Probing neutron-rich isotopes around doubly closed-shell ^{132}Sn and doubly mid-shell ^{170}Dy by combined β-γ and isomer spectroscopy

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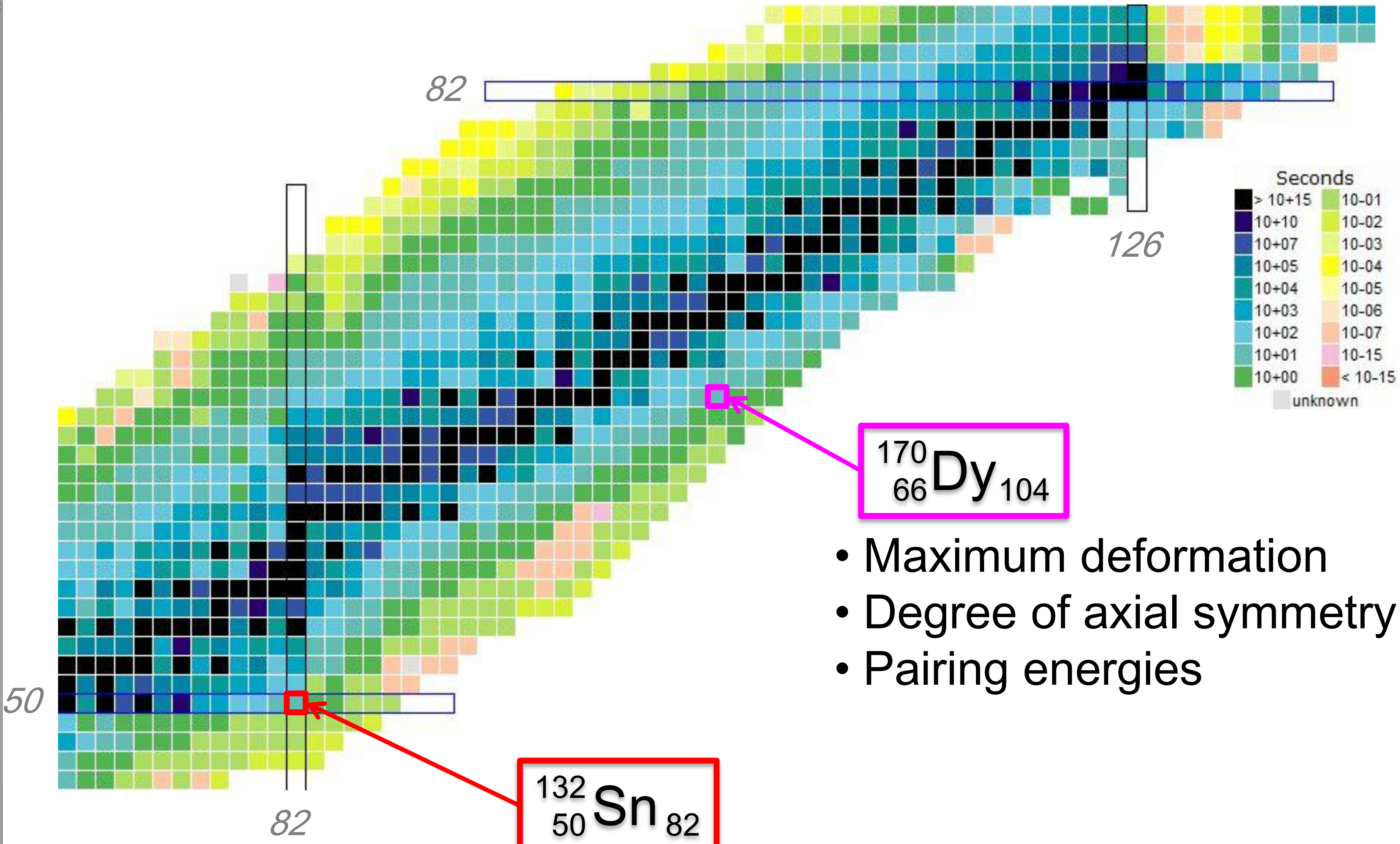
Outline

- Prospects for decay spectroscopy of neutron-rich isotopes in the vicinity of
  - **Doubly closed-shell nucleus ^{132}Sn**
    - Long-lived spin-gap isomers in $_{48}$Cd and $_{47}$Ag isotopes
    - Collective motions in $_{46}$Pd isotopes
  - **Doubly mid-shell nucleus ^{170}Dy**
    - Maximum ground-state deformation
    - γ- and β- vibrations
    - K isomers
- Summary



$^{170}_{66}\mathrm{Dy}_{104}$

- Maximum deformation
- Degree of axial symmetry
- Pairing energies

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

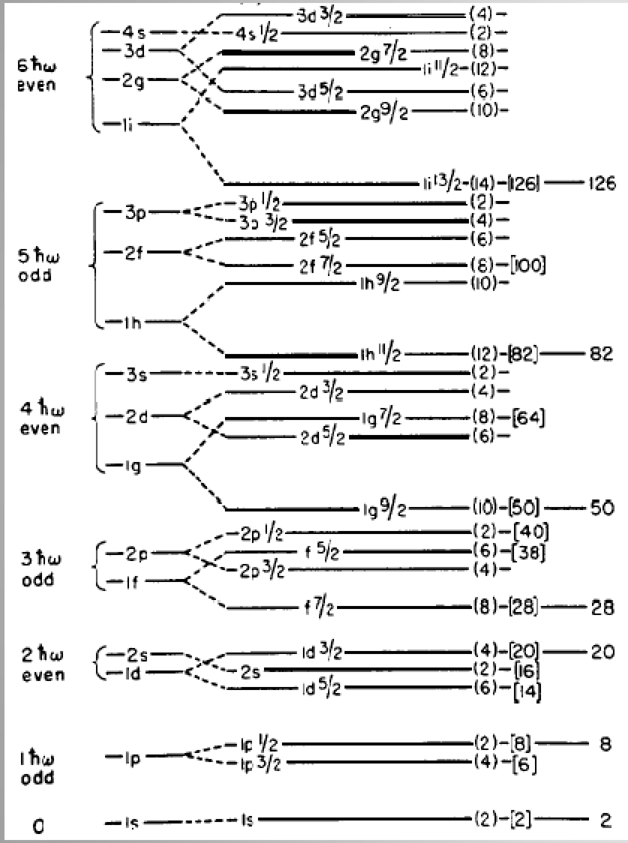
- Single-particle levels
- Residual interactions
- Collectivity and shell quenching

Single-particle energies & Residual interactions

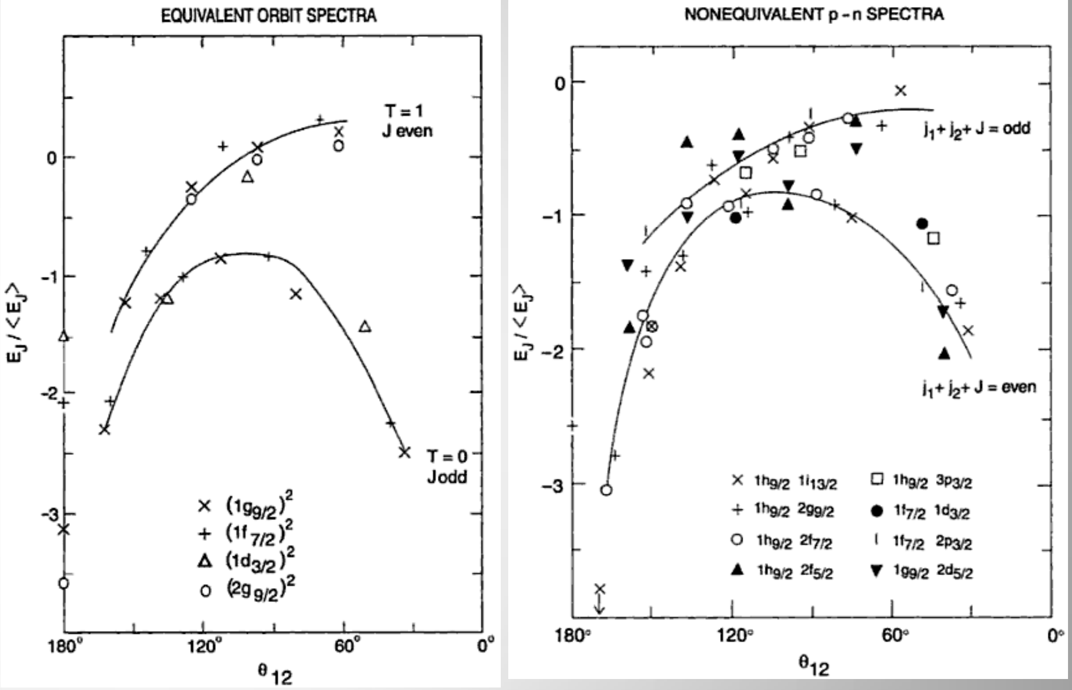
⇒ Key ingredients for shell-model calculations

Single-particle orbits

Residual interactions



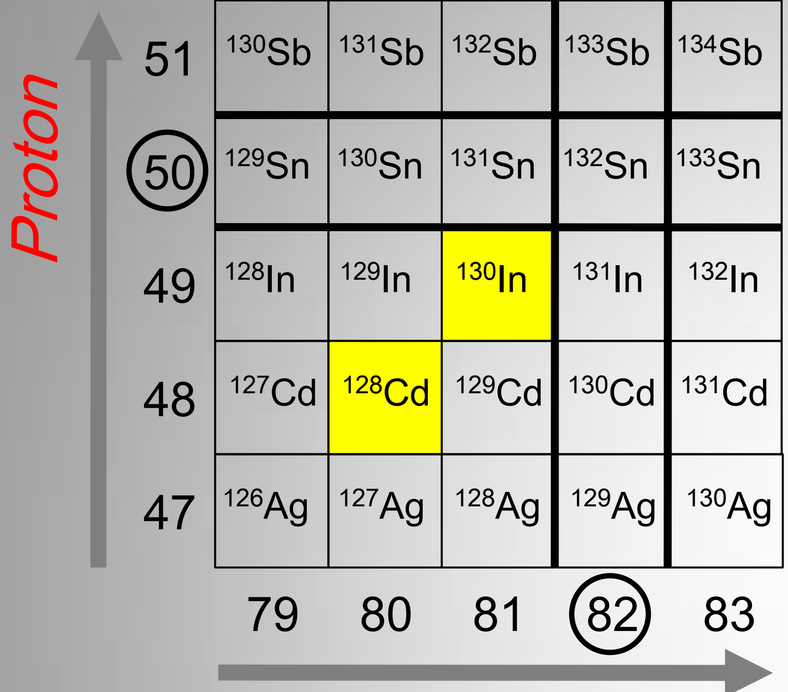
M.G. Mayer, Nobel Lecture (Dec. 12 1963)



J.P. Schiffer, Ann. Phys. 66, 798 (1971)

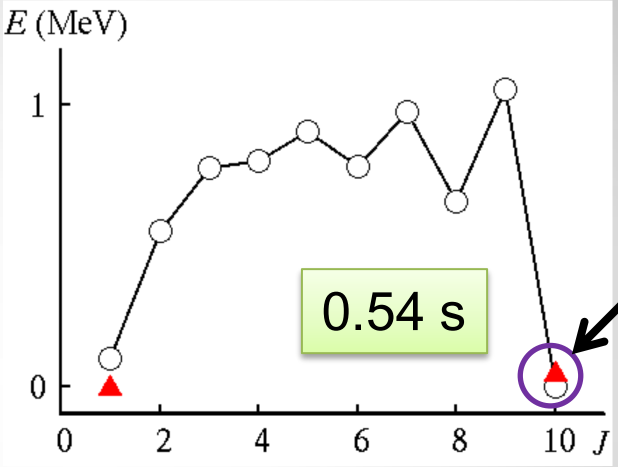
Isomers near shell-closures are sensitive probes to reveal the nature of single-particle energies and residual interactions

Long-lived isomers in the vicinity of ^{132}Sn



	79	80	81	⑧②	83
51	^{130}Sb	^{131}Sb	^{132}Sb	^{133}Sb	^{134}Sb
⑤⓪	^{129}Sn	^{130}Sn	^{131}Sn	^{132}Sn	^{133}Sn
49	^{128}In	^{129}In	^{130}In	^{131}In	^{132}In
48	^{127}Cd	^{128}Cd	^{129}Cd	^{130}Cd	^{131}Cd
47	^{126}Ag	^{127}Ag	^{128}Ag	^{129}Ag	^{130}Ag

High-j orbits, $\nu h_{11/2}$ and $\pi g_{9/2}$, play an important role in the construction of levels

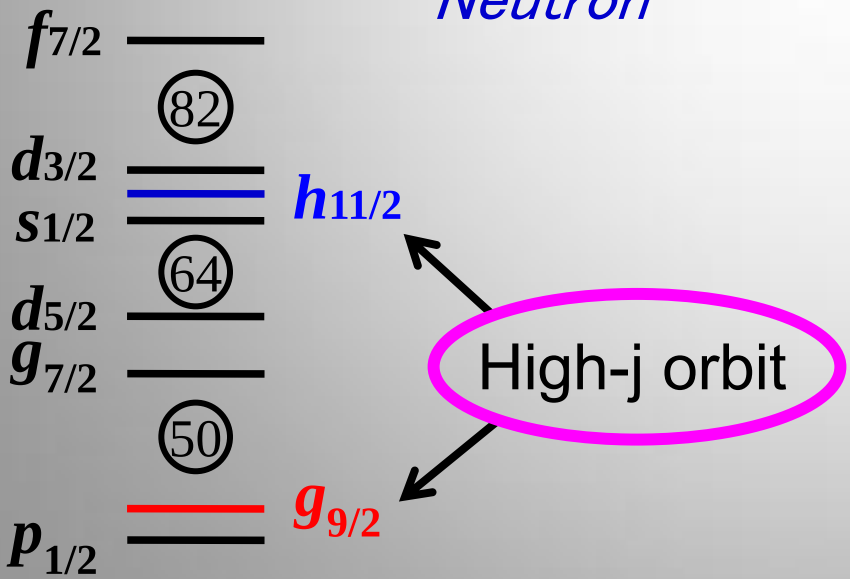


0.54 s

^{130}In

$J^{\pi} = 10^{-}$

$\pi g_{9/2}^{-1} \nu h_{11/2}^{-1}$



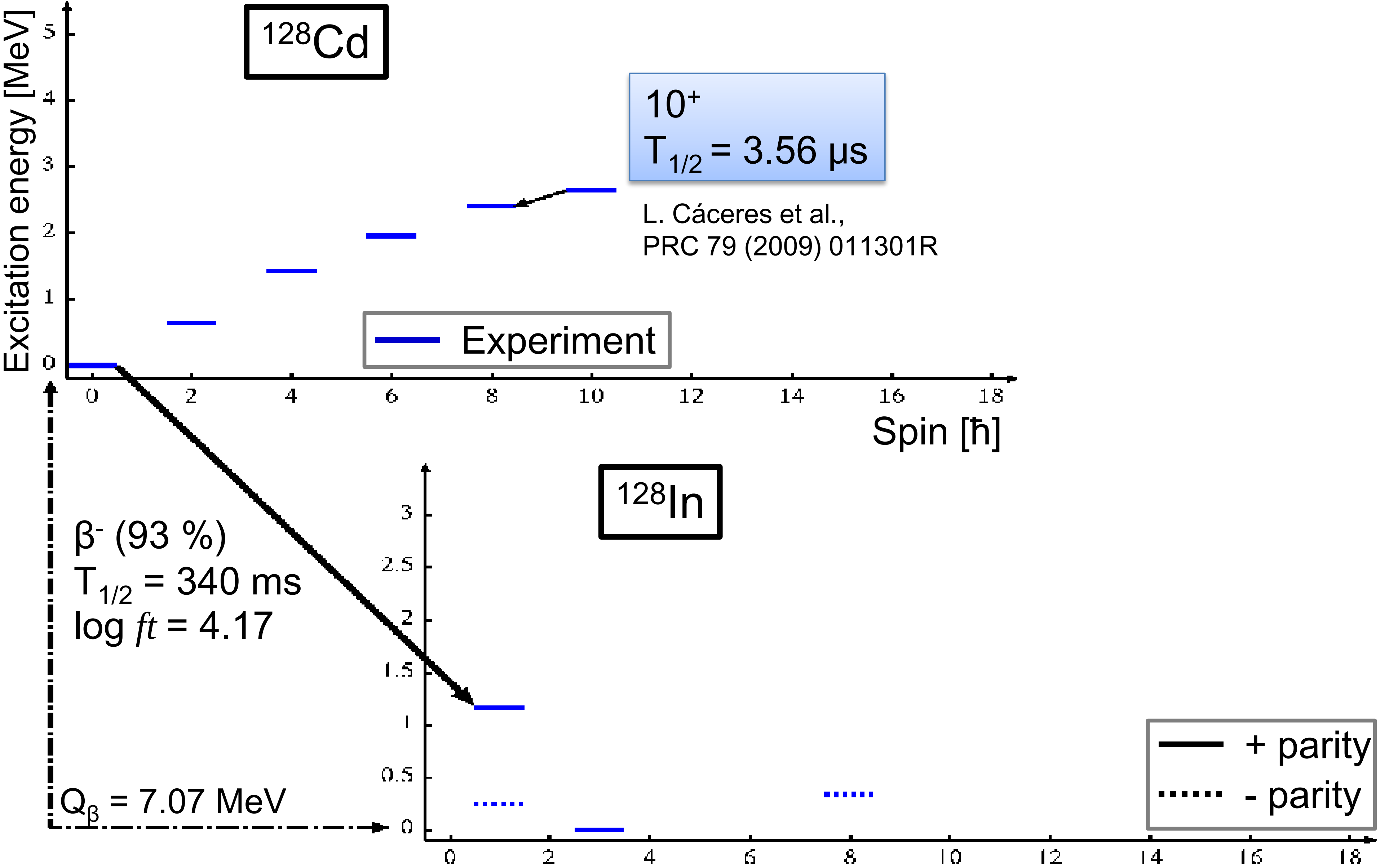
Attractive proton-neutron interactions depress the stretch-aligned configuration

^{128}Cd

$J^{\pi} = 18^{+}$

$\pi(g_{9/2}^{-2})_{8+}\ \nu(h_{11/2}^{-2})_{10+}$

Long-lived isomers in the vicinity of ^{132}Sn



10^{+}

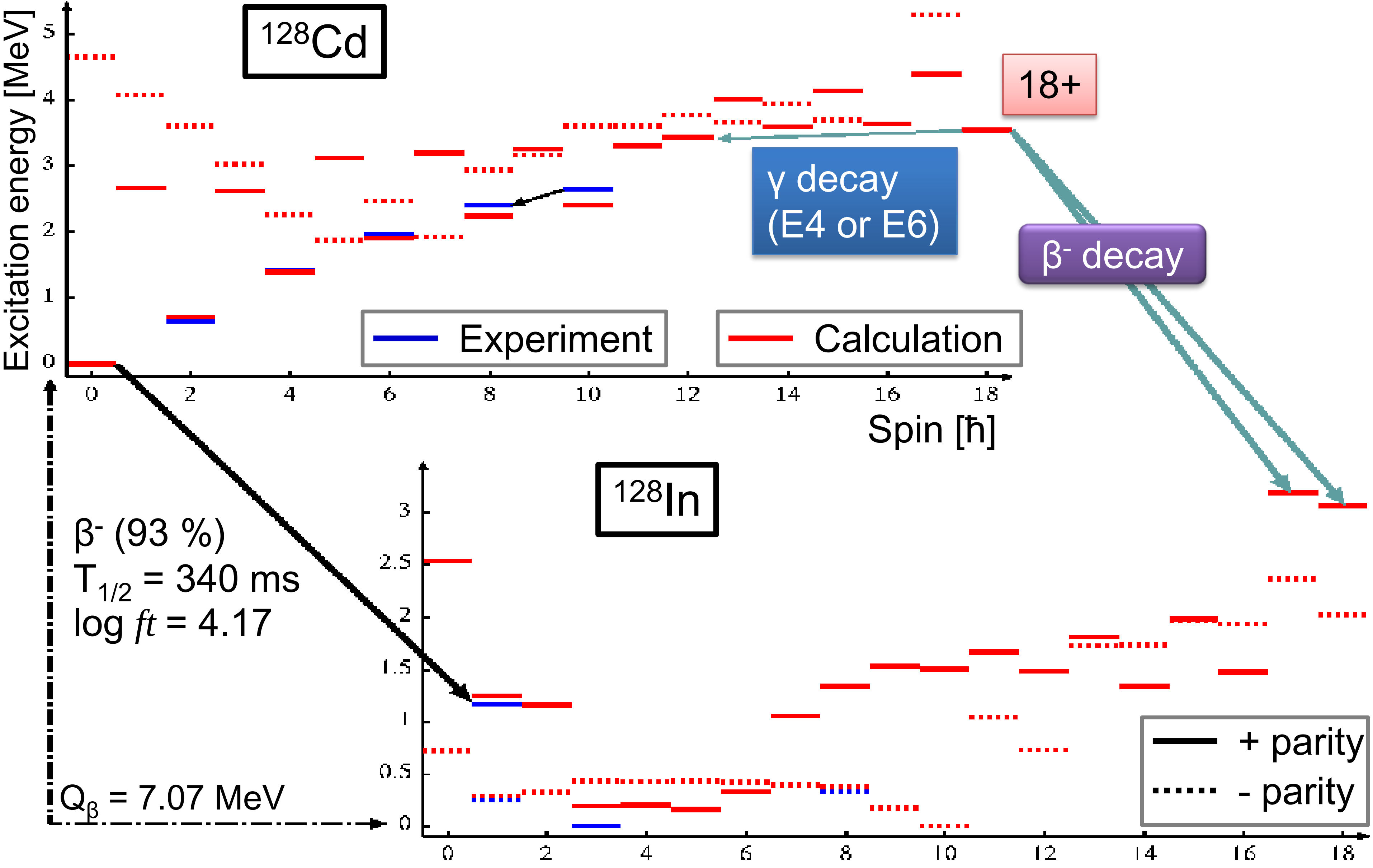
$T_{1/2} = 3.56\ \mu s$

L. Cáceres et al.,
PRC 79 (2009) 011301R

β^{-} (93 %)
$T_{1/2} = 340$ ms
log $ft = 4.17$

$Q_{\beta} = 7.07$ MeV

Long-lived isomers in the vicinity of ^{132}Sn



18+

γ decay
(E4 or E6)

β^- decay

β^- (93 %)
$T_{1/2}$ = 340 ms
log *ft* = 4.17

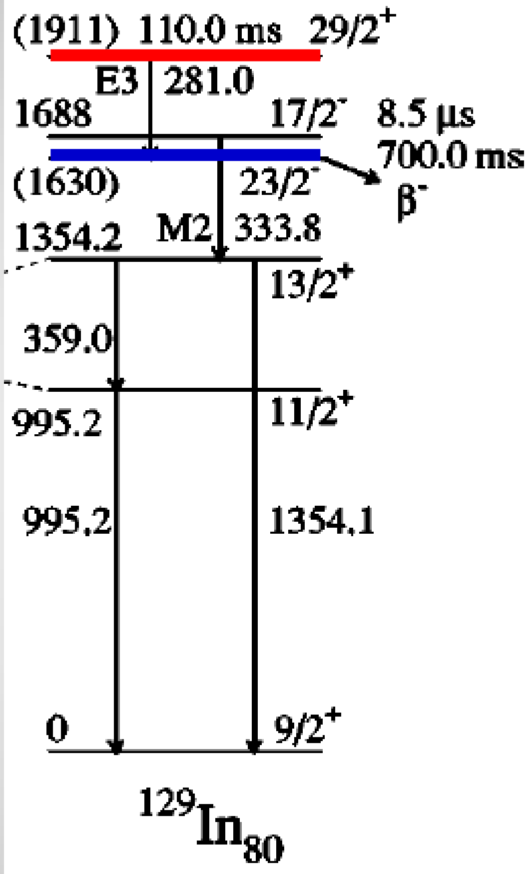
Q_β = 7.07 MeV

Long-lived isomers in the vicinity of ^{132}Sn

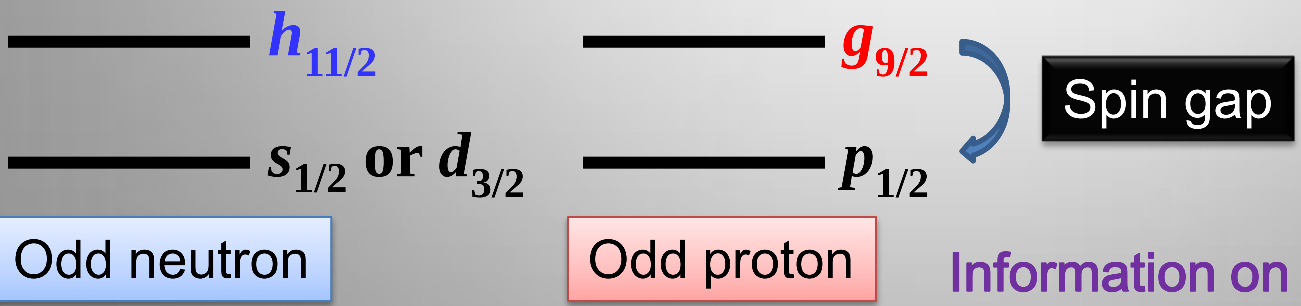
A. Scherillo et al.,
PRC 70 (2004)
054318

Multi-quasiparticle isomers at high spins

Nucleus	J^π	Configuration	Decay mode
^{129}In	**$23/2^-$**	$\pi(g_{9/2}^{-1})\otimes\nu(h_{11/2}^{-1}d_{3/2}^{-1})$	β
	$29/2^+$	$\pi(g_{9/2}^{-1})\otimes\nu(h_{11/2}^{-2})$	E3
^{128}Cd	**18^+**	$\pi(g_{9/2}^{-2})\otimes\nu(h_{11/2}^{-2})$	E4, E6, or β
^{129}Cd	**$27/2^-$**	$\pi(g_{9/2}^{-2})\otimes\nu(h_{11/2}^{-1})$	E3 or β
^{127}Ag	**$29/2^+$**	$\pi(g_{9/2}^{-1})\otimes\nu(h_{11/2}^{-2})$	E3 or β
	$37/2^-$	$\pi(g_{9/2}^{-2}p_{1/2})\otimes\nu(h_{11/2}^{-2})$	M2, E3, or β
^{128}Pd$_{82}$	**8^+**	$\pi(g_{9/2}^{-2})$	E2



Low-lying single-particle(hole) isomers



$h_{11/2}$

$s_{1/2}$ or $d_{3/2}$

$g_{9/2}$

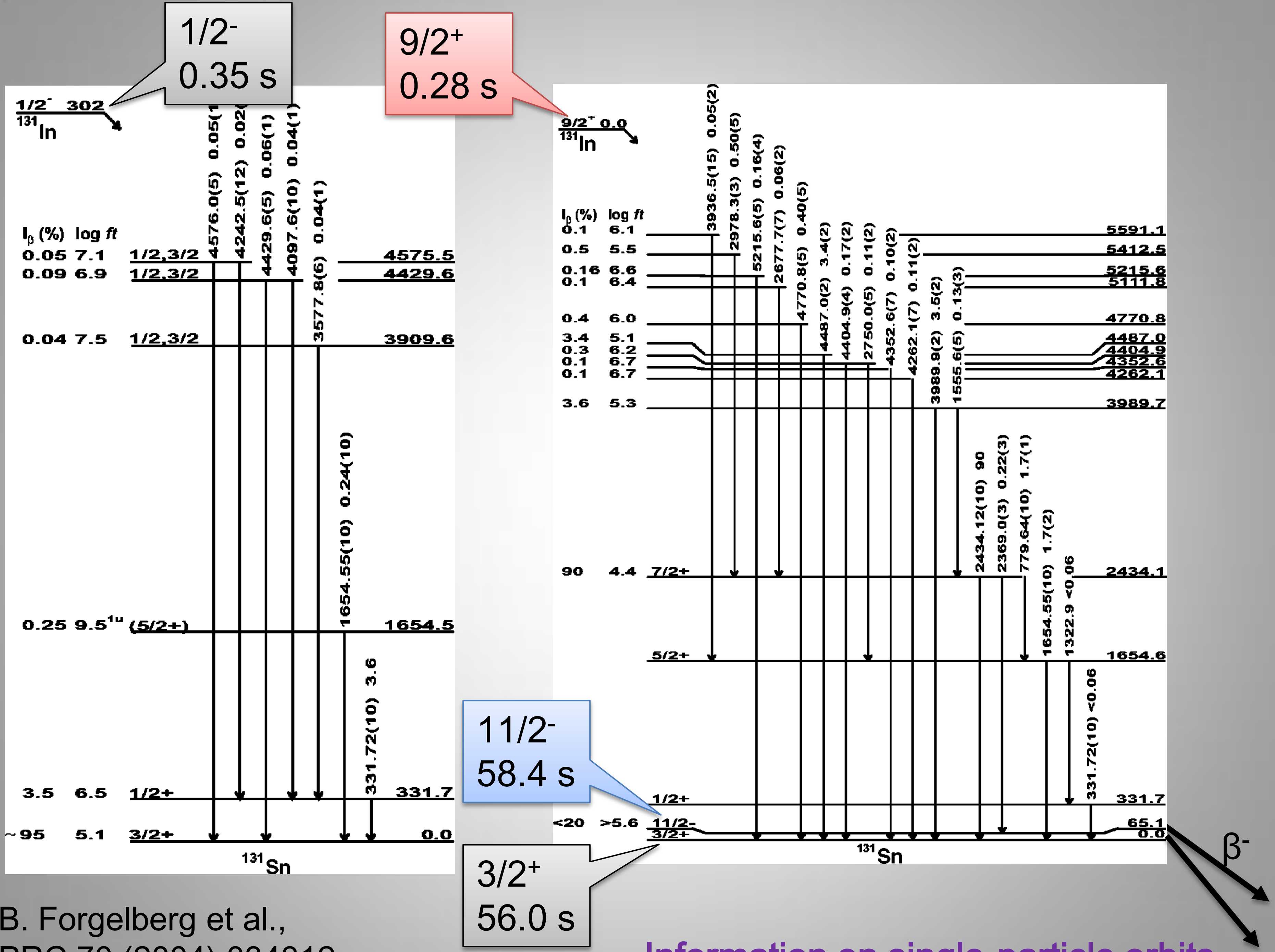
$p_{1/2}$

Spin gap

Odd neutron

Odd proton

Information on single-particle orbits



$1/2^-$
0.35 s

$9/2^+$
0.28 s

$11/2^-$
58.4 s

$3/2^+$
56.0 s

B. Forgelberg et al.,
PRC 70 (2004) 034312

Information on single-particle orbits

Yield estimation for the 18^+ isomer in ^{128}Cd

- ☐ Primary beam: ^{136}Xe at 345 MeV/nucleon, 1 pnA
- ☐ Production target: Be, 1 g/cm^2

6 days of beam time approved by the 3rd PAC meeting

Intensity of ^{128}Cd at F11: 14.3 /s
Isomer ratio: 5 % (assumed)

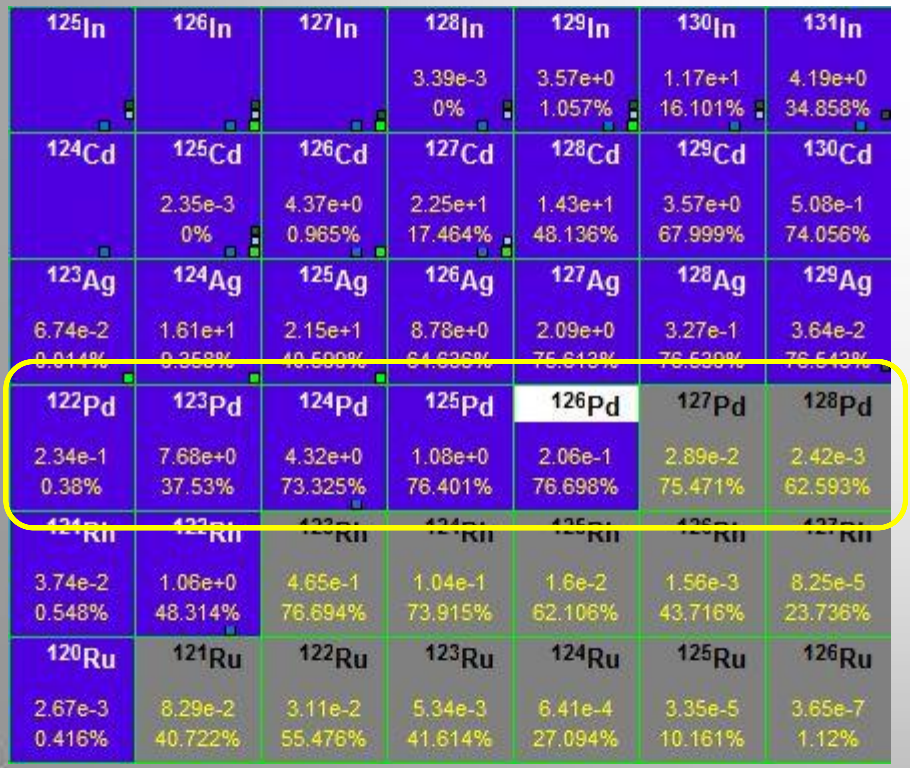
Detection efficiency

- $\Sigma\varepsilon_\gamma$ = 15 % @ 661 keV
- $\Sigma\varepsilon_{\gamma\gamma}$ = 2.1 %
- ε_β = 50 %

- ➢ γ-ray singles: 28k /6 days
- ➢ γ-γ coincidence: 3.9k /6 days

Angular correlation may be possible

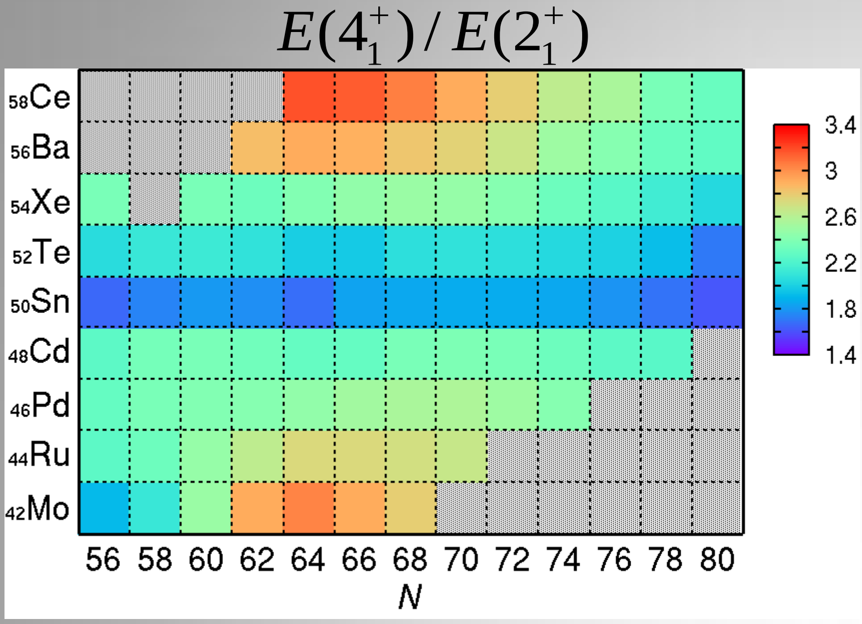
Total implantation rate : 130 /s



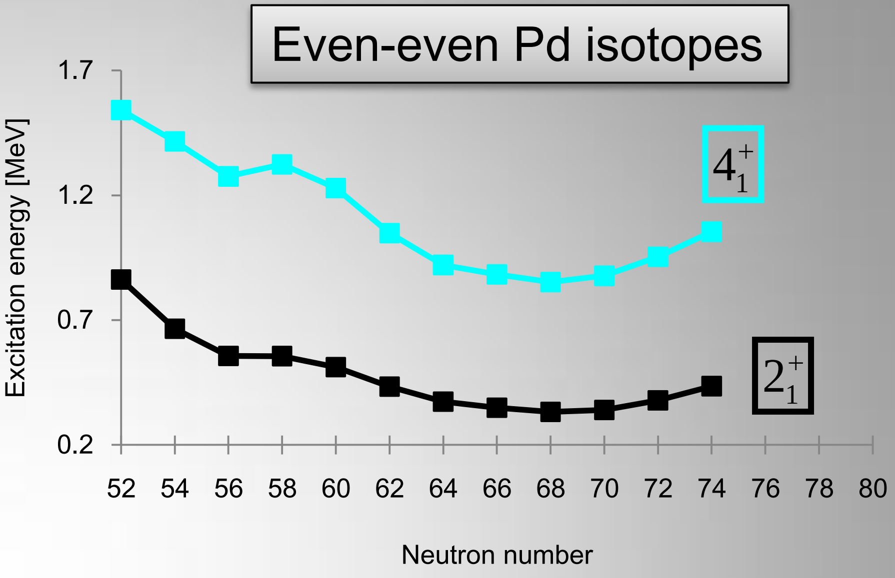
^{125}In	^{126}In	^{127}In	^{128}In 3.39e-3 0%	^{129}In 3.57e+0 1.057%	^{130}In 1.17e+1 16.101%	^{131}In 4.19e+0 34.858%
^{124}Cd	^{125}Cd 2.35e-3 0%	^{126}Cd 4.37e+0 0.965%	^{127}Cd 2.25e+1 17.464%	^{128}Cd 1.43e+1 48.136%	^{129}Cd 3.57e+0 67.999%	^{130}Cd 5.08e-1 74.056%
^{123}Ag 6.74e-2 0.014%	^{124}Ag 1.61e+1 9.358%	^{125}Ag 2.15e+1 40.599%	^{126}Ag 8.78e+0 64.636%	^{127}Ag 2.09e+0 75.613%	^{128}Ag 3.27e-1 76.539%	^{129}Ag 3.64e-2 76.543%
^{122}Pd 2.34e-1 0.38%	^{123}Pd 7.68e+0 37.53%	^{124}Pd 4.32e+0 73.325%	^{125}Pd 1.08e+0 76.401%	^{126}Pd 2.06e-1 76.698%	^{127}Pd 2.89e-2 75.471%	^{128}Pd 2.42e-3 62.593%
^{121}Rh 3.74e-2 0.548%	^{122}Rh 1.06e+0 48.314%	^{123}Rh 4.65e-1 76.694%	^{124}Rh 1.04e-1 73.915%	^{125}Rh 1.6e-2 62.106%	^{126}Rh 1.56e-3 43.716%	^{127}Rh 8.25e-5 23.736%
^{120}Ru 2.67e-3 0.416%	^{121}Ru 8.29e-2 40.722%	^{122}Ru 3.11e-2 55.476%	^{123}Ru 5.34e-3 41.614%	^{124}Ru 6.41e-4 27.094%	^{125}Ru 3.35e-5 10.161%	^{126}Ru 3.65e-7 1.12%

Neutron-rich Pd isotopes are within the scope of this proposal

Collective motions in neutron-rich $_{46}$Pd isotopes

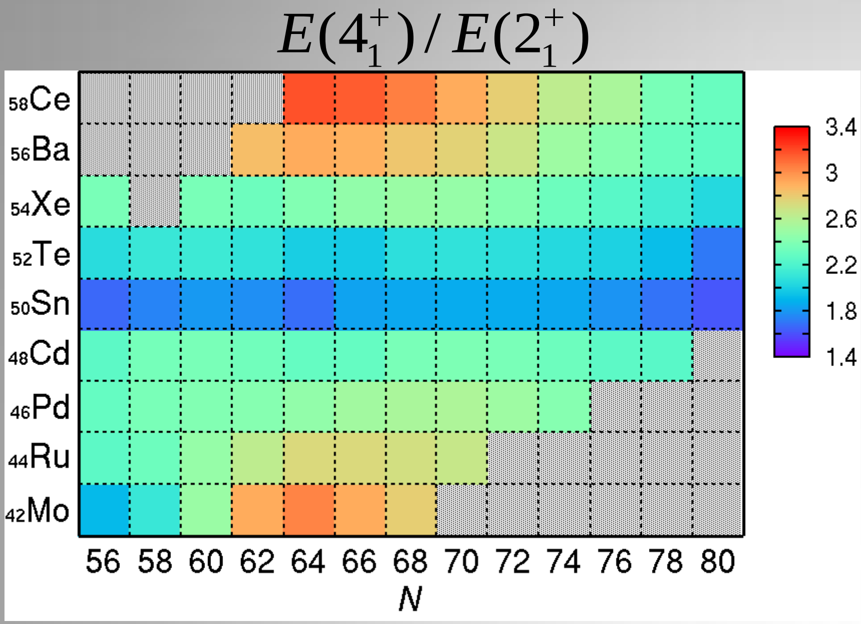


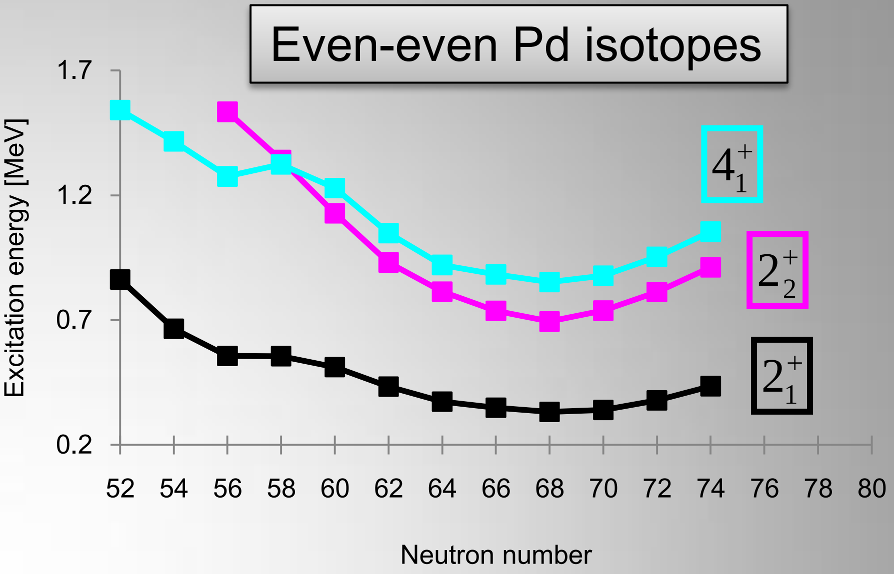
$E(4_1^+)/E(2_1^+)$



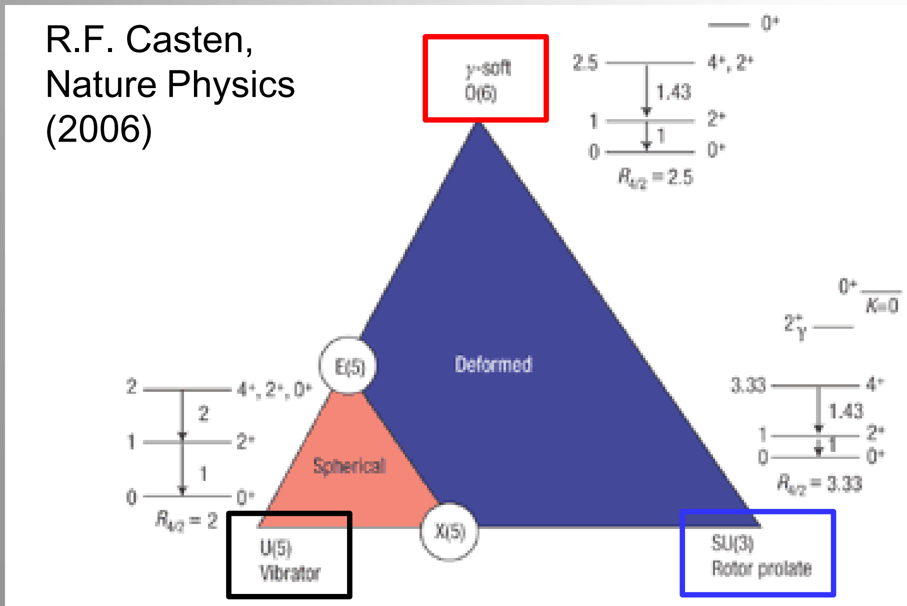
Even-even Pd isotopes

Collective motions in neutron-rich $_{46}$Pd isotopes





The 2^+_2 states are the keys to quantifying structural evolutions



R.F. Casten,
Nature Physics
(2006)

- 🟦 Symmetric rotor

  $\Rightarrow 3.33 \times E(2^+_1) \approx E(4^+_1) << E(2^+_2)$

- ⬜ Spherical vibrator

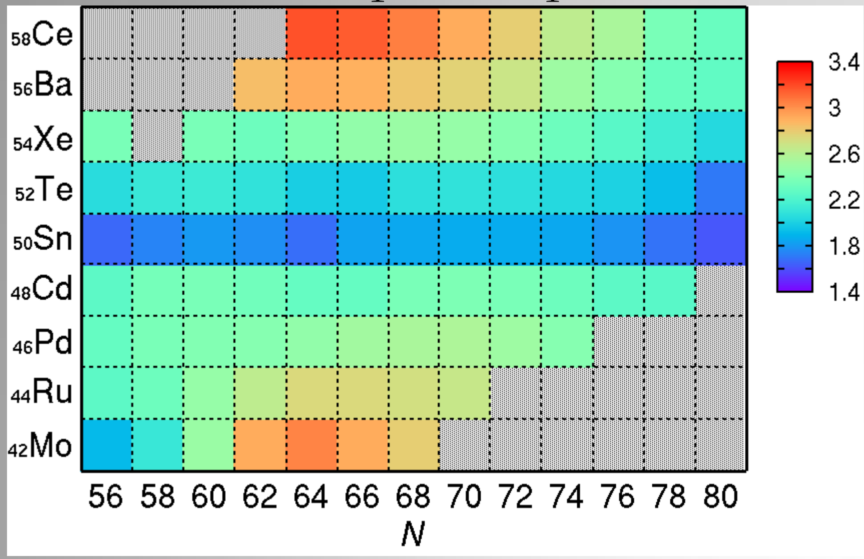
  $\Rightarrow 2 \times E(2^+_1) \approx E(4^+_1) \approx E(2^+_2)$

- 🟥 Axial asymmetry (γ-softness)

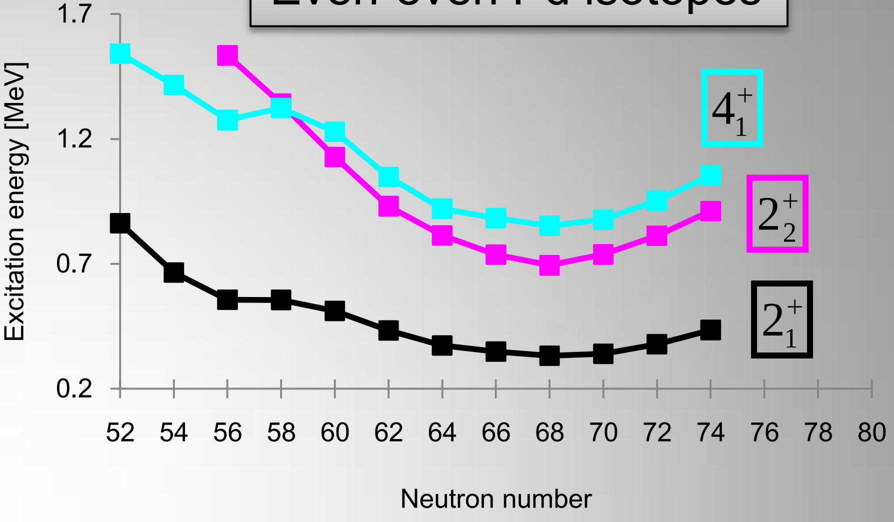
  $\Rightarrow 2.5 \times E(2^+_1) \approx E(4^+_1) \geq E(2^+_2)$

Collective motions in neutron-rich $_{46}$Pd isotopes

$E(4_1^+)/E(2_1^+)$

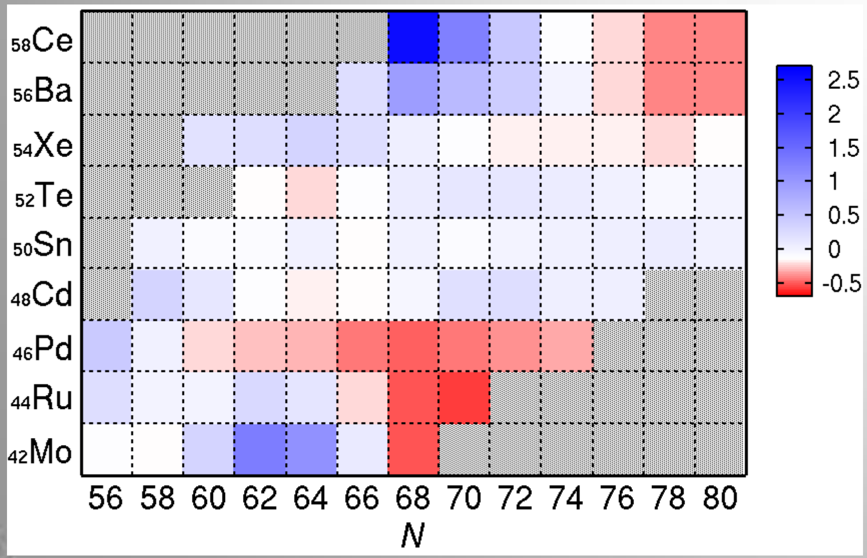


Even-even Pd isotopes



The 2^+_2 states are the keys to quantifying structural evolutions

$[E(2_2^+)-E(4_1^+)]/E(2_1^+)$



🟦 Symmetric rotor

$\Rightarrow [E(2_2^+)-E(4_1^+)]/E(2_1^+) \gg 0$

⬜ Spherical vibrator

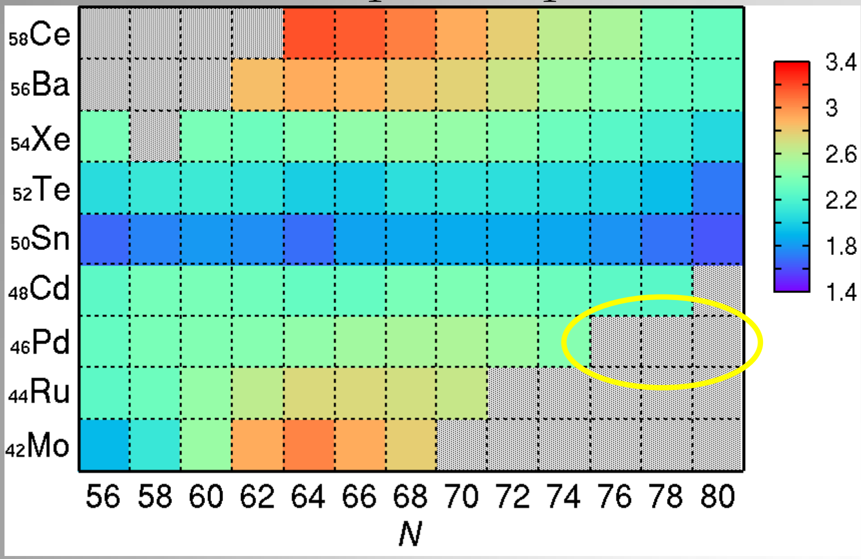
$\Rightarrow [E(2_2^+)-E(4_1^+)]/E(2_1^+) \approx 0$

🟥 Axial asymmetry (γ-softness)

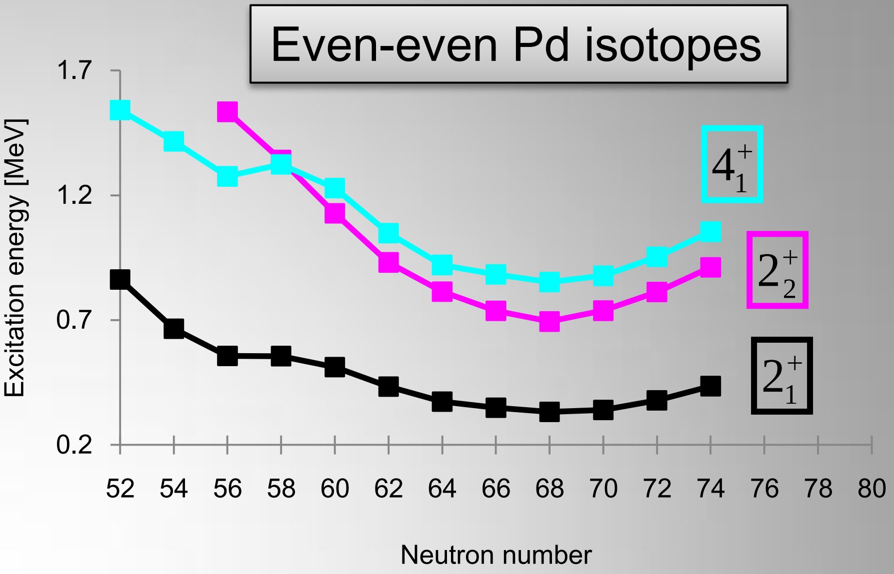
$\Rightarrow [E(2_2^+)-E(4_1^+)]/E(2_1^+) \approx -0.5$

Collective motions in neutron-rich $_{46}$Pd isotopes

$$E(4_1^+)/E(2_1^+)$$

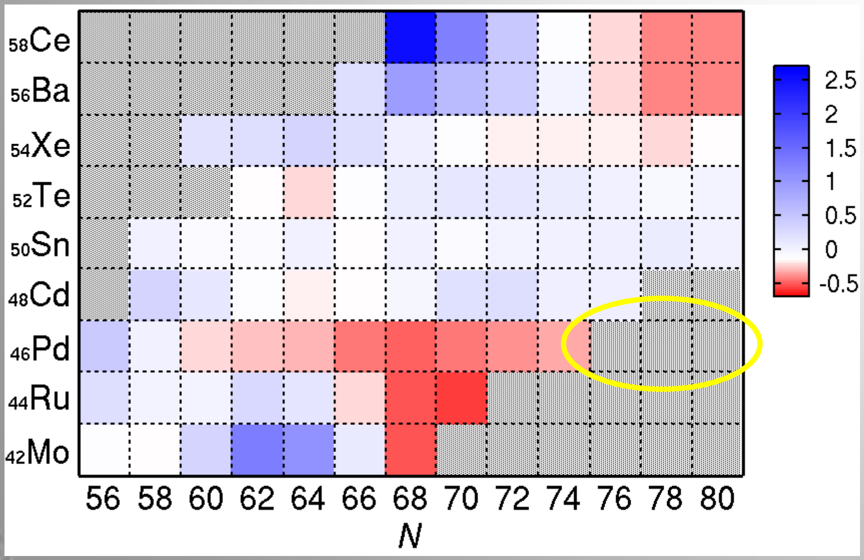


Even-even Pd isotopes



The 2^+_2 states are the keys to quantifying structural evolutions

$$[E(2_2^+)-E(4_1^+)]/E(2_1^+)$$

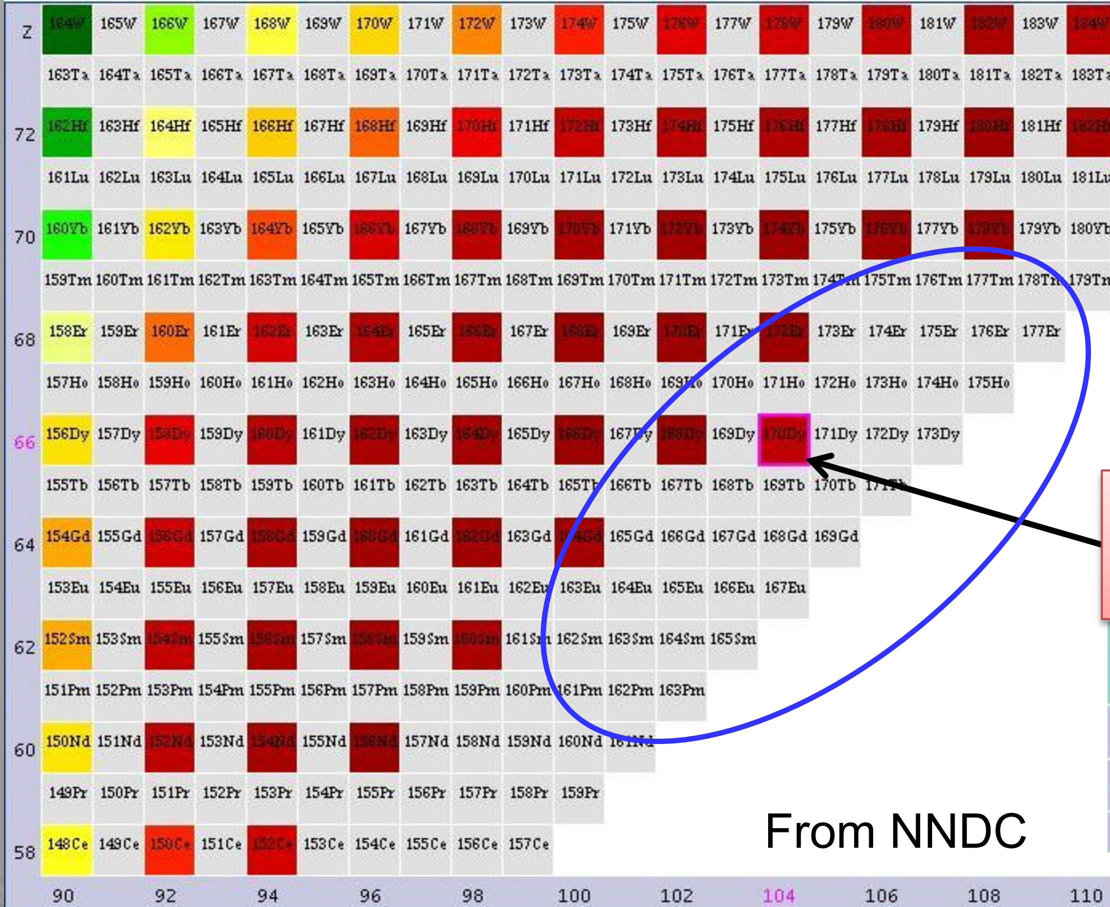


- What shape do the Pd isotopes have, γ-soft, oblate, or spherical?
- Does the shell quenching occur?

Deformed region: Neutron-rich A ~ 170 nuclei

Rare-earth isotopes with N > 90 are well-deformed

- ➢ Where is the largest deformation?
- ➢ What does the neutron excess affect shapes, pairing ....?
- ➢ Are there any deformed sub-shell closures?



^{170}Dy has the maximum number of valence protons and neutrons

E_{level} (keV)	XREF	Jπ	$T_{1/2}$	E_γ (keV)
0.0	A	0+	% β⁻ = 100	
72 Calc. ?	A	(2+)		72 Calc. S
≈235?	A	(4+)		163?

Tentative assignment

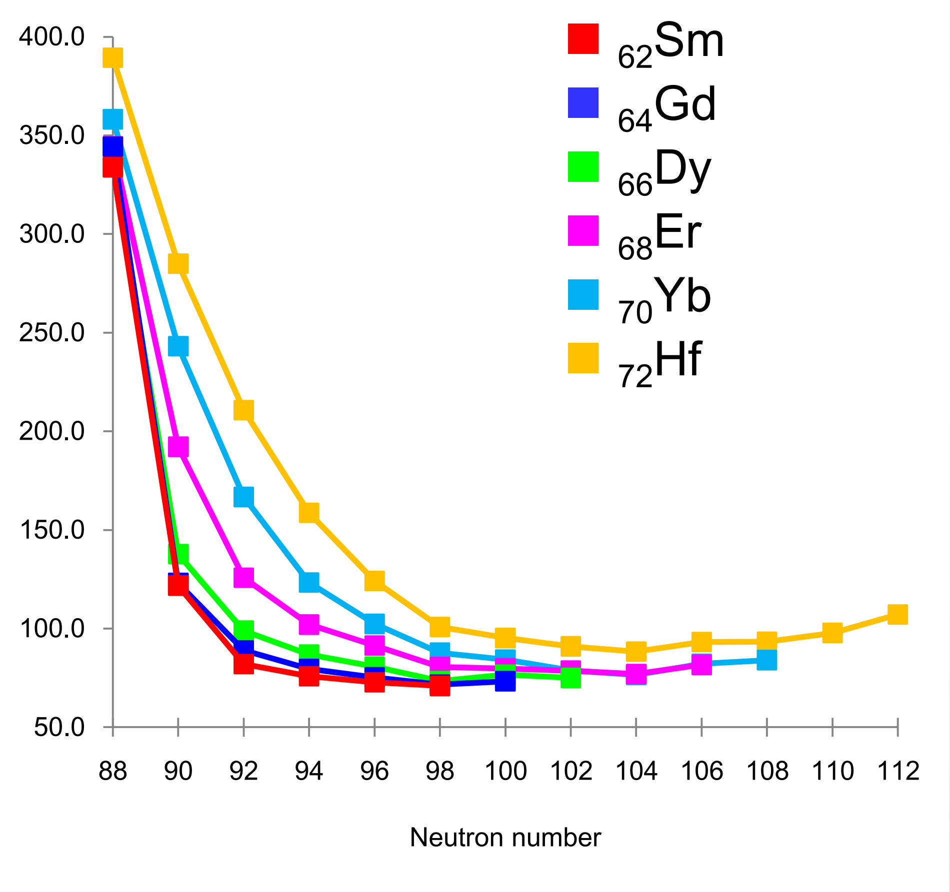
From NNDC

Deformed region: Neutron-rich A ~ 170 nuclei

The 2^+ level energy in even-even nuclei

⇒ Measure of the ground-state deformation

$E_{ex}(2^+)[keV]$



Deformed region: Neutron-rich A ~ 170 nuclei

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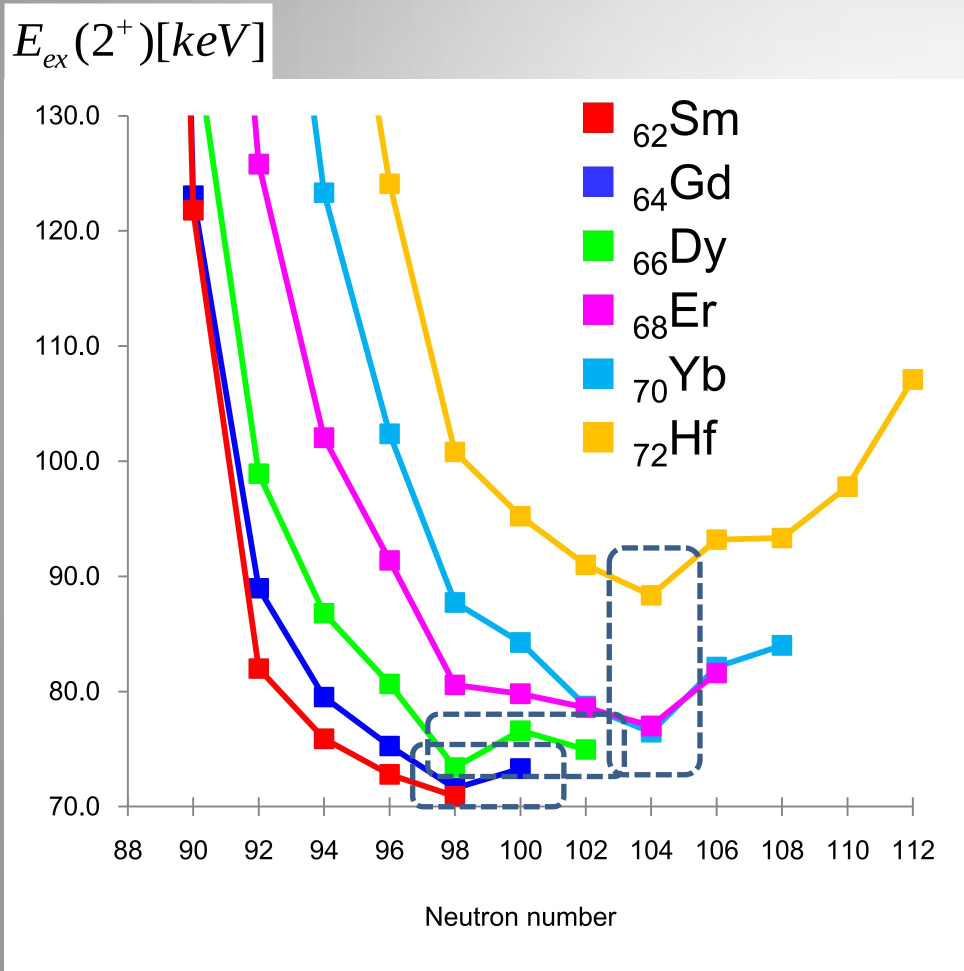


$E(2^+)$ reaches a minimum at N = 104 for $_{68}$Er, $_{70}$Yb, and $_{72}$Hf isotopes.

For $_{64}$Gd isotopes, the 2^+ state energy drops at N = 98, and increases at N = 100.

The behavior of $E(2^+)$ in $_{66}$Dy isotopes is erratic for N = 98 - 102.

Deformed region: Neutron-rich A ~ 170 nuclei

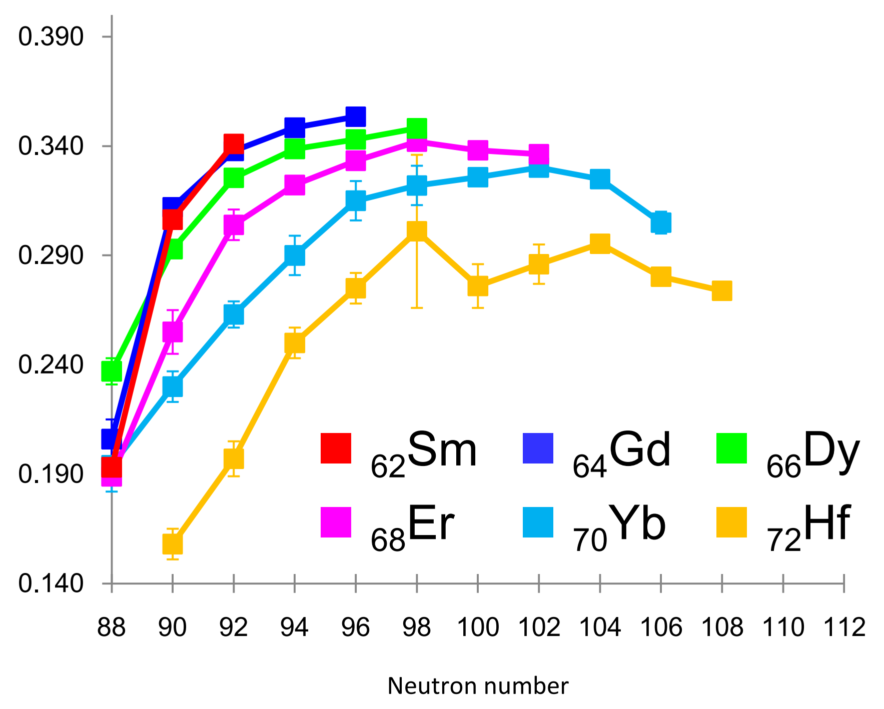
S. Raman et al.,
At. Data Tables 78 (2001) 1

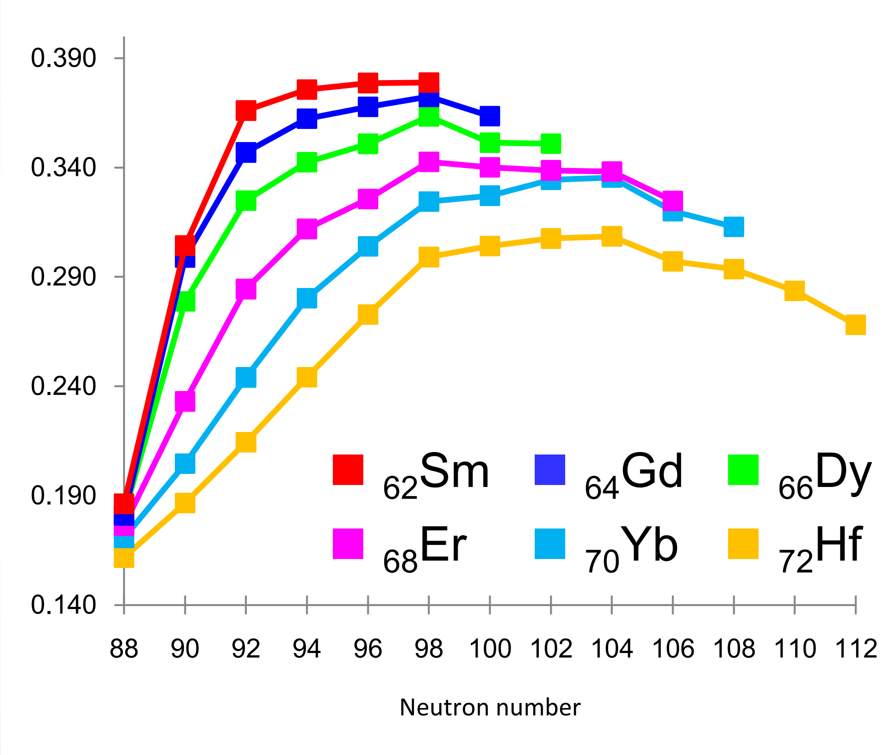
Lifetime measurement

$$\beta = \frac{4\pi}{3} Z R_0^2 \sqrt{B(E2)}$$

Global Best Fit

$$\beta = \frac{(466 \pm 41)\cdot\sqrt{1.2}}{\sqrt{E_{ex}(2^+)}\cdot A}$$





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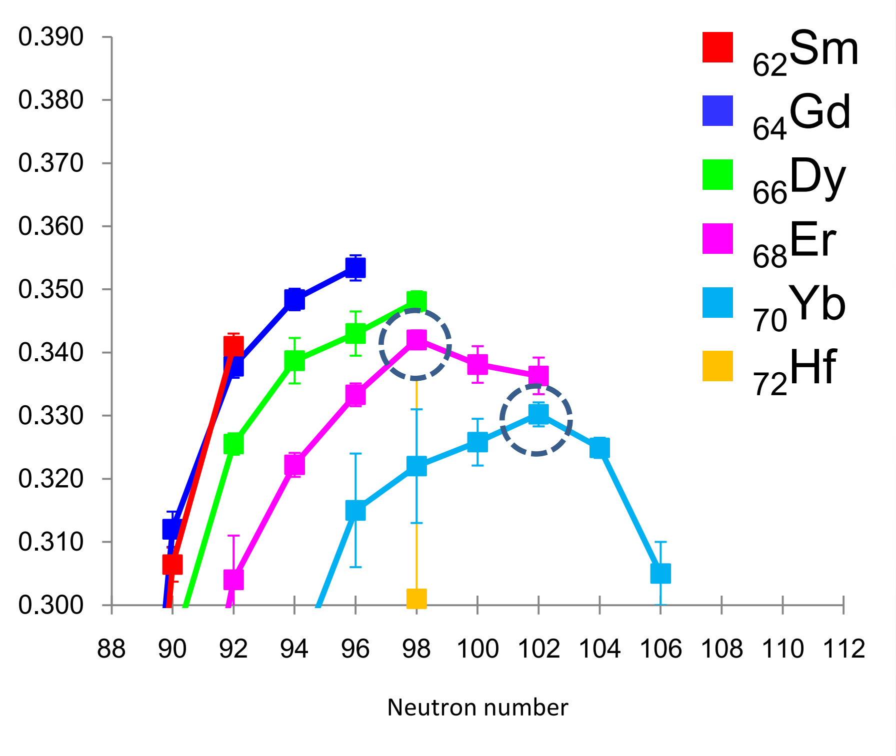
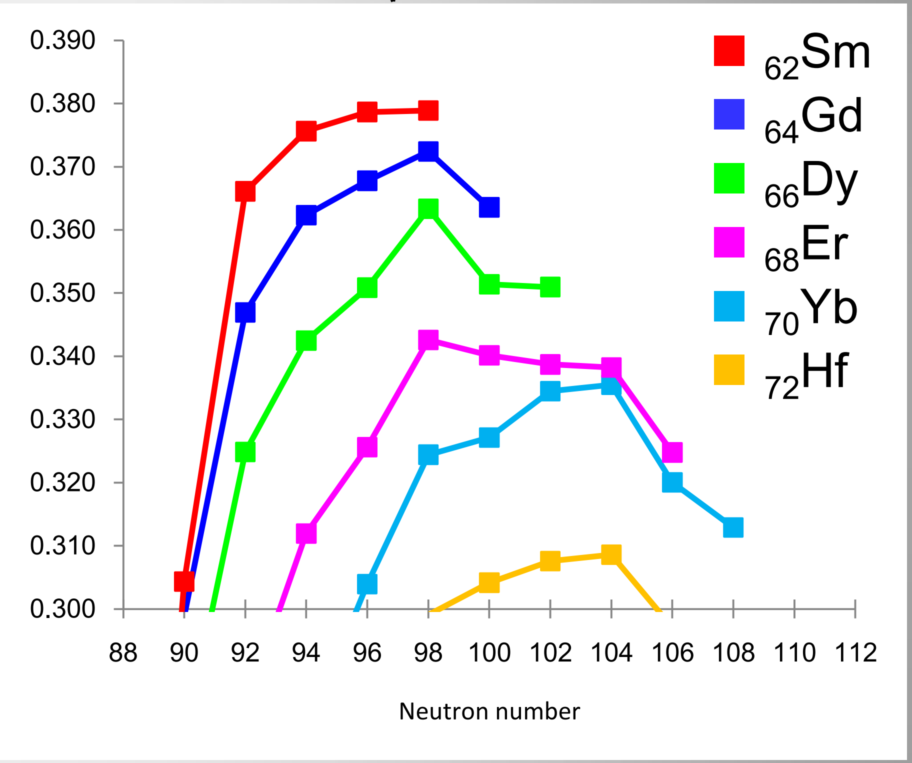




Maximum deformation at

- N = 102 for $_{70}$Yb isotopes
- N = 98 for $_{68}$Er isotopes

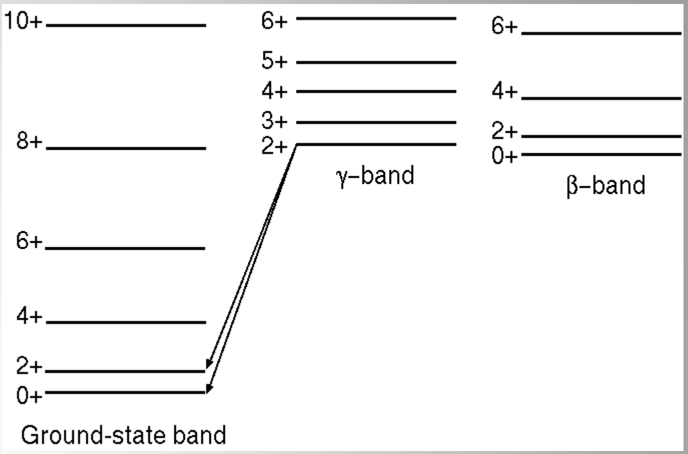
⇨

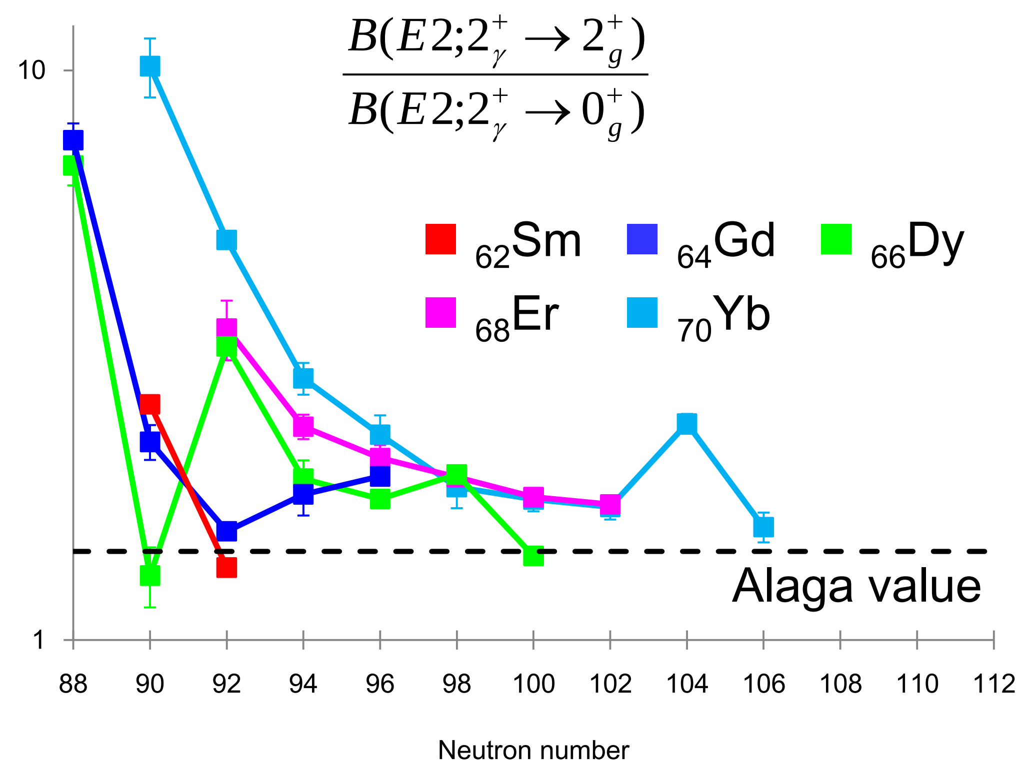
Deformed sub-shell closure at N = 98 for $_{62}$Sm, $_{64}$Gd, and $_{66}$Dy isotopes?

Deformed region: Neutron-rich A ~ 170 nuclei

γ and β vibrations ⇒ Measure of axial symmetry

If the nuclear is a perfect axial rotor,
these intrinsic states are high in energy
and less mixed with the ground-state band.





Alaga value

$$\frac{B(E2;2_\gamma^+ \to 2_g^+)}{B(E2;2_\gamma^+ \to 0_g^+)} = \underset{\uparrow}{1.43} \times \left(\frac{1+2Z_\gamma}{1-Z_\gamma} \right)^2$$

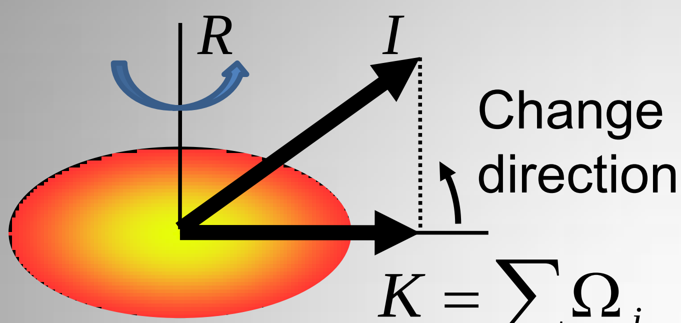
$$Z_\gamma = -\sqrt{\frac{15}{2\pi}} \frac{eQ_0 \cdot \alpha}{\langle \phi_g | E2 | \phi_\gamma \rangle}$$

Band-mixing amplitude

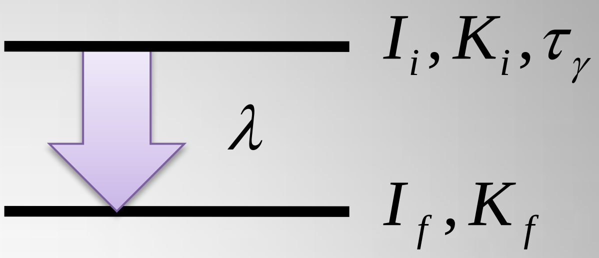
Intrinsic matrix element

Deformed region: Neutron-rich A ~ 170 nuclei

K quantum number and collective rotation: K isomers



$$K = \sum_j \Omega_j$$



$\lambda \geq |I_i - I_f|$ Spin selection … Yes

$\lambda \geq |K_i - K_f|$ K-selection … Sort of !

K hindered transitions

Weisskopf hindrance $F = \tau_\gamma^{\exp} / \tau_W$

Reduced hindrance $f_\nu = F^{1/\nu}$

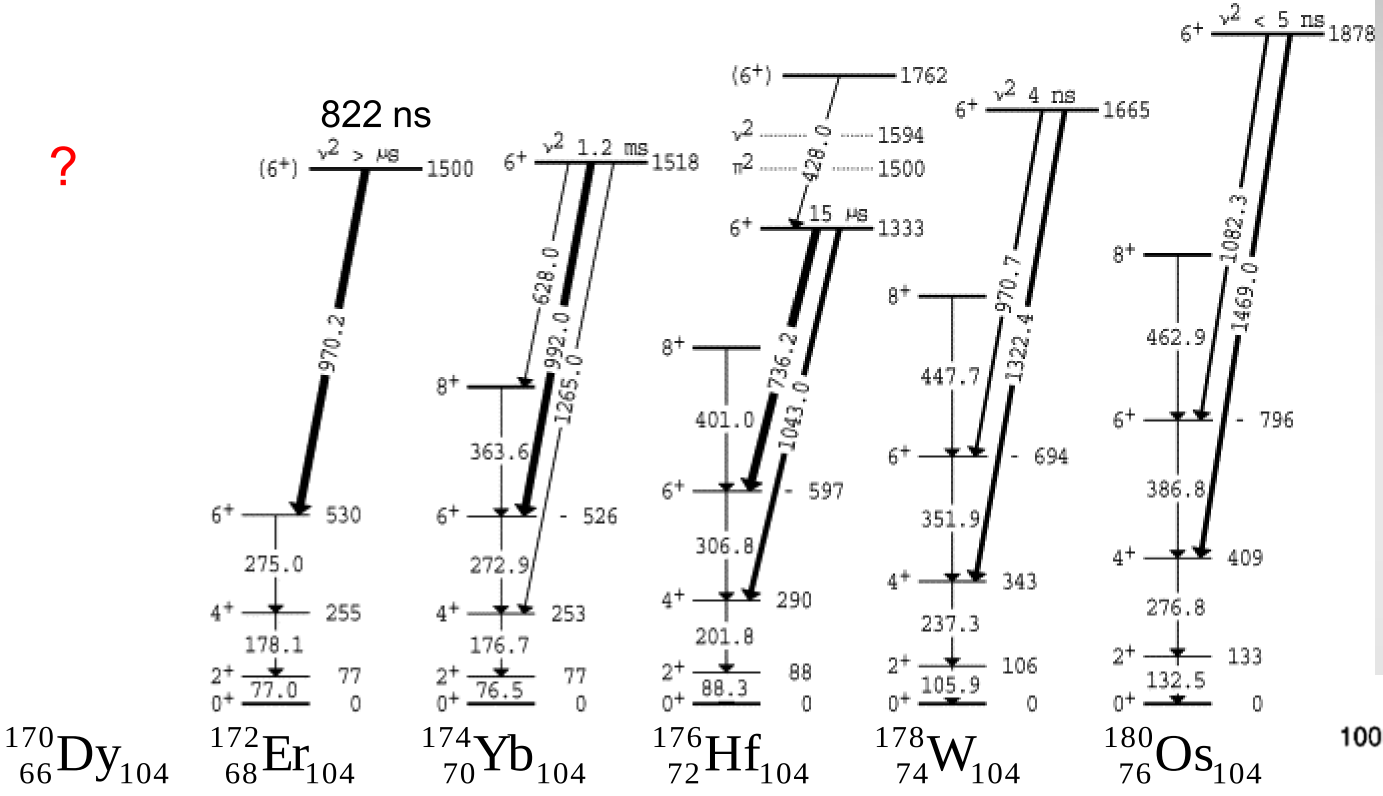
The degree of K forbiddenness $\nu = \Delta K - \lambda$

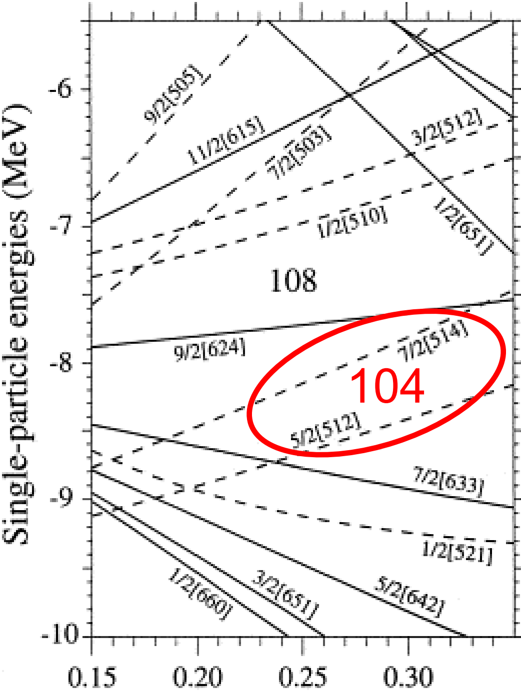
The identification and characterization of K-isomers provides information on

- ✓ Intrinsic orbits near the Fermi surface
- ✓ Pairing energies
- ✓ The degree of axial symmetry

Deformed region: Neutron-rich A ~ 170 nuclei

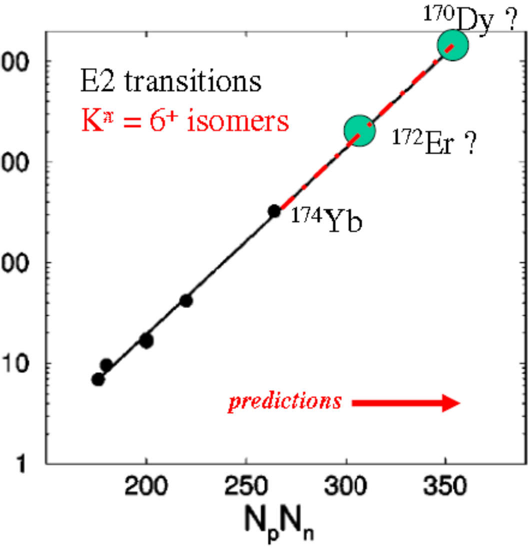
$K^\pi = 6^+$ isomers in N = 104 isotones





F.R. Xu et al.,
PLB 435 (1998) 257

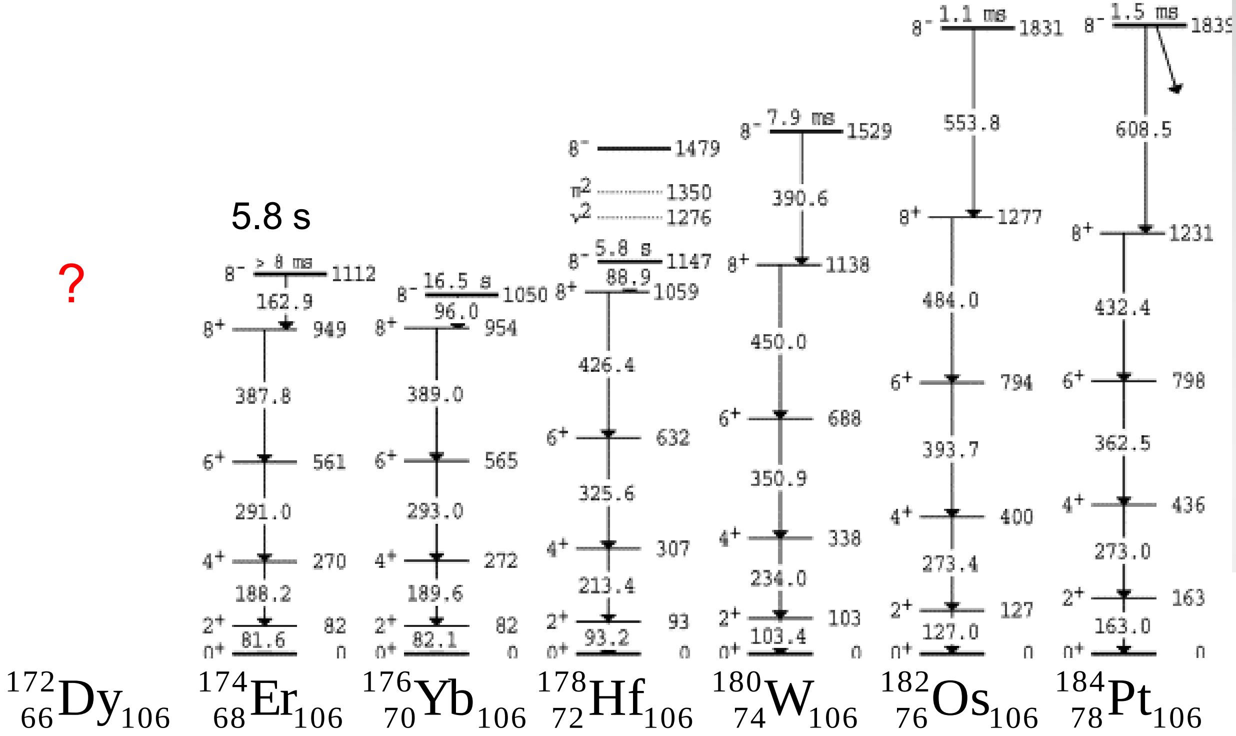
G.D. Dracoulis et al.,
PLB 635 (2006) 200



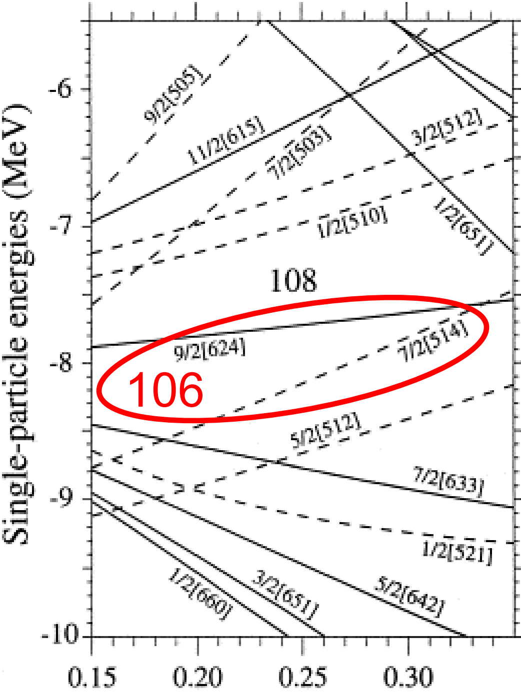
P.H. Regan et al.,
PRC 65 (2002) 037302

Deformed region: Neutron-rich A ~ 170 nuclei

$K^\pi = 8^-$ isomers in N = 106 isotones and E1 decays



G.D. Dracoulis et al., PLB 635 (2006) 200



F.R. Xu et al.,
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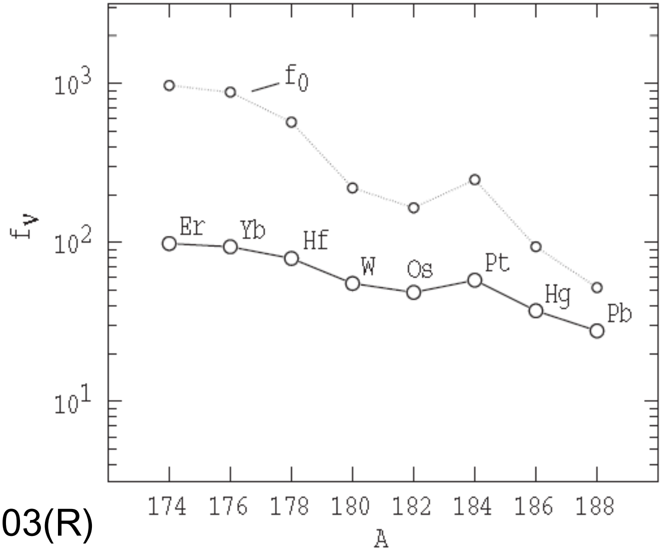
E1 reduced hindrances



G.D. Dracoulis et al.,
PRC 79 (2009) 061303(R)

f_ν~100 from systematics
assume E_γ = 150 keV

$T_{1/2}$ ~ 6.5 s
⇒ compete with β decay?

Feasibility

2^+_1 state unknown

^{167}Er	^{168}Er	^{169}Er	^{170}Er 6.49e-3 0.001%	^{171}Er 1.8e-1 0.088%	^{172}Er 1.23e+0 1.366%	^{173}Er 2.98e+0 7.551%	^{174}Er 3.59e+0 20.986%	^{175}Er 2.86e+0 39.05%	^{176}Er 1.78e+0 57.584%	^{177}Er 9.28e-1 71.67%	^{178}Er 4.25e-1 79.459%	^{179}Er 1.73e-1 79.137%
^{166}Ho	^{167}Ho 8.27e-3 0%	^{168}Ho 8.54e-2 0.032%	^{169}Ho 7.24e-1 0.663%	^{170}Ho 2.09e+0 4.81%	^{171}Ho 2.91e+0 15.942%	^{172}Ho 2.49e+0 32.909%	^{173}Ho 1.61e+0 51.828%	^{174}Ho 8.68e-1 68.357%	Ho 4.03e-1 78.483%	^{176}Ho 1.69e-1 82.557%	^{177}Ho 6.87e-2 84.534%	^{178}Ho 2.58e-2 80.933%
^{165}Dy 3.58e-2 0.009%	^{166}Dy 4.94e-1 0.27%	^{167}Dy 1.53e+0 2.755%	^{168}Dy 2.56e+0 11.385%	^{169}Dy 2.28e+0 26.647%	^{170}Dy 1.52e+0 45.173%	^{171}Dy 8.12e-1 63.111%	^{172}Dy 3.79e-1 75.615%	^{173}Dy 1.6e-1 81.99%	^{174}Dy 6.41e-2 84.77%	^{175}Dy 2.48e-2 85.573%	^{176}Dy 9.36e-3 84.931%	^{177}Dy 3.2e-3 76.825%
^{164}Tb 8.13e-1 0.925%	^{165}Tb 2.47e+0 6.557%	^{166}Tb 2.55e+0 19.984%	^{167}Tb 1.85e+0 38.217%	^{168}Tb 9.26e-1 56.976%	Tb 3.87e-1 71.757%	^{170}Tb 1.53e-1 80.26%	^{171}Tb 5.97e-2 83.148%	^{172}Tb 2.29e-2 85.238%	^{173}Tb 8.5e-3 85.511%	^{174}Tb 3.01e-3 82.243%	^{175}Tb 9.77e-4 73.202%	^{176}Tb 2.82e-4 58.165%
^{163}Gd 1.94e+0 8.041%	^{164}Gd 2.82e+0 25.455%	^{165}Gd 1.55e+0 47.242%	^{166}Gd 6.54e-1 66.36%	^{167}Gd 1.83e-1 77.813%	^{168}Gd 5.69e-2 81.688%	^{169}Gd 2.15e-2 84.665%	^{170}Gd 7.82e-3 85.512%	^{171}Gd 2.72e-3 83.187%	^{172}Gd 8.77e-4 75.48%	^{173}Gd 2.59e-4 63.232%	^{174}Gd 7.03e-5 48.819%	^{175}Gd 1.66e-5 32.881%
^{162}Eu 1.63e+0 19.382%	^{163}Eu 1.61e+0 45.398%	^{164}Eu 4.61e-1 68.929%	Eu 1.1e-1 78.869%	^{166}Eu 2.05e-2 83.849%	^{167}Eu 7.33e-3 85.334%	^{168}Eu 2.51e-3 83.885%	^{169}Eu 7.99e-4 77.319%	^{170}Eu 2.33e-4 65.852%	^{171}Eu 6.27e-5 51.921%	^{172}Eu 1.52e-5 37.185%	^{173}Eu 3.16e-6 22.836%	^{174}Eu 5.25e-7 11.243%
^{161}Sm 5.87e-1 25.836%	^{162}Sm 3.41e-1 52.863%	^{163}Sm 5.69e-2 74.833%	^{164}Sm 6.91e-3 83.706%	^{165}Sm 2.36e-3 84.358%	^{166}Sm 7.41e-4 78.917%	^{167}Sm 2.14e-4 68.426%	^{168}Sm 5.69e-5 54.992%	^{169}Sm 1.35e-5 39.603%	^{170}Sm 2.9e-6 25.959%	^{171}Sm 5.04e-7 13.826%	^{172}Sm 7.46e-8 6.288%	^{173}Sm 9.96e-9 2.585%
^{160}Pm 9.91e-2 25.756%	Pm 2.81e-2 53.437%	^{162}Pm 1.99e-3 74.489%	^{163}Pm 6.86e-4 78.664%	^{164}Pm 1.99e-4 70.709%	^{165}Pm 4.73e-5 52.249%	^{166}Pm 1.22e-5 42.318%	^{167}Pm 2.65e-6 28.898%	^{168}Pm 4.61e-7 15.919%	^{169}Pm 7.03e-8 7.694%	^{170}Pm 9.47e-9 3.298%	^{171}Pm 1.25e-9 1.384%	^{172}Pm 1.6e-10 0.565%

Y_{RI} > 0.01 /s
γ-γ coin: 9.1/ 10 days

Y_{RI} > 0.001 /s
γ-singles: 6.5 / 10 days

^{238}U intensity: 1 pnA
Total rate: 110 cps

Population: 10 %
$\Sigma\varepsilon_\gamma$ = 15 % @ 661 keV
$\Sigma\varepsilon_{\gamma\gamma}$ = 2.1 %
ε_β = 50 %

Expected γ-ray yield

Decay	$T_{1/2}$ (syst.)	Y_{RI} [s^{-1}]	N_γ [/10 days]	$N_{\gamma\gamma}$[/10 days]
^{162}Pm→^{162}Sm	≈ 0.6 s	1.99E-03	12.9	1.8
^{166}Eu→^{166}Gd	≈ 1.0 s	2.05E-02	133	18.6
^{170}Tb→^{170}Dy	≈ 2.0 s	1.53E-01	991	139
^{176}Ho→^{176}Er	≈ 1.0 s	4.03E-01	2611	366

Summary

- Decay spectroscopy in the vicinity of the **doubly closed-shell nucleus ^{132}Sn** (⇒ 6 days of beam time approved)
  - Spin-gap isomers in $_{48}$Cd and $_{47}$Ag isotopes
    - Multi-quasiparticle configurations at high spins
    - Single-particle configurations at low excitation energy
  - Collectivities in $_{46}$Pd isotopes
    - Shape transitions and shell quenching

- Decay spectroscopy in the vicinity of the **doubly mid-shell nucleus ^{170}Dy** (⇒ to be proposed for the E(U)RICA campaigns)
  - The first 2^+ states and ground-state deformation
  - γ- and β- vibrations as indicators of axial symmetry
  - K isomers in N = 104 and 106 isotones