be associated with α particles. This high α-clustering probability indicates α-particle condensation in low-density nuclear matter.

NUCLEAR REACTIONS ^{232}Th, ^{238}U$(d,^6\mathrm{Li})$, $E=54.8$ MeV; measured $\sigma(\theta)$; DWBA analysis; ^{228}Ra, ^{234}Th deduced levels, S_α, $\gamma_\alpha{}^2$ (10.5 fm), α-clustering probabilities.

Rare-earth region K = 0+ excited bands exhibit a wide range of "rotational" energy spacing, the significance of which is essentially unexplored#

Isotope	i	ΔE^i_{20}	r	Isotope	i	ΔE^i_{20}	r
^{156}Gd	1	89		^{170}Yb	1	84	
	2	70			2	70	
	4	56	0.63	^{172}Yb	1	79	
	5	64			4	55	0.70
^{158}Gd	1	80			5	61	0.77
	2	64		^{178}Yb	1	84	
	4	49	0.61		2	72	
^{160}Gd	1	75		^{172}Hf	1	91	
	2	51			4	61	0.67
	3	56		^{176}Hf	1	88	
^{160}Dy	1	87			2	77	
	2	70		^{178}Hf	1	93	
	5	59	0.68		2	78	
^{164}Er	1	91			3	62	
	2	69			4	70	
	3	67		^{178}W	1	106	
^{166}Er	1	81			2	86	
	2	68		^{152}Nd	1	73	
^{168}Er	1	80			2	112	1.53
	2	59	0.75	^{182}W	1	100	
	4	59	0.75		2	121	1.21
^{170}Er	1	79		^{186}W	1	123	
	2	69			2	146	1.19
	3	61	0.75	^{184}Os	1	120	
^{164}Yb	1	123			2	163	1.36
	2	98					
^{168}Yb	1	88					
	4	62					

The 2^+ - 0^+ energy differences of K = 0 bands in the rare-earth region: i = 1,2,3, … labels successive bands, i = 1 (gs). The ratios of these energies, 'r', with the ground state band are given where they significantly differ from unity.

Table from K. Heyde and J.L. Wood, Rev. Mod. Phys. 83, 1467 (2011)

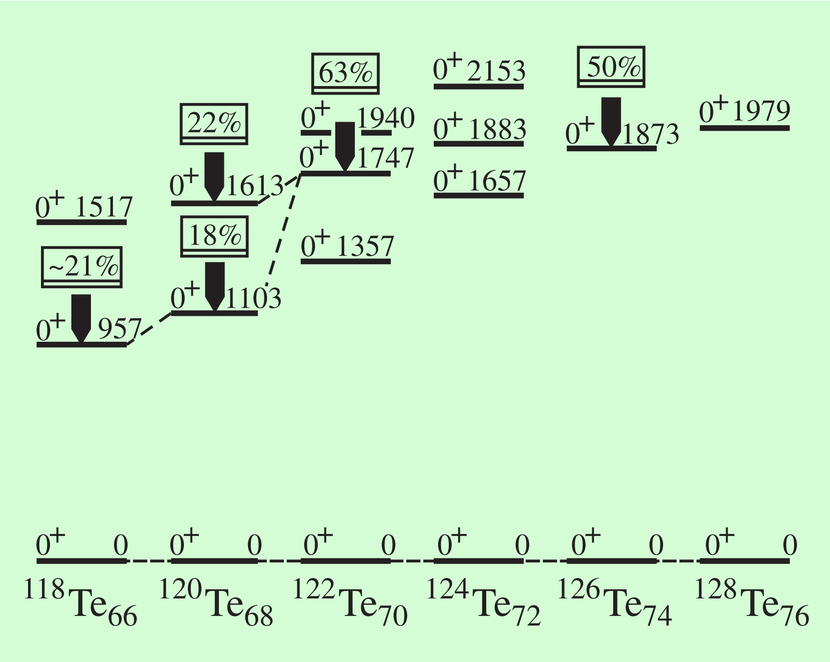
Exploration using gamma-ray and conversion electron spectroscopy following radioactive decay is needed.

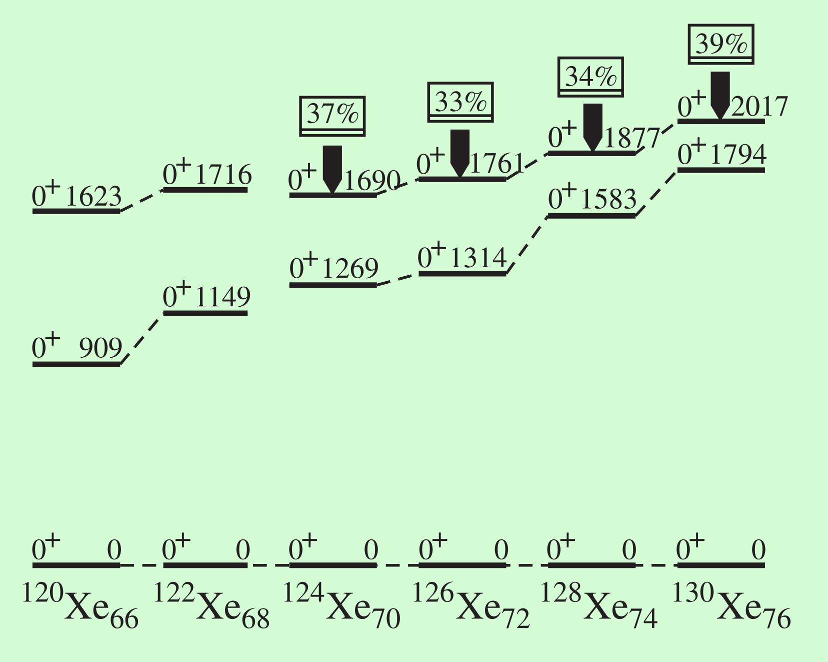
Table from Heyde & Wood

Excited 0^+ states in the Te, Xe isotopes with strong population in two-proton stripping reactions

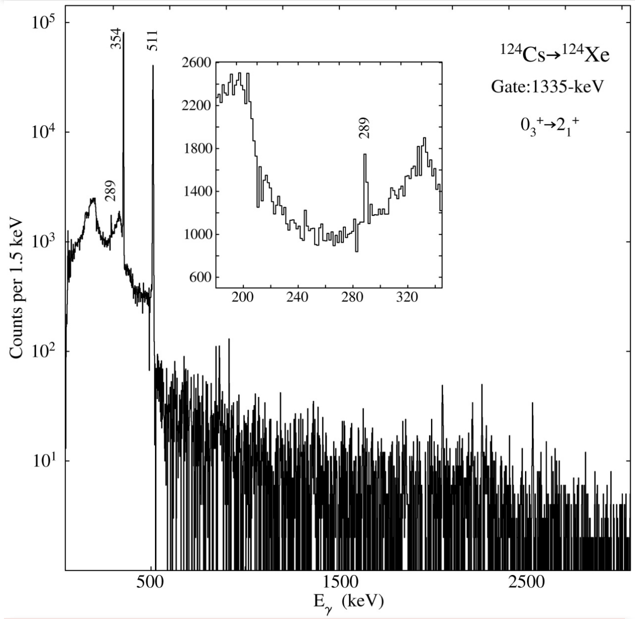
Figure from Heyde & Wood

0^+ state population in (^{3}He,n) shown as % of the ground-sate population—data taken from W.P. Alford et al., NP A323 339 (1979) and H.W. Fielding et al., NP A304 520 (1978)





Coexistence in ^{124}Xe (subshell pairing isomer?)



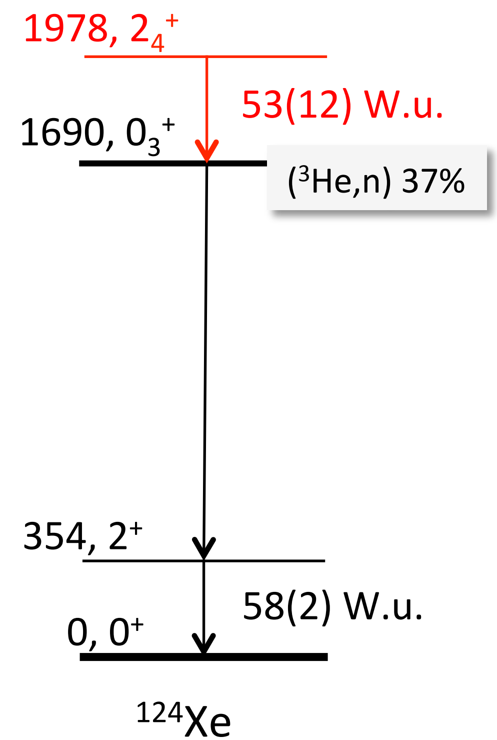
Intensity of 289-keV line is 10^{-5} of the $2^+ \rightarrow 0^+$ in ^{124}Cs (EC)

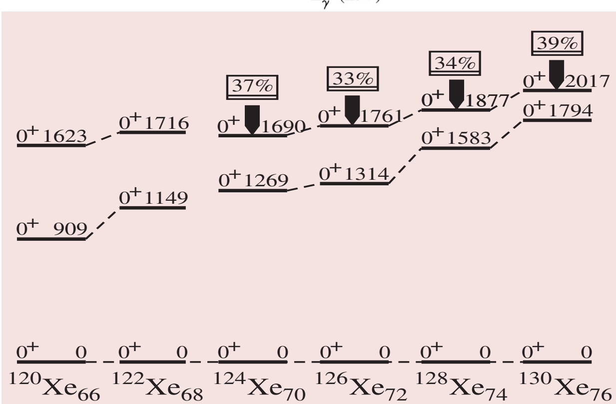
Time-random background subtracted γγ matrix 3.7×10^8 events

0.84% branch → 59(18) W.u.
(preliminary)

$T_{1/2}$ 1978 from Coulex
Rainovski PL B683 11 2010

Radich
unpublished (U. Guelph/TRIUMF)

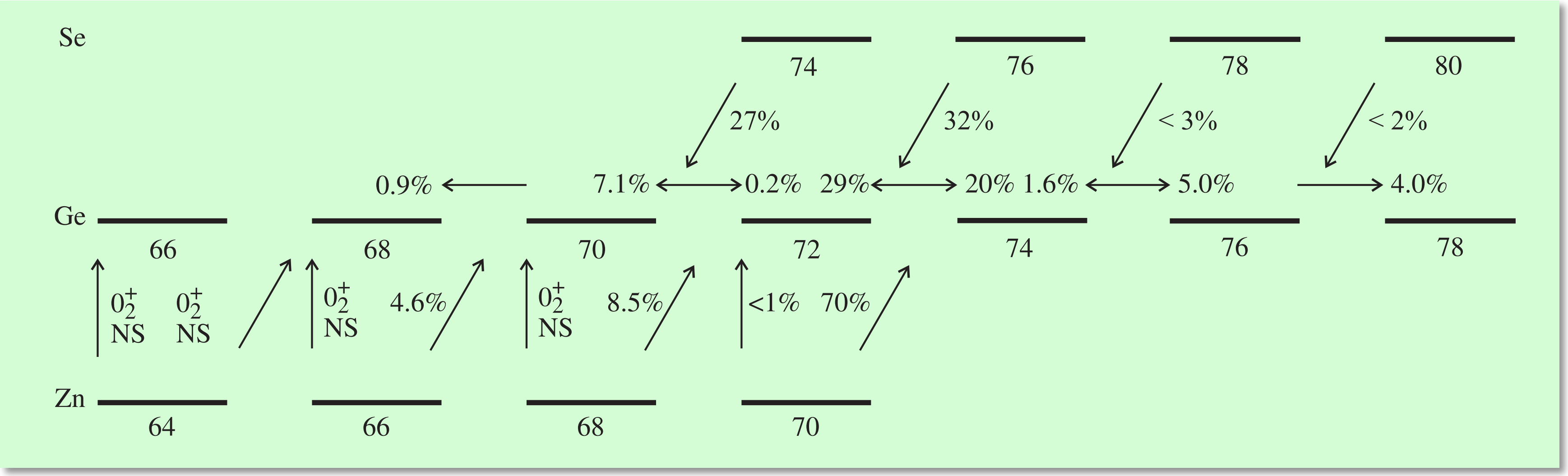




Te(^{3}He,n)Xe % population cf. gs
Alford NP A323 339 1979

The Ge isotopes have excited 0^+ states that are strongly populated in two- and four-nucleon transfer reactions

Figure from Heyde and Wood



Data taken from:

D. Ardoin et al., PR C22 2253 (1980)

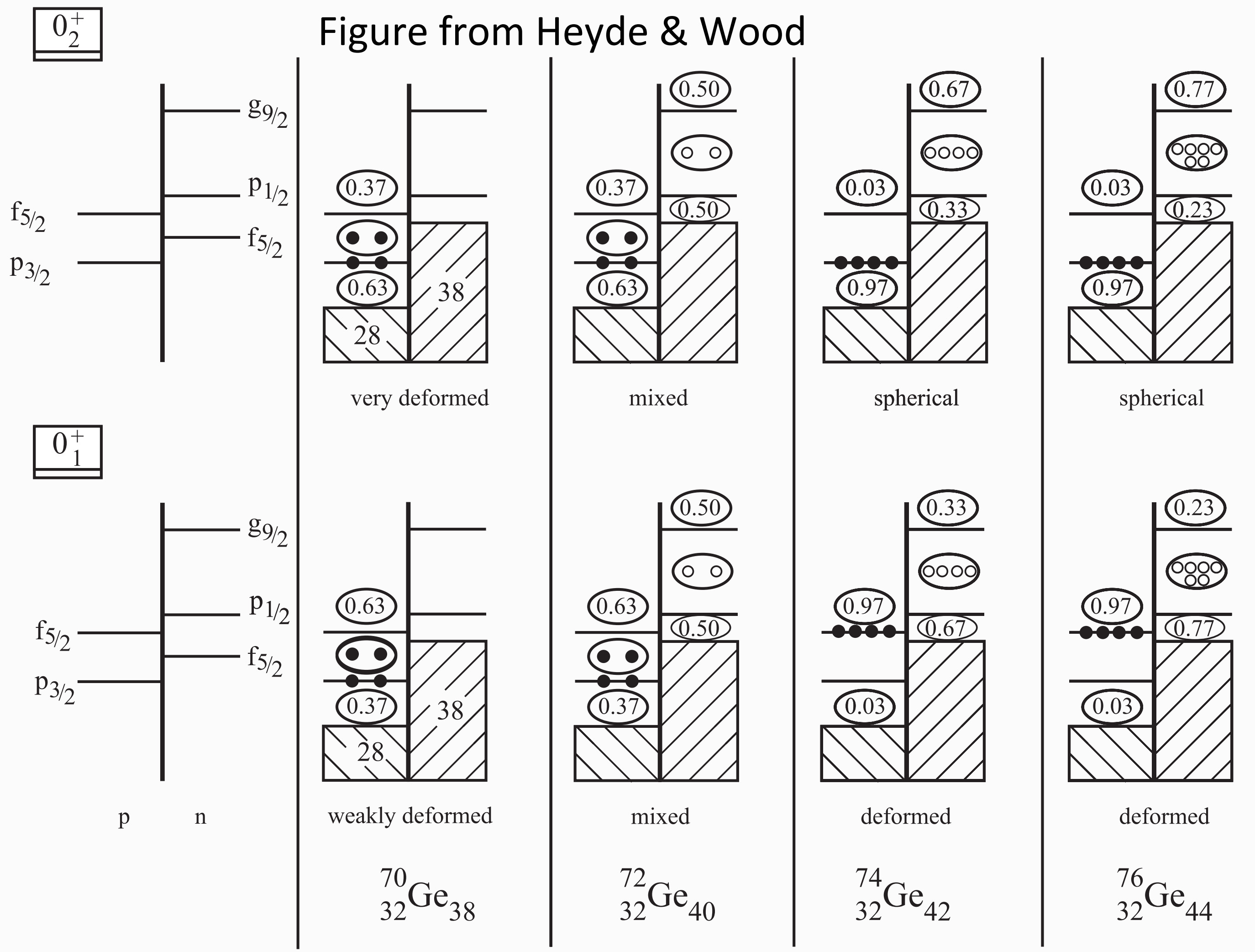
A. Boucenna et al. PR C42 1297 (1990)

A.M. Van den Berghe et al. NP A379 239 (1982)

and references in Heyde and Wood

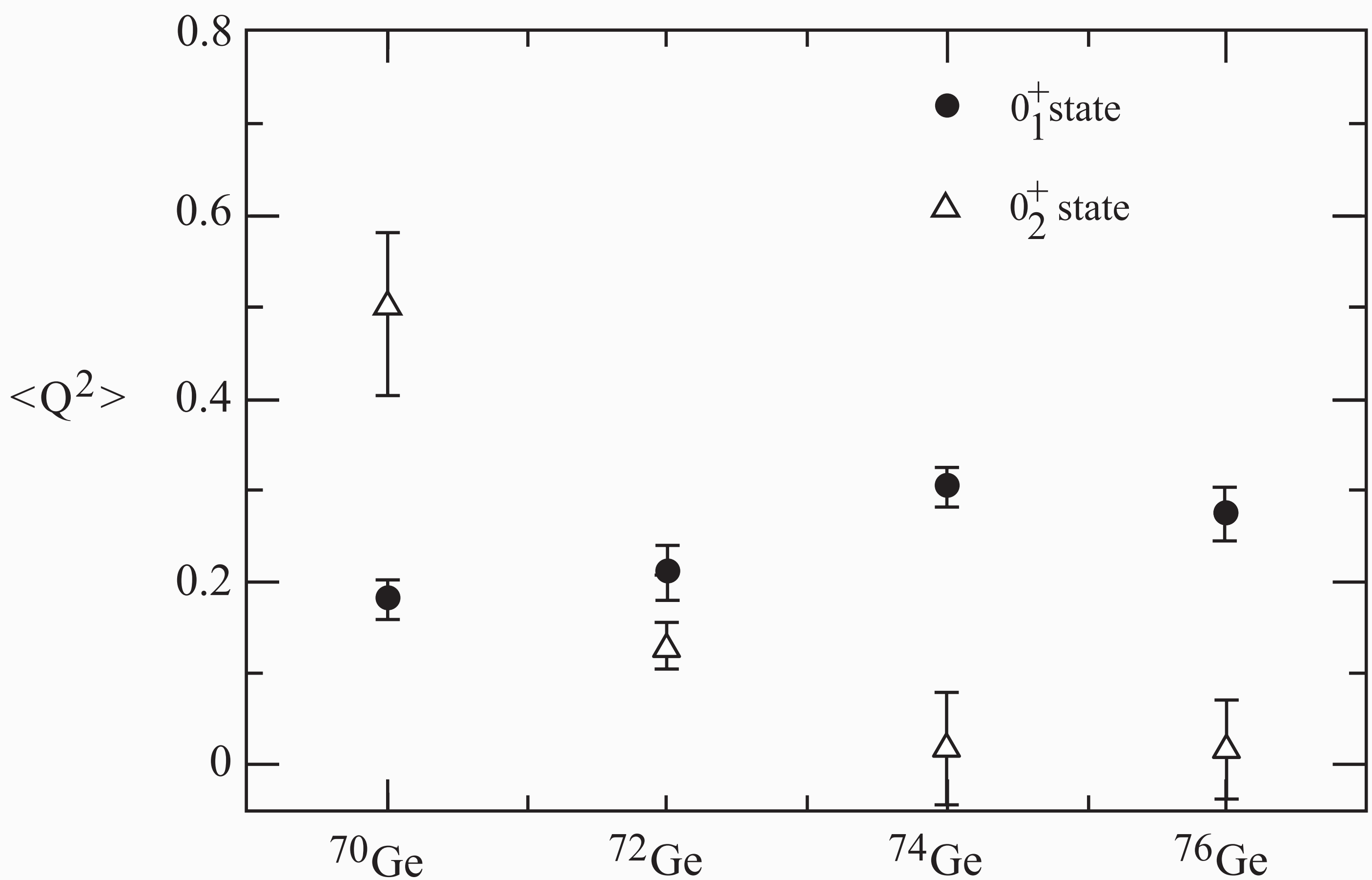
0_1^+ and 0_2^+ states in $^{70-76}$Ge: the importance of mapping pair occupancies

Figure from Heyde & Wood

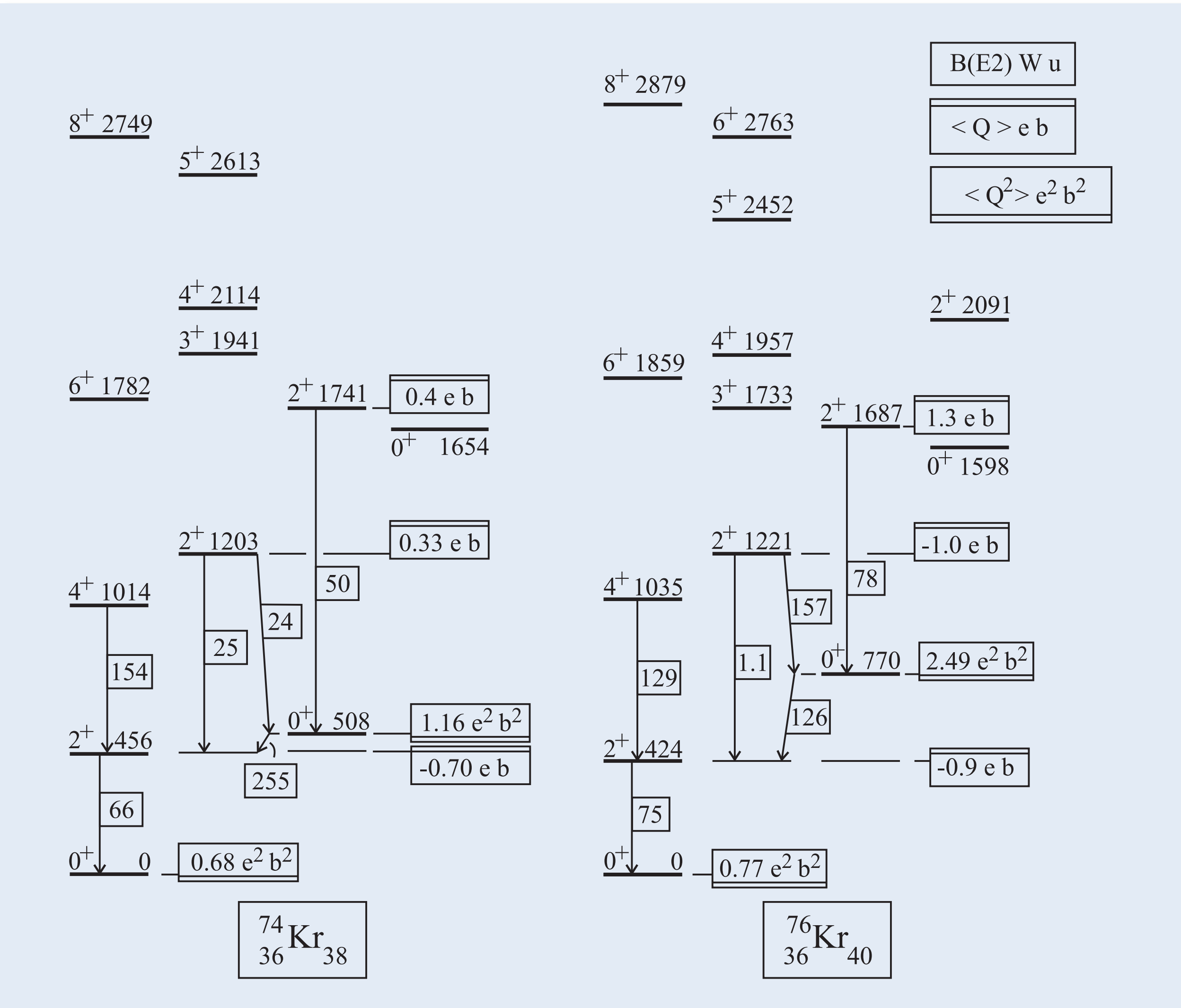


0_1^+ and 0_2^+ states in $^{70-76}$Ge: the importance of mapping E2 strength

Figure from Heyde & Wood



Excited 0^+ states in ^{74,76}Kr: are they prolate and oblate coexisting structures?



Data from:
E. Clement et al., Phys. Rev. C 75 054313 2007

Do we understand excited 0^+ states in nuclei?

- CONCLUSIONS:
- Nuclei do not possess low-energy vibrations associated with the quadrupole degree of freedom
- Pairing (off diagonal) is sufficiently weak that pair excitations across shell and subshell gaps give rise to 0^+ states at low excitation energy
- Identification and characterization of E0 transitions is essential to understanding excited 0^+ states and associated collective bands
- Transfer reaction data are critical for understanding excited 0^+ states
- Ultra-high statistics β decay data is needed to see high-lying, low-energy γ-ray transitions

This program is in collaboration with P.E. Garrett, K. Heyde, W.D. Kulp, S.W. Yates, E.F. Zganjar, and many others