SSNET'18: Shapes and Symmetries in Nuclei – From Experiment to Theory

Shape coexistence and collective low-spin states in ^{112,114}Sn

(Lifetime measurements with SONIC@HORUS)

M. Spieker *et al.*, PRC **97**, 054319 (2018)

Mark Spieker[1], P. Petkov[2,3], S. G. Pickstone[2], S. Prill[2], P. Scholz[2], and A. Zilges[2]

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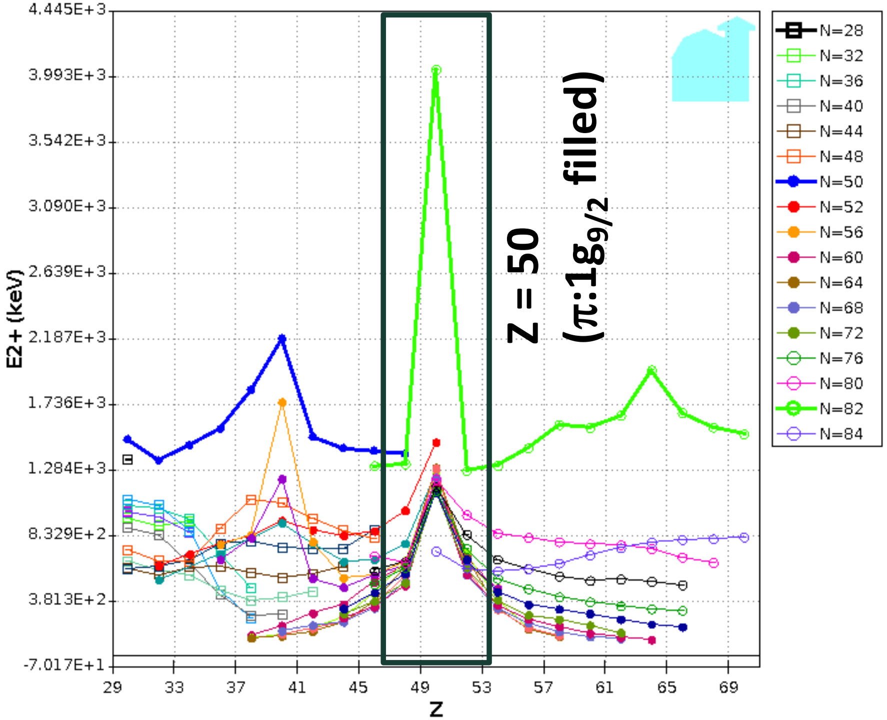
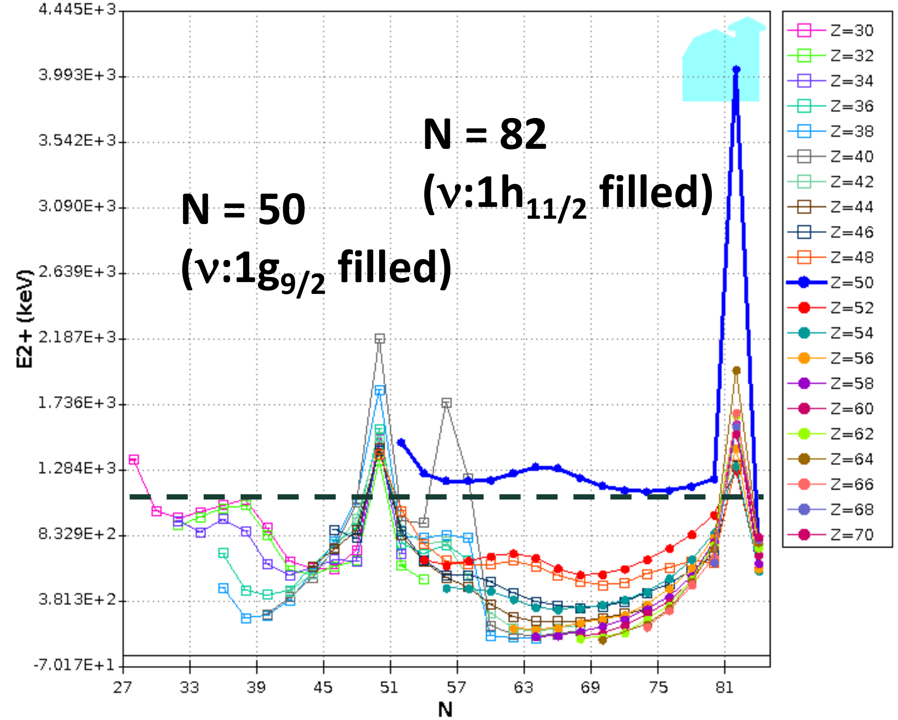
[2] Institute for Nuclear Physics, University of Cologne, Germany
[3] IFIN-HH, Bucharest, Romania

supported by DFG (ZI 510/7-1)

MS supported in part by the National Science Foundation under Contract No. PHY-1565546 (NSCL)

Sn – transitional nuclei and collectivity?





[**Figures:** NNDC, NuDat (2018)]

- **Sn isotopes considered as one of the prime examples for spherical nuclei**
  - → Well-developed Z = 50 magic shell closure (no significant contribution of protons to low-lying excitation spectrum)
  - → Little variation of $E_{2_1^+}$, i.e. no strong p-n interaction and no onset of deformation

The $B(E2; 0_1^+ \rightarrow 2_1^+)$ puzzle understood?

Novel Shape Evolution in Sn Isotopes from Magic Numbers 50 to 82

Tomoaki Togashi,[1] Yusuke Tsunoda,[1] Takaharu Otsuka,[2,1,3,4,5,*] Noritaka Shimizu,[1] and Michio Honma[6]
[1]*Center for Nuclear Study, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
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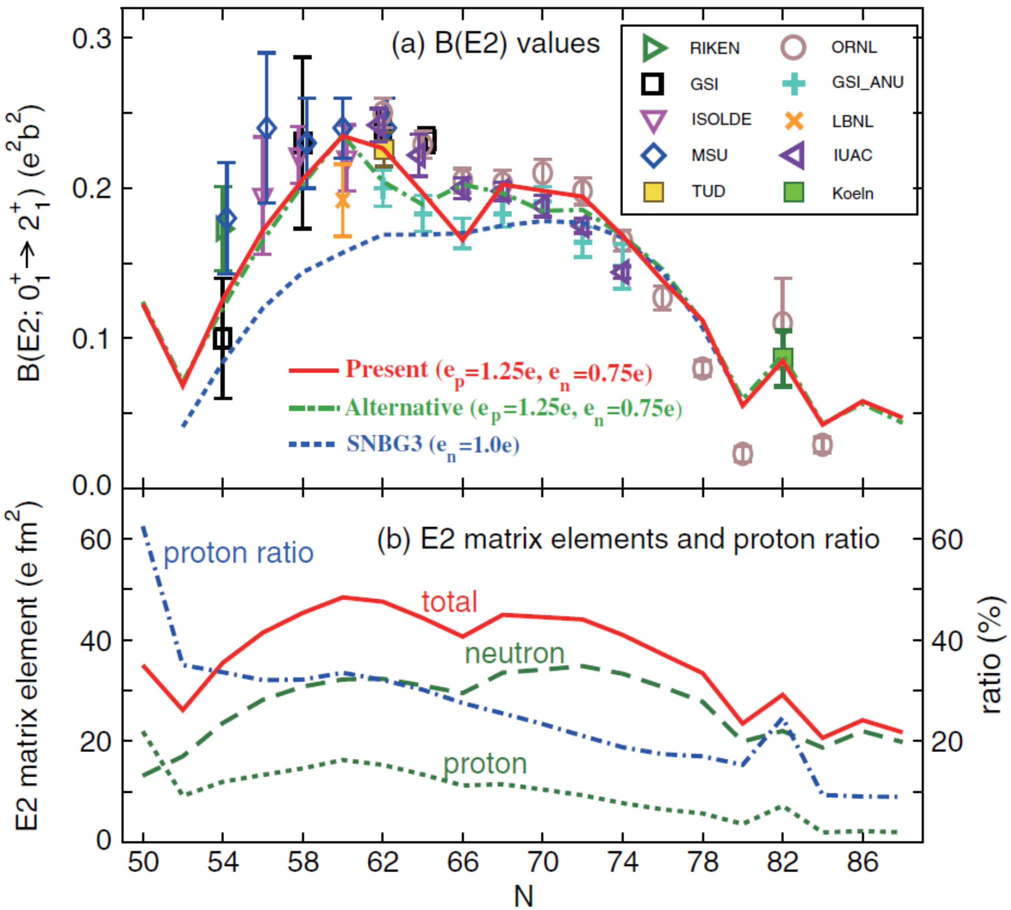
[4]*Instituut voor Kern- en Stralingsfysica, KU Leuven, B-3001 Leuven, Belgium*
[5]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[6]*Center for Mathematical Sciences, University of Aizu, Ikki-machi, Aizu-Wakamatsu, Fukushima 965-8580, Japan*



- **Activating protons in the $1g_{9/2}$** shown to provide a possible explanation (proton holes)
  → **Breaking of Z = 50 core!**
  → **Modest prolate deformation** in N = 50 to 64 isotopes
  → **2nd-order phase transition** from modestly deformed to pairing phase in Sn nuclei (N = 66)!

[T. Togashi, Y. Tsunoda, T. Otsuka, *et al.*, PRL **121**, 062501 (2018)]

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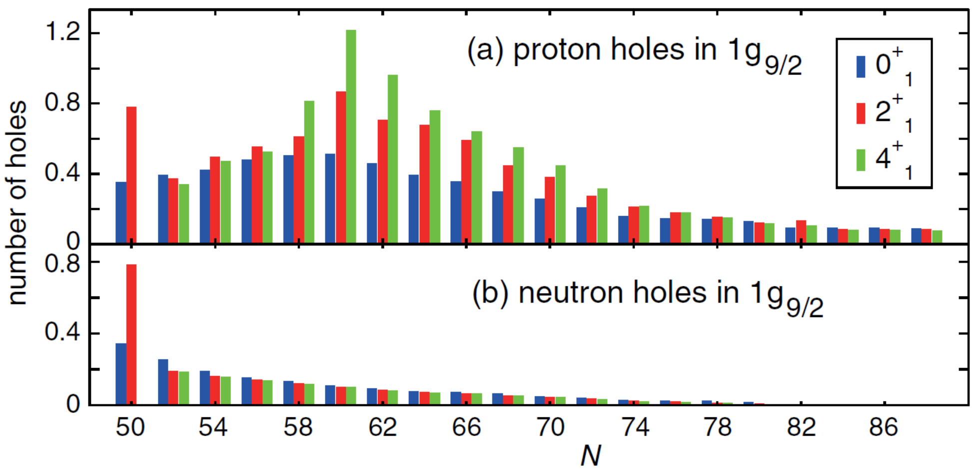

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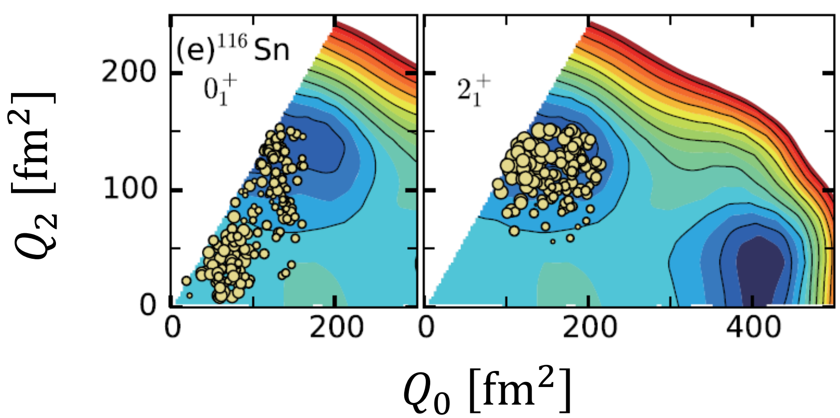
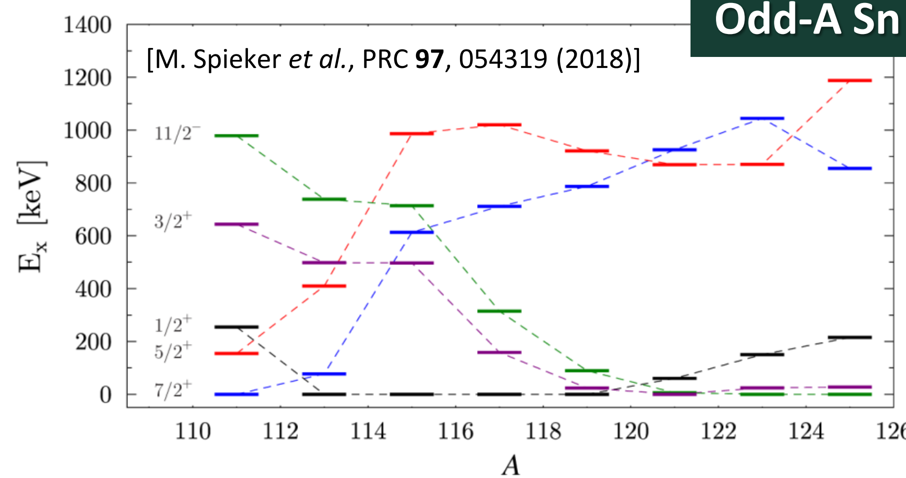
[T. Togashi, Y. Tsunoda, T. Otsuka, *et al.*, PRL **121**, 062501 (2018)]

T- Plot for ^{116}Sn:



Odd-A Sn



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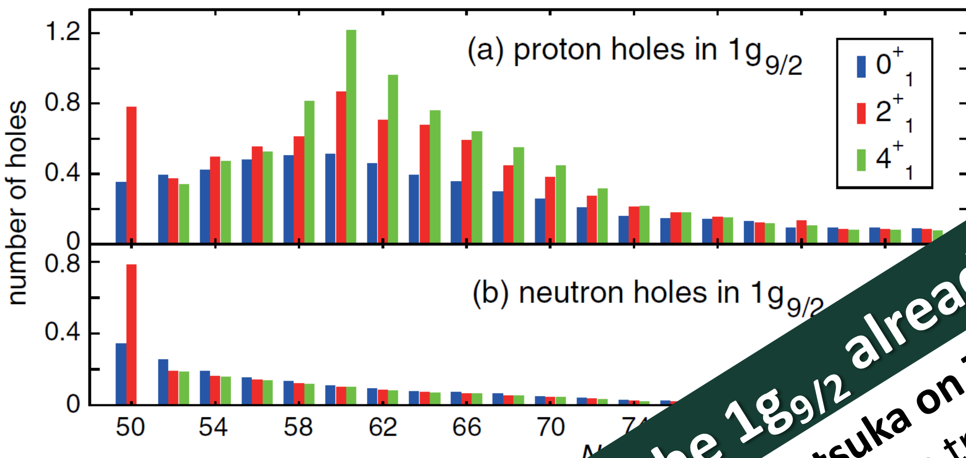

- **Activating protons in the 1...** shown to provide a n... explanation (pr...
  → **Breakin...**
  → **Mo... ...ation** in ...es
  ...**e transition** from ...deformed to pairing ...e in Sn nuclei (N = 66)!

Togashi, Y. Tsunoda, T. Otsuka, *et al.*, PRL **121**, 062501 (2018)]

Proton excitations out of the $1g_{9/2}$ already contribute to the g.s. and 2^+_1!

Talk by T. Otsuka on Tuesday, 4PM
“Quantum phase transitions and shape evolution in nuclei”

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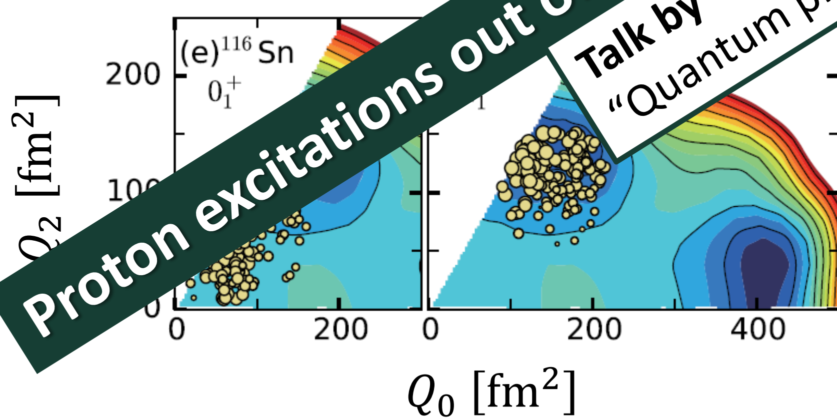

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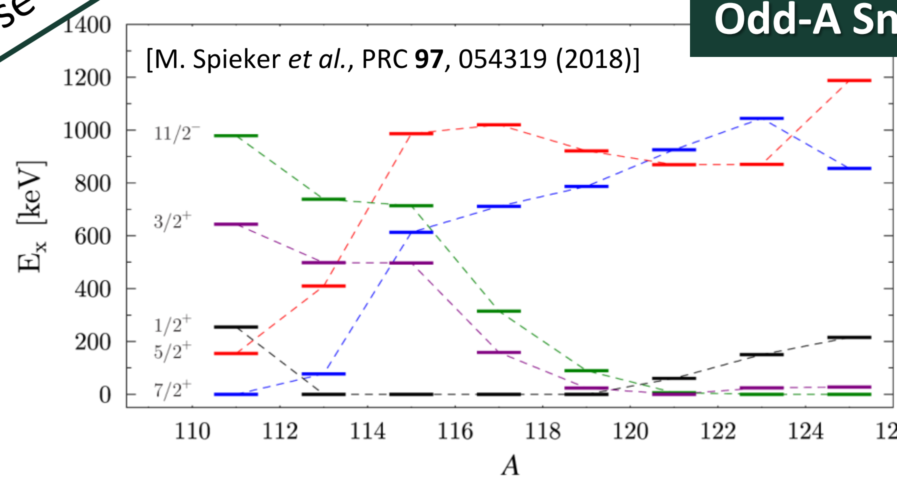
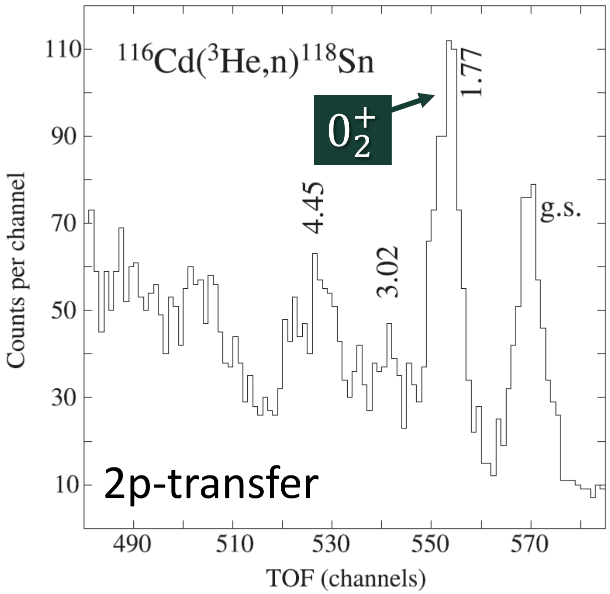
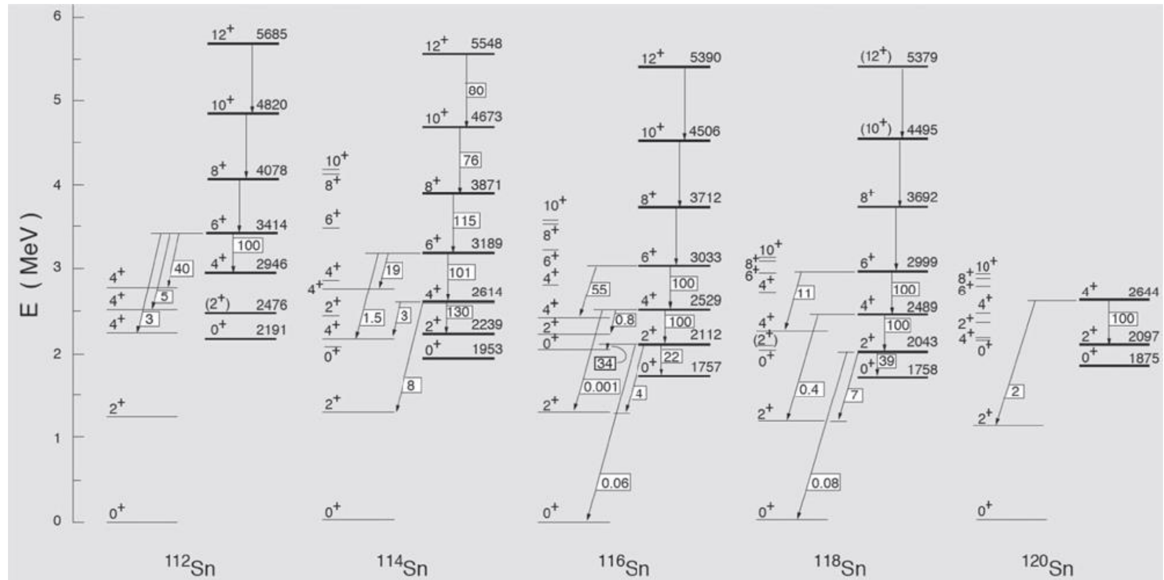


Shape coexistence in Sn isotopes



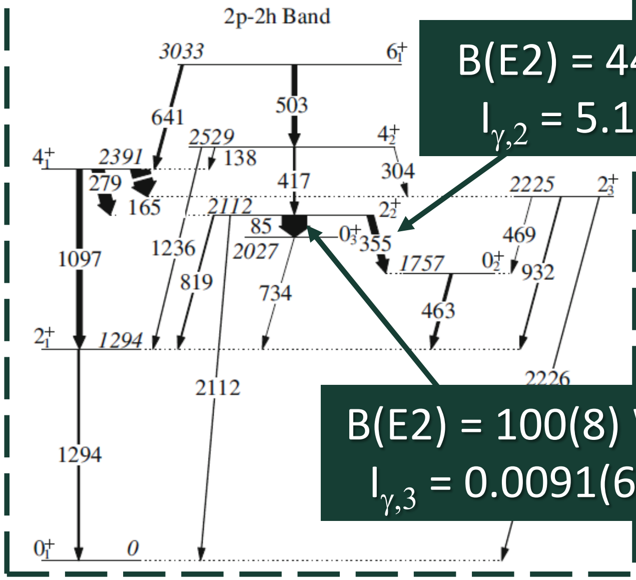


[P.E. Garrett, J. Phys. G **43**, 084002 (2016); D. Rowe and J.L. Wood, *Models of Nuclear Structure: Foundational Models* (World Scientific, Singapore, 2010)]

- **Excited 0⁺ state strongly excited in two-proton transfer reaction**
  → 2p-2h proton structure?
- **Parabolic evolution of additional structure with minimum at midshell**
  → One of the key signatures of intruder configurations
- **Large $\rho^2(E0; 0^+_3 \rightarrow 0^+_2)$ suggests strong mixing between excited 0⁺ states in ^{116}Sn**
  → Which 0⁺ state is the bandhead of the intruder structure?
- **Collective intraband *E2* transitions**

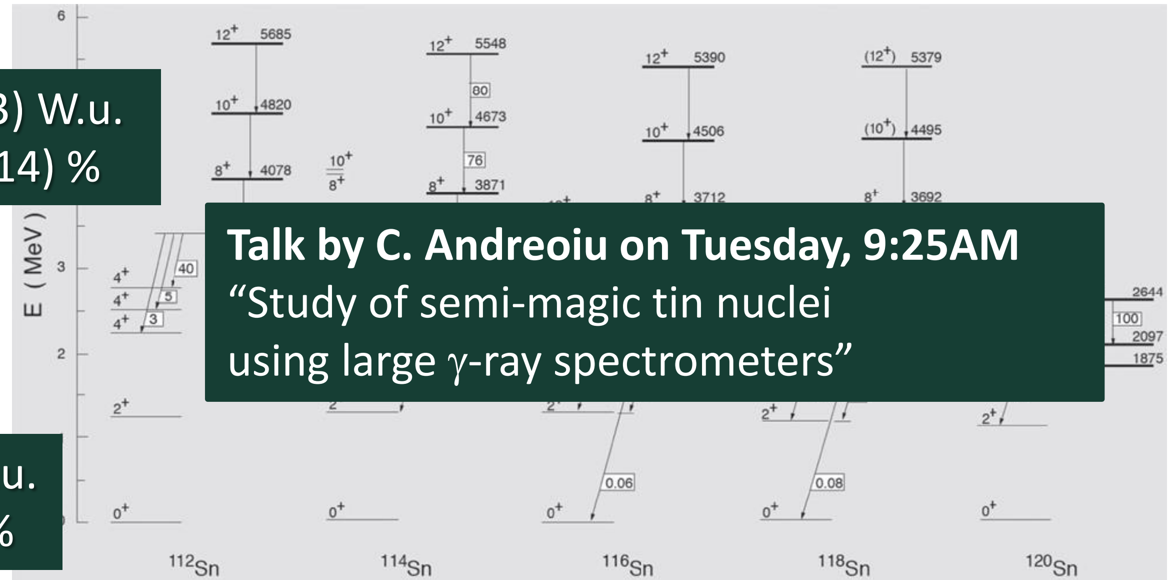
Shape coexistence in Sn isotopes

^{116}Sn – 3rd 0$^+$ bandhead?



B(E2) = 44(3) W.u.
$I_{\gamma,2}$ = 5.16(14) %

B(E2) = 100(8) W.u.
$I_{\gamma,3}$ = 0.0091(6) %



Talk by C. Andreoiu on Tuesday, 9:25AM
"Study of semi-magic tin nuclei using large γ-ray spectrometers"

[J.L. Pore *et al.*, EPJA **52**, 27 (2017); D. Rowe and J.L. Wood, *Models of Nuclear Structure: Foundational Models* (World Scientific, Singapore, 2010)]

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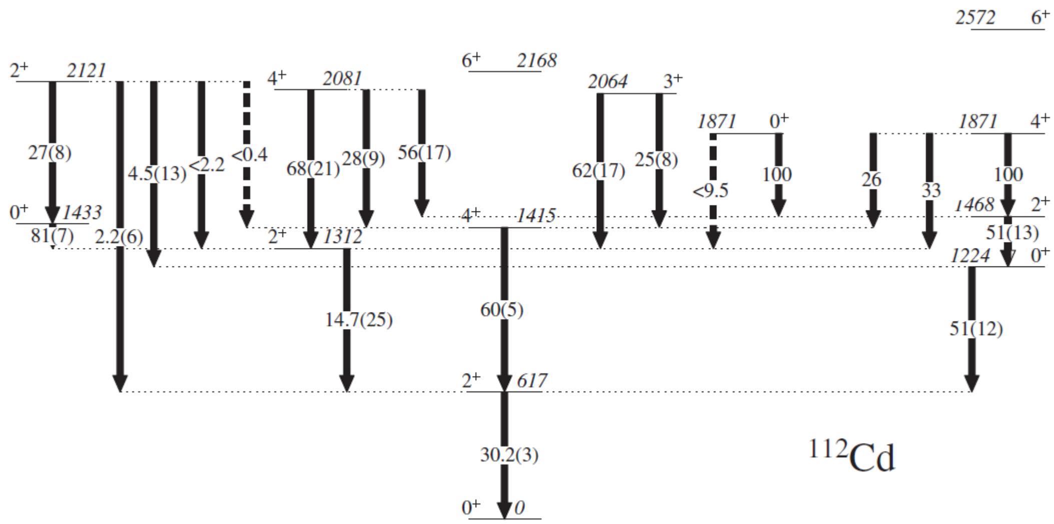
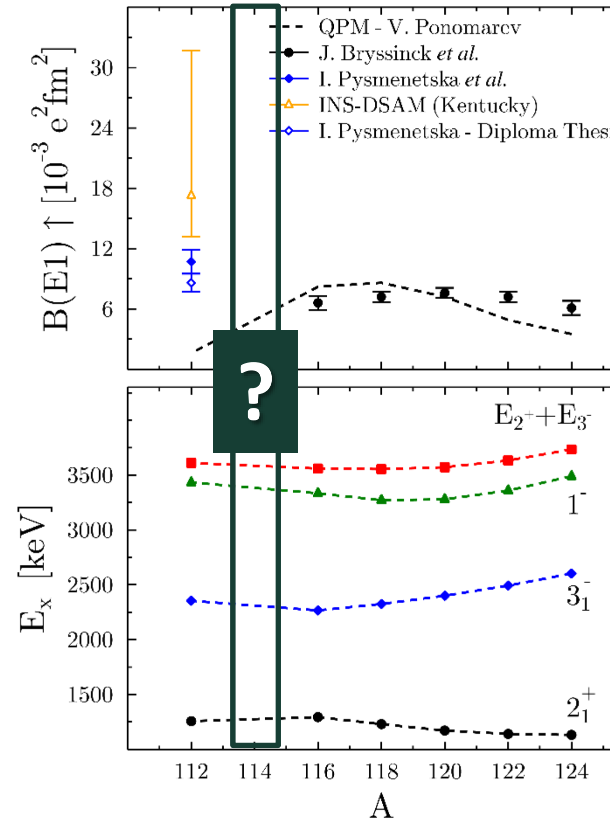
Collective structures in Sn isotopes?

Quasi-rotational structure of Cd isotopes and mixing between the different configurations
(are there “true“ vibrational states at all?)



[P.E. Garrett and J.L. Wood, J. Phys. G **37**, 064028 (2010)]



$(2^+_1 \otimes 3^-_1)$ multiphonon states in ^{114}Sn?

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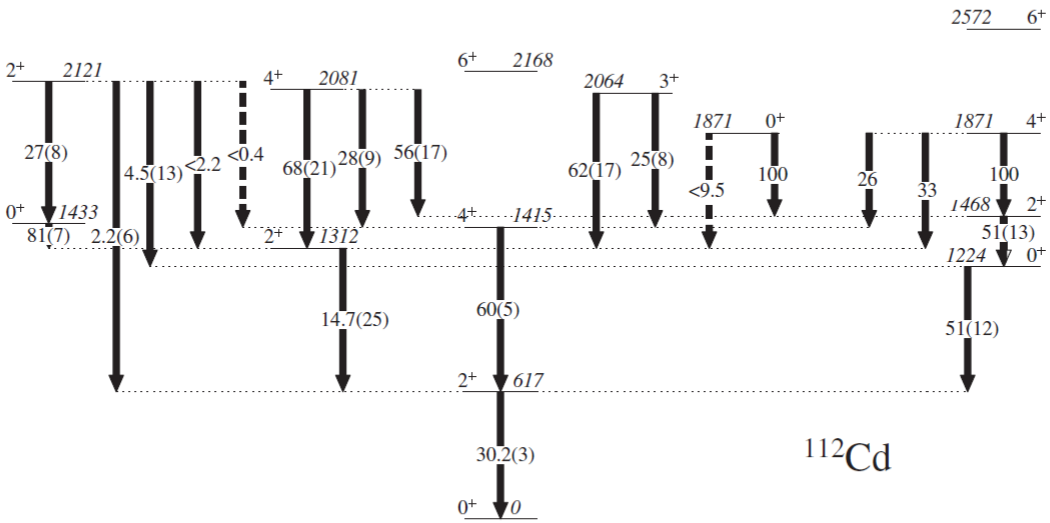

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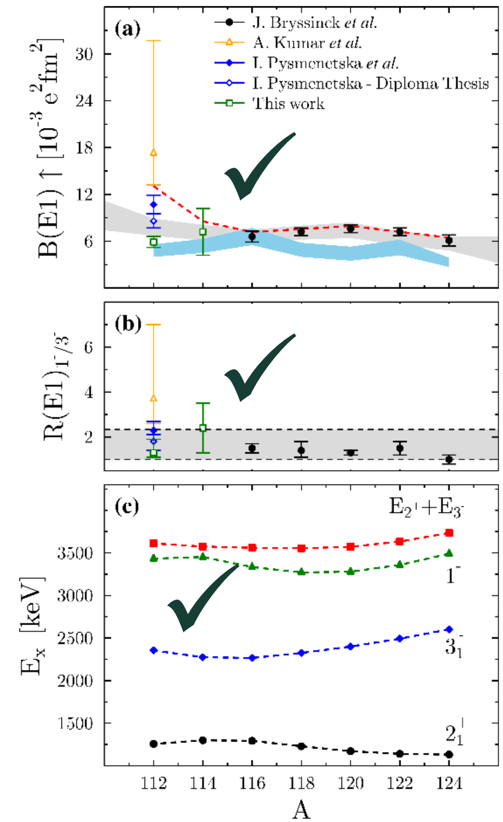

New experimental data from Cologne.

$(2_1^+ \otimes 3_1^-)$ multiphonon states in ^{114}Sn?

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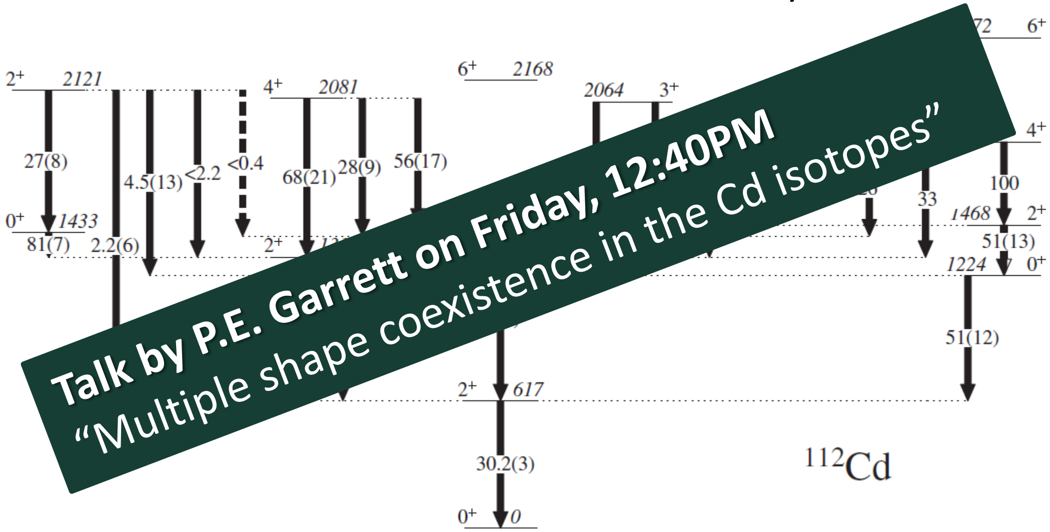
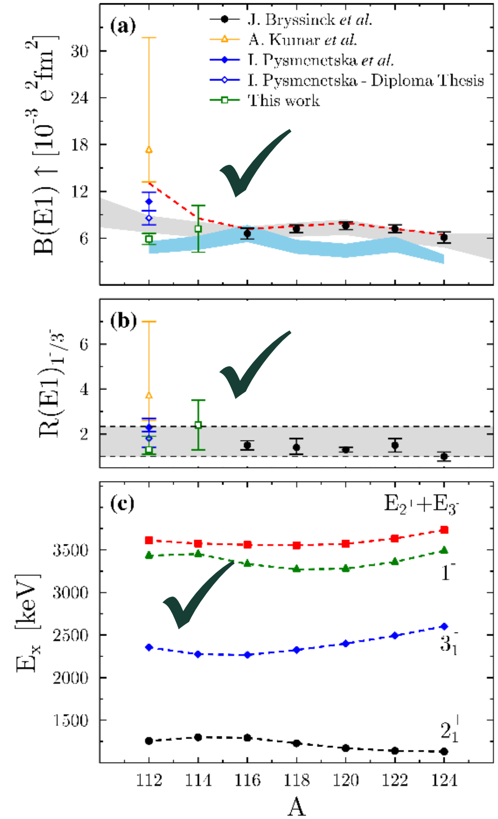


Talk by P.E. Garrett on Friday, 12:40PM
“Multiple shape coexistence in the Cd isotopes”

[P.E. Garrett and J.L. Wood, J. Phys. G **37**, 064028 (2010)]



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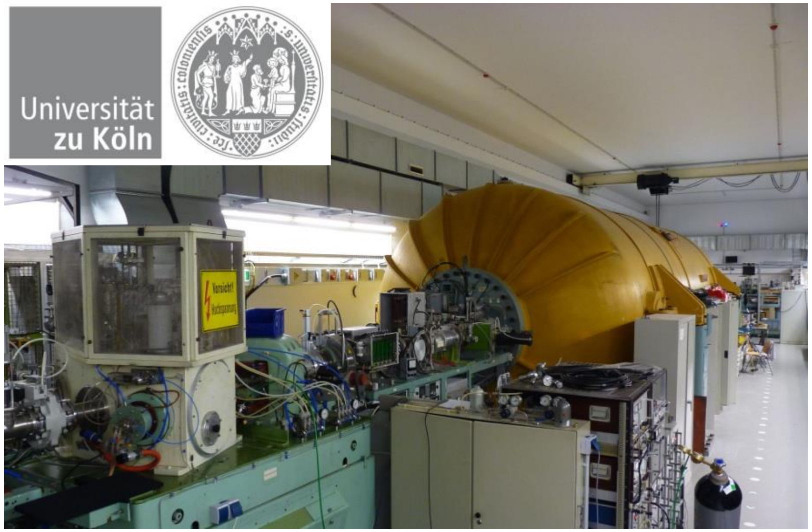
$(2_1^+ \otimes 3_1^-)$ multiphonon states in ^{114}Sn?

Experimental requirements:

- Selective probe needed to excite those low-spin states (non-Yrast)
- Small γ-decay branching ratios need to be detected
- Lifetimes and multipole-mixing ratios need to be measured for the determination of reduced transition strengths

Proton-γ coincidences with SONIC@HORUS



10 MV FN Tandem ion accelerator

- Three ion sources available
  → typically ions up to Z = 30
- Terminal voltages from 1 MV to 10 MV
- Current on target up to 1 μA (protons)
- **Experimental setups:**
  new AMS beamline, Plunger setup, Orange spectrometer, LYCCA, HORUS spectrometer

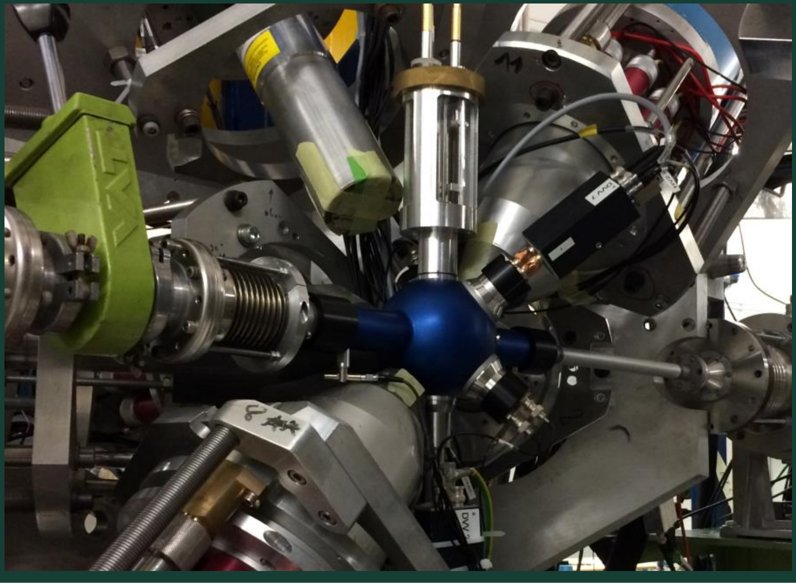
The SONIC@HORUS setup

HORUS for γ-ray detection

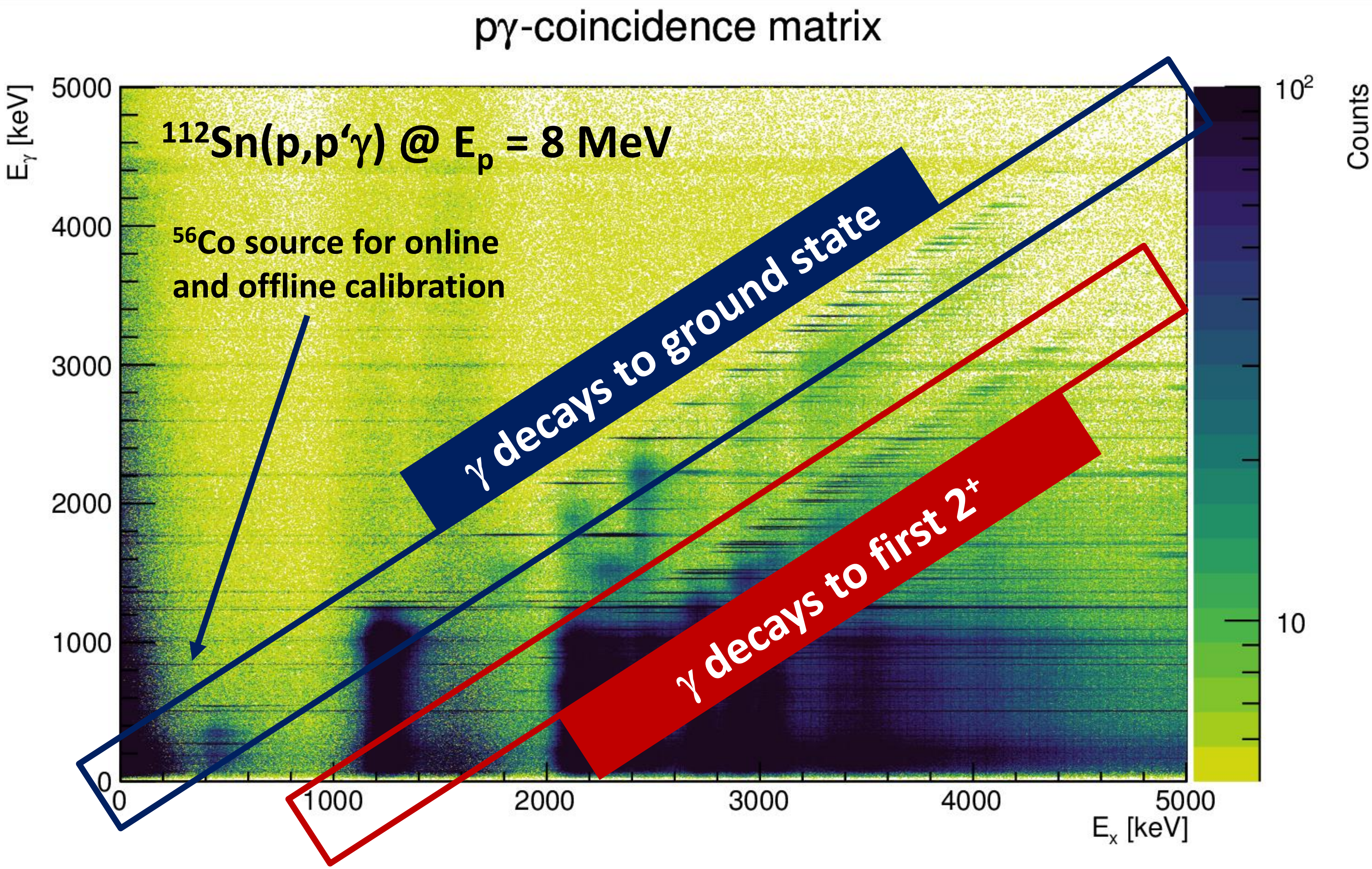
- Up to 14 HPGe detectors (ε_{FEP} ~ 2% @ 1.3 MeV)
  → Six BGO shields and two Clover HPGe detectors available

SONIC for particle detection

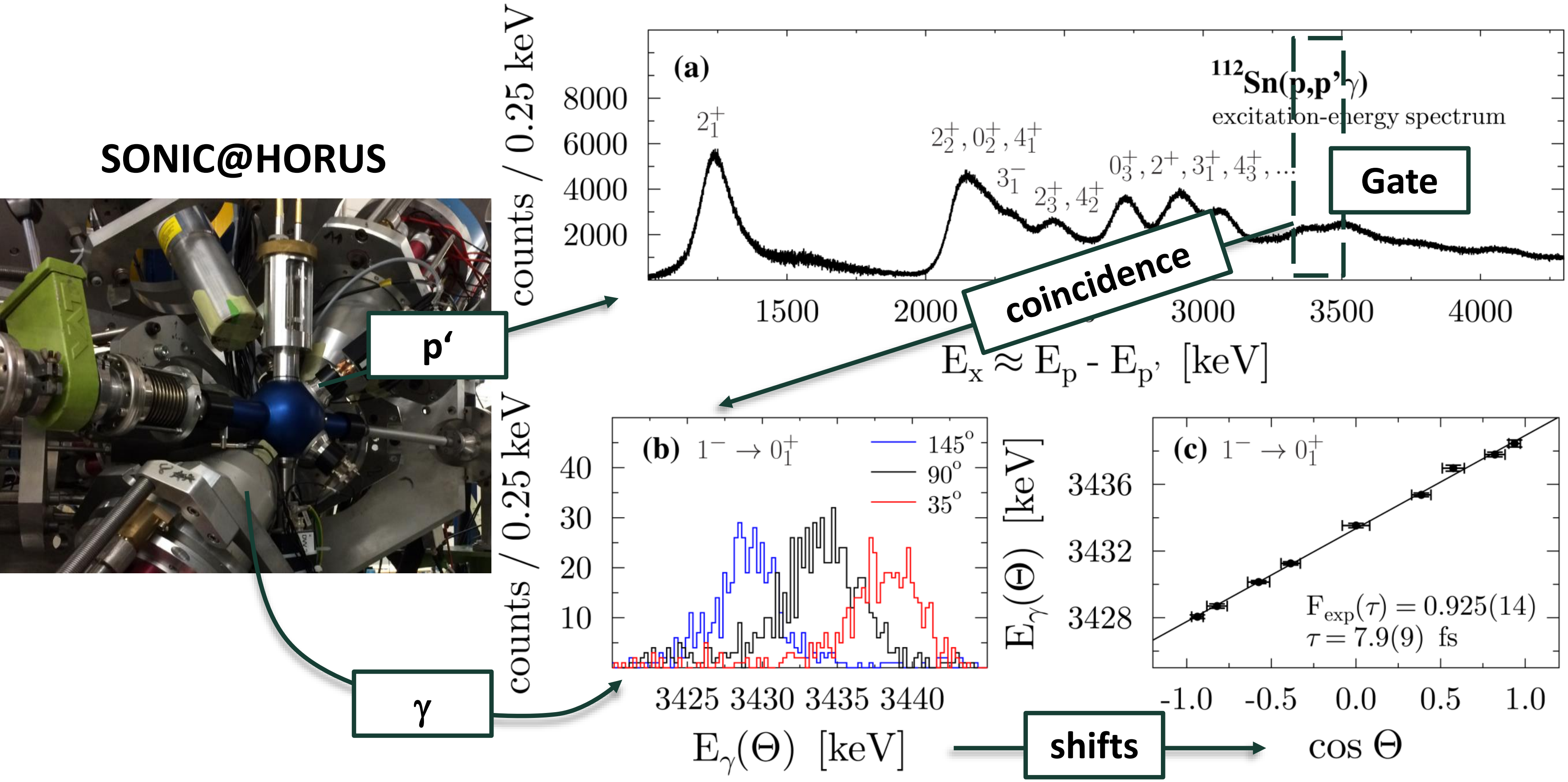
- 7-12 silicon detectors (thickness $\leq$ 1.5 mm)
- Particle-γ coincidences (Lifetimes, branching ratios, angular correlations)



Proton-γ coincidences with SONIC@HORUS



(p,p’γ) DSA coincidence technique



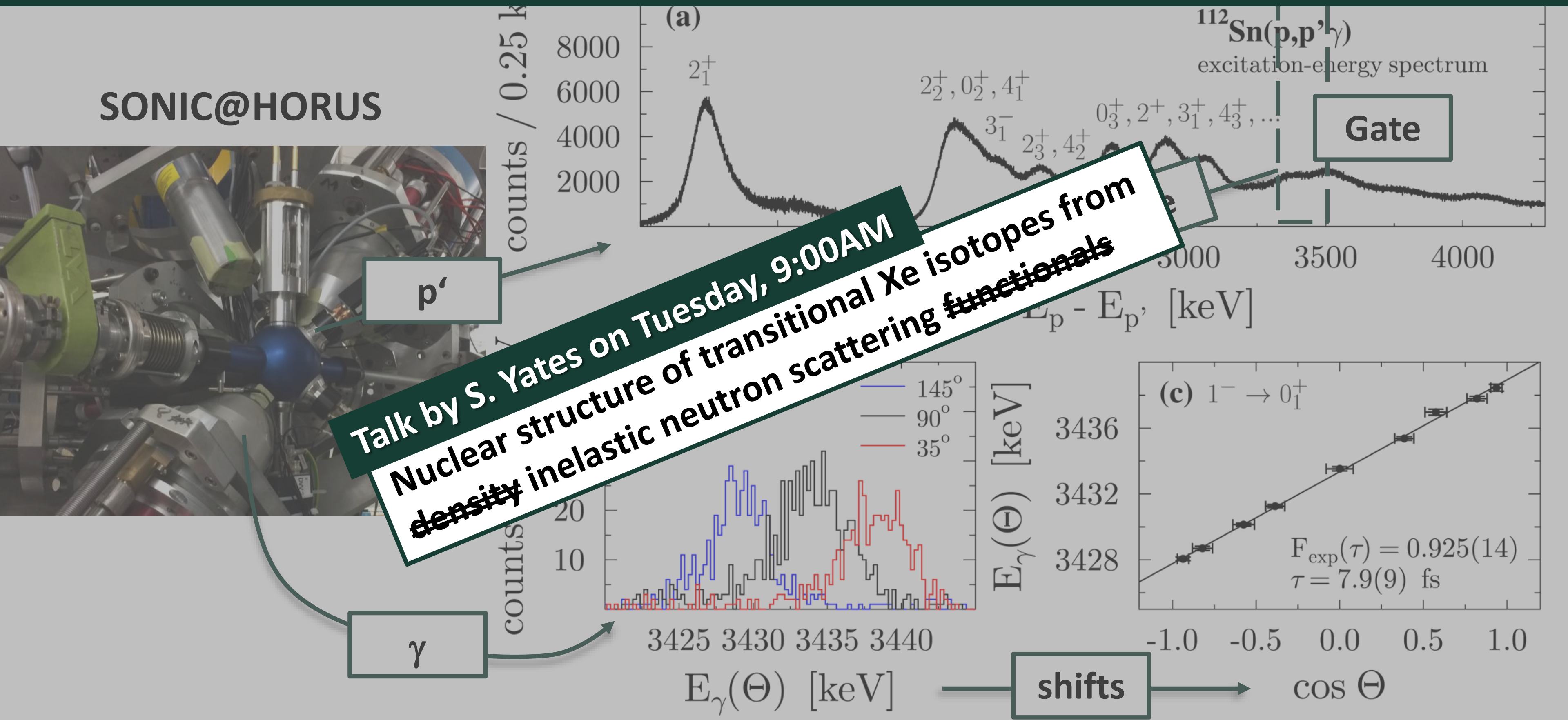
(p,p‘γ) DSA coincidence technique: A. Hennig *et al.*, NIM **794**, 171 (2015)

SONIC@HORUS (UoC, Germany): S.G. Pickstone *et al.*, NIM **875**, 104 (2017)

(p,p'γ) DSA coincidence technique

Our method is very similar to the (n,n'γ) technique used at the University of Kentucky (USA)

SONIC@HORUS



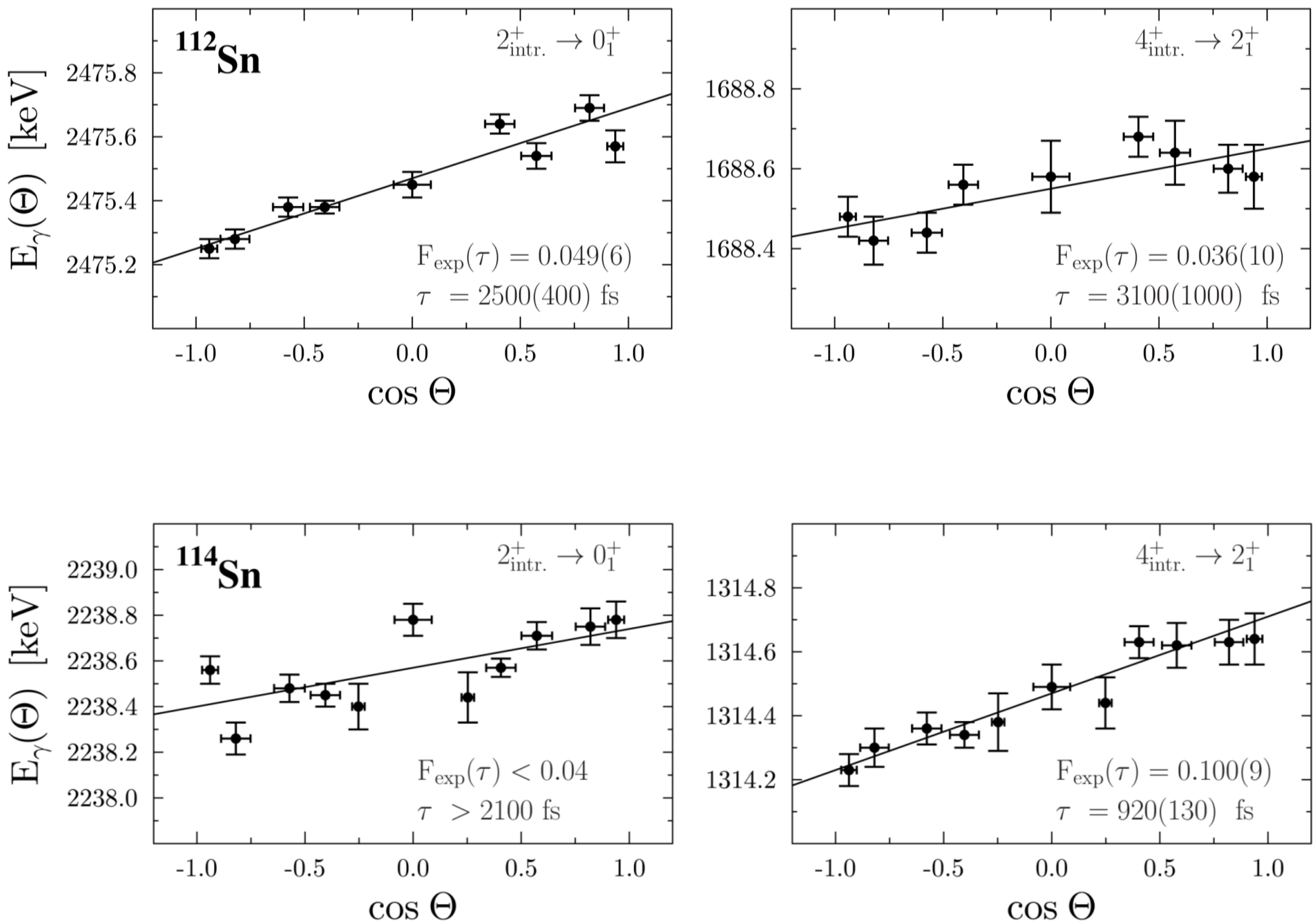
Talk by S. Yates on Tuesday, 9:00AM

Nuclear structure of transitional Xe isotopes from ~~density~~ inelastic neutron scattering ~~functionals~~

(p,p'γ) DSA coincidence technique: A. Hennig *et al.*, NIM **794**, 171 (2015)

SONIC@HORUS (UoC, Germany): S.G. Pickstone *et al.*, NIM **875**, 104 (2017)

Lifetimes of intruder states in ^{112,114}Sn



γ-decay behavior of the states of interest

^{112}Sn

E_x [keV]	J_i^π	J_f^π	E_γ [keV]	I_γ [%]
1256.5(2)	2_1^+	0_1^+	1256.5(2)	100
2150.5(3)	2_2^+	0_1^+	2150.5(2)	20(3)
	2_2^+	2_1^+	893.9(2)	100
2190.5(2)	0_2^+	2_1^+	934.0(2)	100
2247.0(3)	4_1^+	2_1^+	990.47(10)	100
2353.7(2)	3_1^-	2_1^+	1097.2(2)	100
2475.5(2)	2_3^+	0_1^+	2475.5(2)	100
	2_3^+	2_1^+	1218.9(2)	36(5)
	2_3^+	0_2^+	284.9(2)	0.70(10)
2520.5(2)	4_2^+	2_1^+	1264.0(2)	100
		[⋮]		
2945.0(7)	4^+	2_1^+	1688.5(2)	100
	4^+	2_2^+	794.2(2)	5.4(10)
	4^+	4_1^+	697.9(2)*	<1.5
	4^+	2_3^+	469.5(2)	18(3)
	4^+	4_2^+	424.6(3)*	4.9(9)
	4^+	6_1^+	396.4(4)*	2.3(5)
	4^+	4^+	161.4(2)*	9(2)

^{114}Sn

E_x [keV]	J_i^π	J_f^π	E_γ [keV]	I_γ [%]
1299.7(2)	2_1^+	0_1^+	1299.7(2)	100
1952.9(2)	0_2^+	2_1^+	653.2(2)	100
2155.9(2)	0_3^+	2_1^+	856.2(2)	100
2187.3(3)	4_1^+	2_1^+	887.6(2)	100
2238.6(2)	2_2^+	0_1^+	2238.5(2)	100
	2_2^+	2_1^+	938.9(2)	81(12)
	2_2^+	0_2^+	286.5(10)	0.9(3)
2274.5(2)	3_1^-	2_1^+	974.8(2)	100
2420.5(2)	0_4^+	2_1^+	1120.8(2)	100
2453.8(2)	2_3^+	0_1^+	2453.7(2)	28(4)
	2_3^+	2_1^+	1154.0(2)	100
	2_3^+	2_2^+	215.4(4)	1.3(3)
2514.4(2)	3_1^+	4_1^+	327.1(2)	100
2613.7(4)	4_2^+	2_1^+	1314.5(2)	100
	4_2^+	4_1^+	426.0(4)	1.6(6)
	4_2^+	2_2^+	375.2(3)	1.8(6)

γ-decay behavior of the states of interest

^{112}Sn

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* New γ-decay branching

^{114}Sn

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	2_3^+	2_2^+	215.4(4)	1.3(3)
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2613.7(4)	4_2^+	2_1^+	1314.5(2)	100
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“intruder” states

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0^+@2617 keV ⋮

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^{114}Sn

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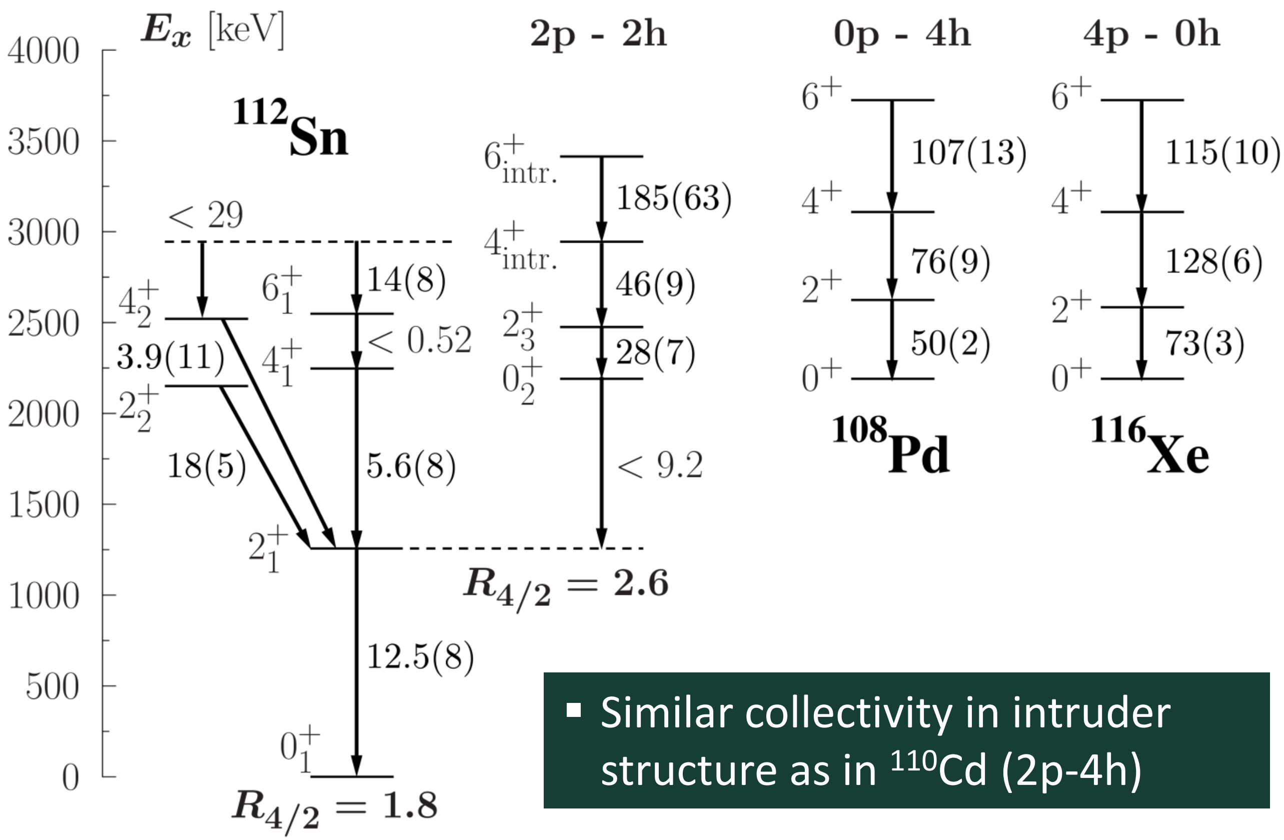
E_x [keV]	J_i^π	J_f^π	E_γ [keV]	I_γ [%]
1299.7(2)	2_1^+	0_1^+	1299.7(2)	100
1952.9(2)	0_2^+	2_1^+	653.2(2)	100
2155.9(2)	0_3^+	2_1^+	856.2(2)	100
2187.3(3)	4_1^+	2_1^+	887.6(2)	100
2238.6(2)	2_2^+	0_1^+	2238.5(2)	100
	2_2^+	2_1^+	938.9(2)	81(12)
	2_2^+	0_2^+	286.5(10)	0.9(3)
2274.5(2)	3_1^-	2_1^+	974.8(2)	100
2420.5(2)	0_4^+	2_1^+	1120.8(2)	100
2453.8(2)	2_3^+	0_1^+	2453.7(2)	28(4)
	2_3^+	2_1^+	1154.0(2)	100
	2_3^+	2_2^+	215.4(4)	1.3(3)
2514.4(2)	3_1^+	4_1^+	327.1(2)	100
2613.7(4)	4_2^+	2_1^+	1314.5(2)	100
	4_2^+	4_1^+	426.0(4)	1.6(6)
	4_2^+	2_2^+	375.2(3)	1.8(6)

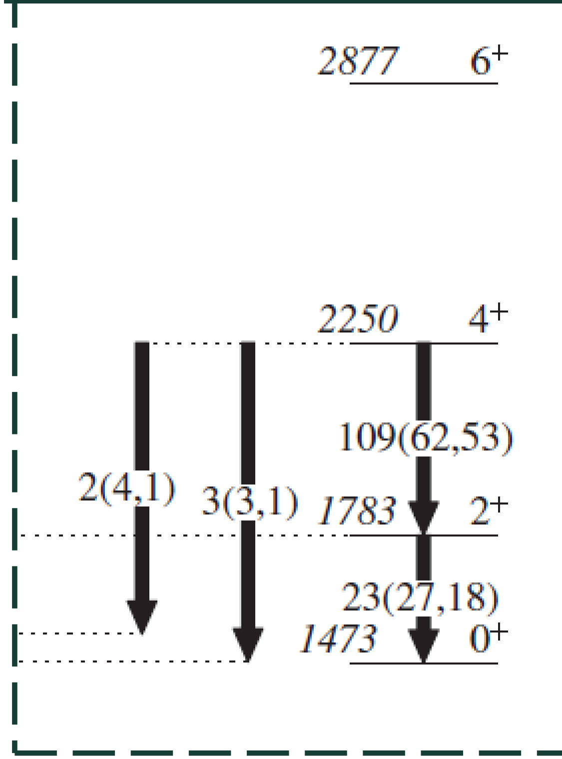
"intruder" states

Shape coexistence in ^{112}Sn

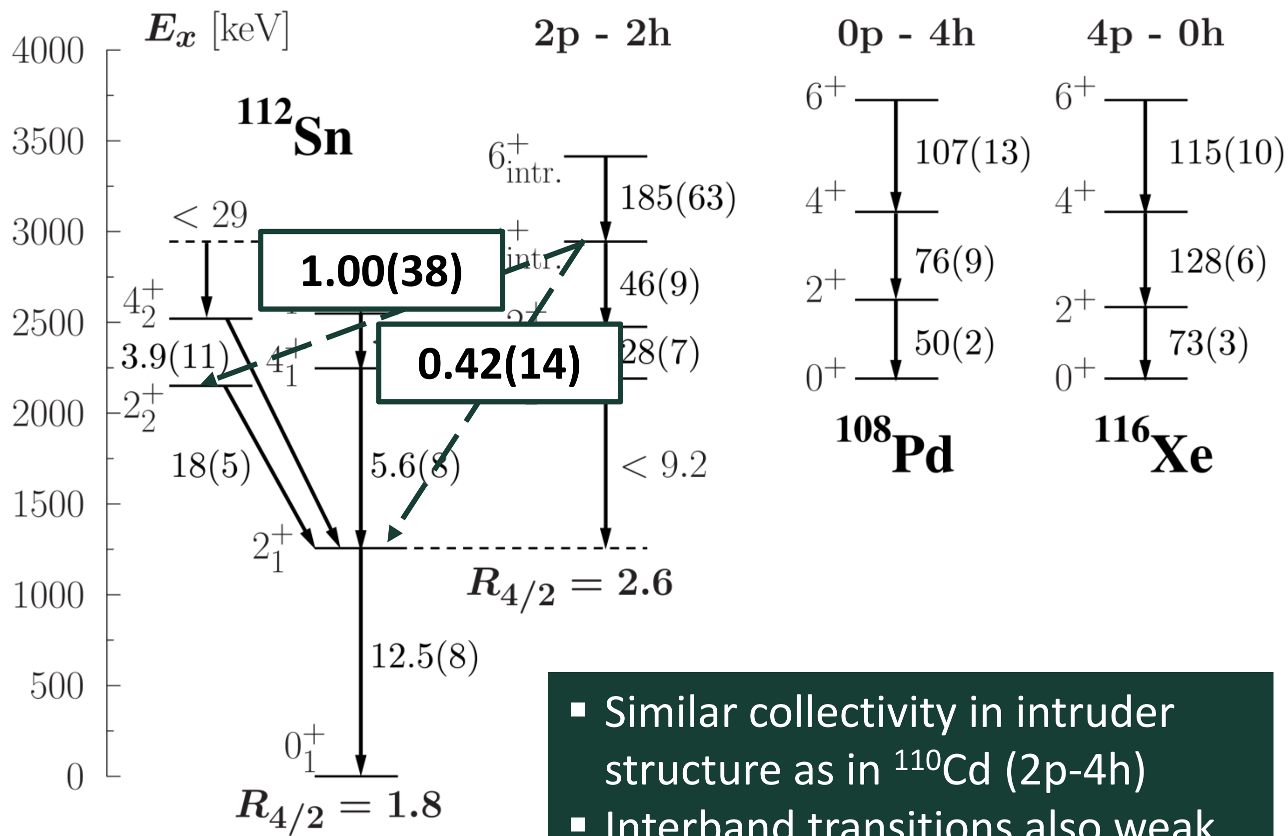


- Similar collectivity in intruder structure as in ^{110}Cd (2p-4h)

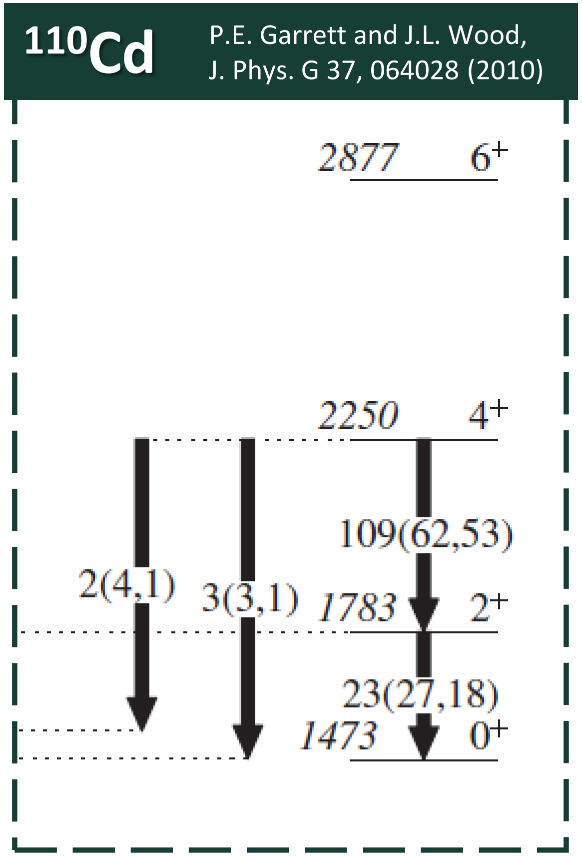
^{110}Cd P.E. Garrett and J.L. Wood, J. Phys. G 37, 064028 (2010)



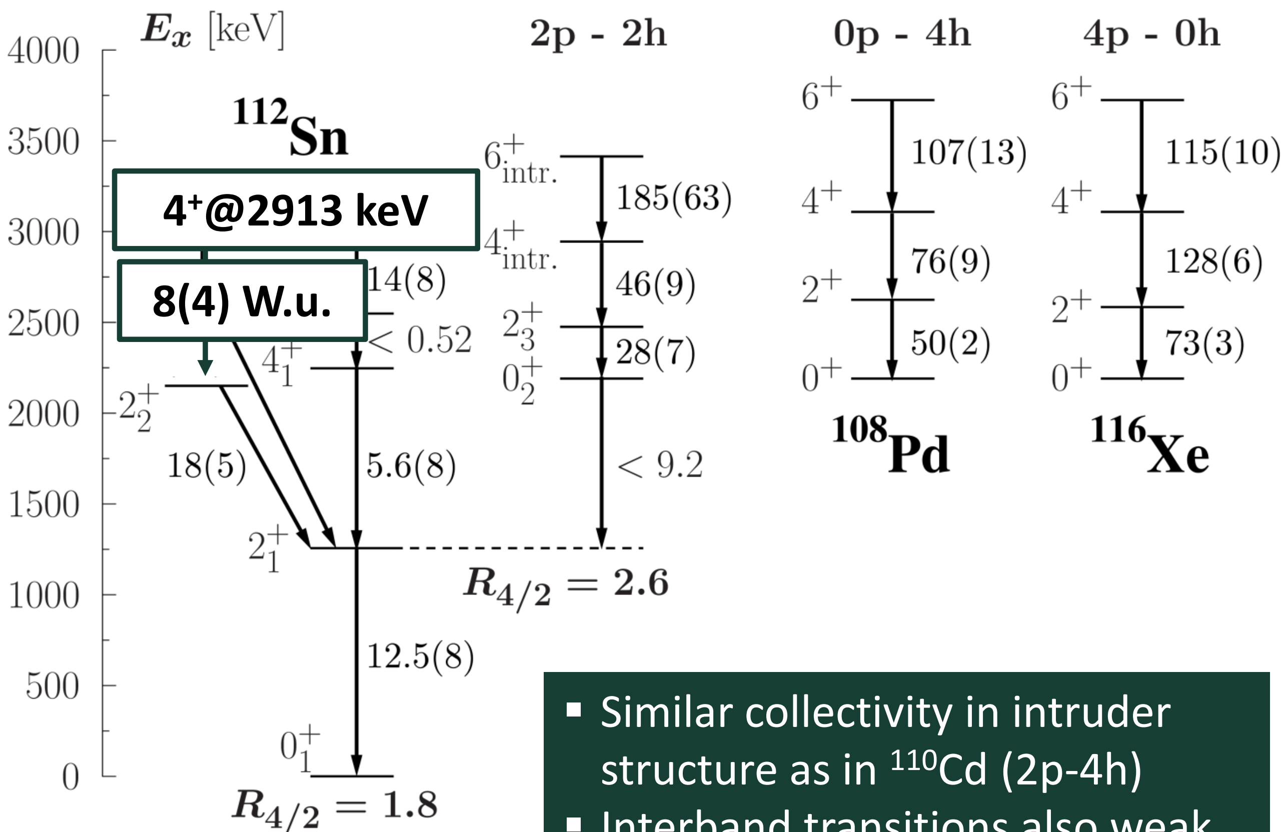
Shape coexistence in ^{112}Sn

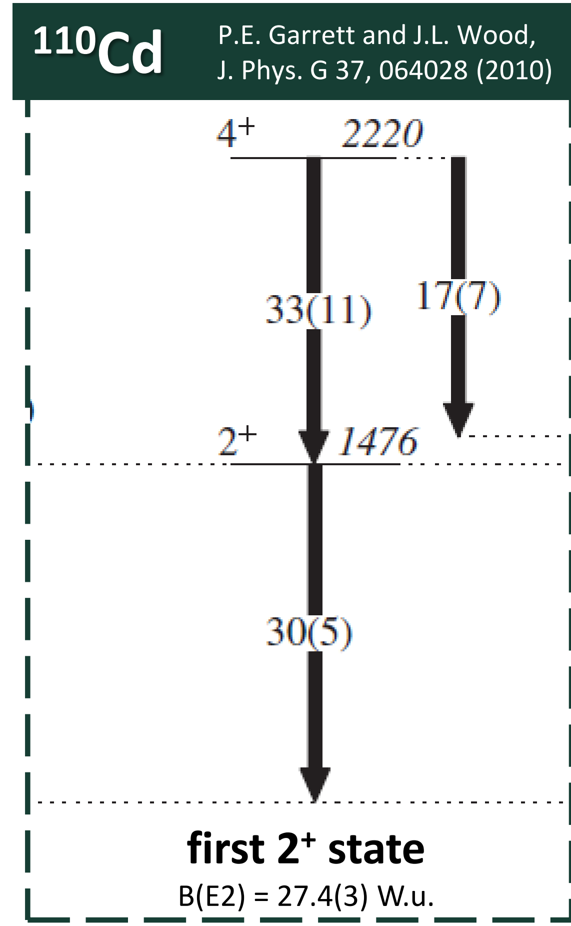


- Similar collectivity in intruder structure as in ^{110}Cd (2p-4h)
- Interband transitions also weak



Shape coexistence in ^{112}Sn

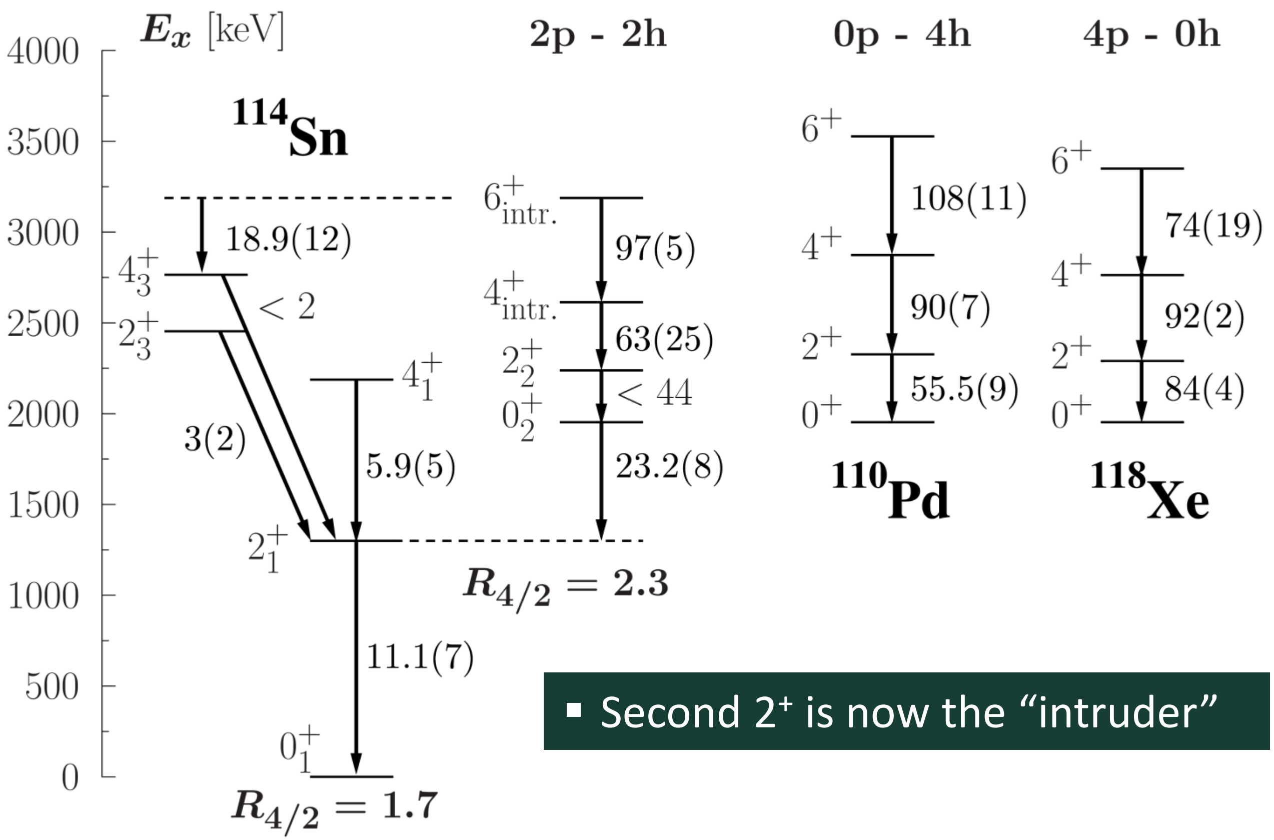


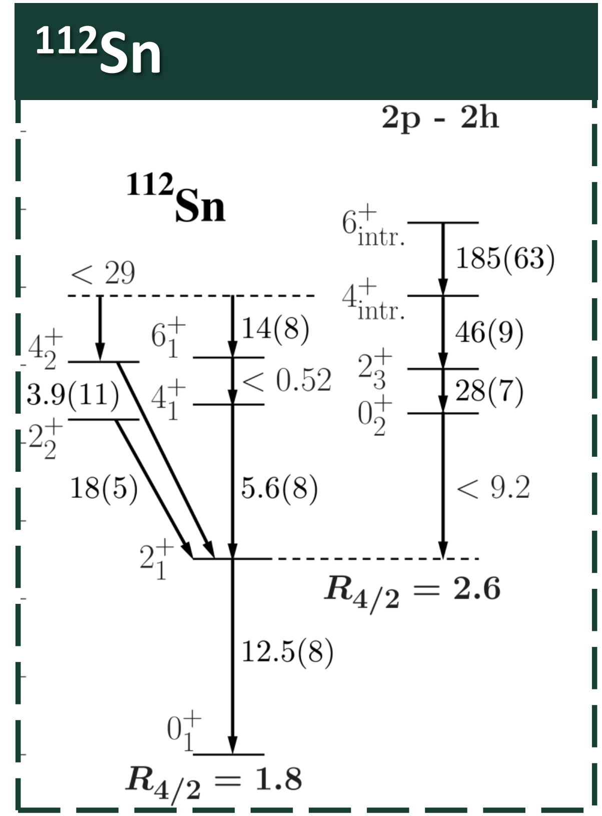


- Similar collectivity in intruder structure as in ^{110}Cd (2p-4h)
- Interband transitions also weak
- Quasi-rotational structure of Cd isotopes was proposed

“Quasi-rotational structure“ already existent at higher energies in Sn isotopes?

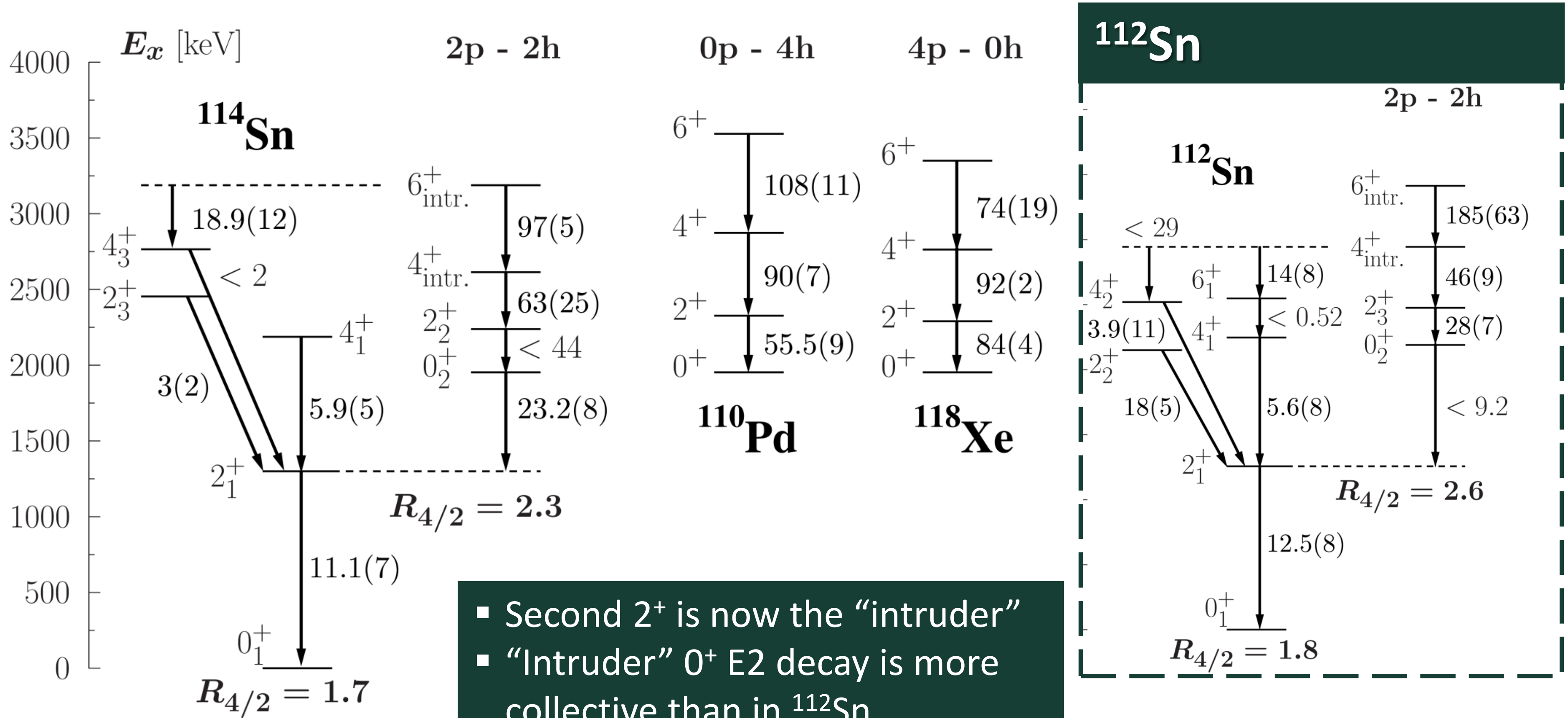
Shape coexistence in ^{114}Sn





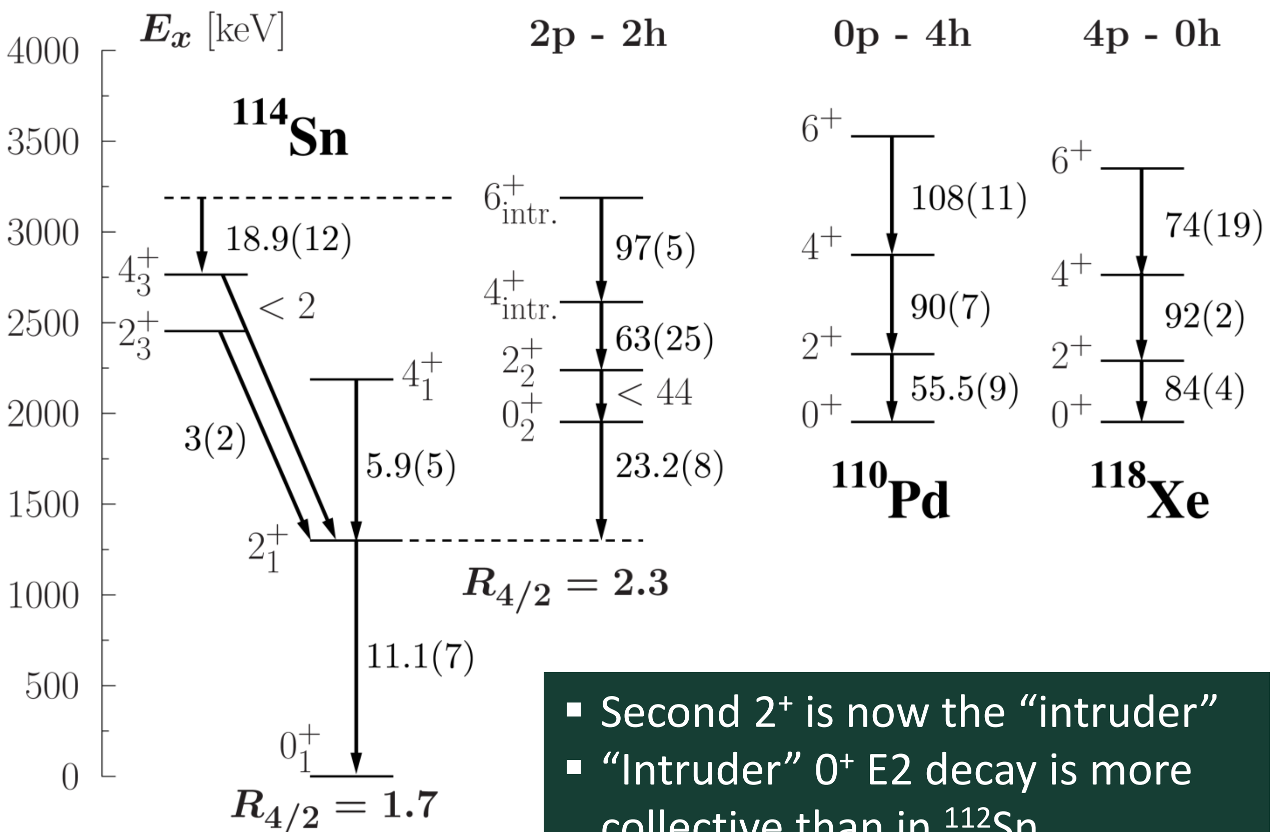
- Second 2^+ is now the “intruder”

Shape coexistence in ^{114}Sn



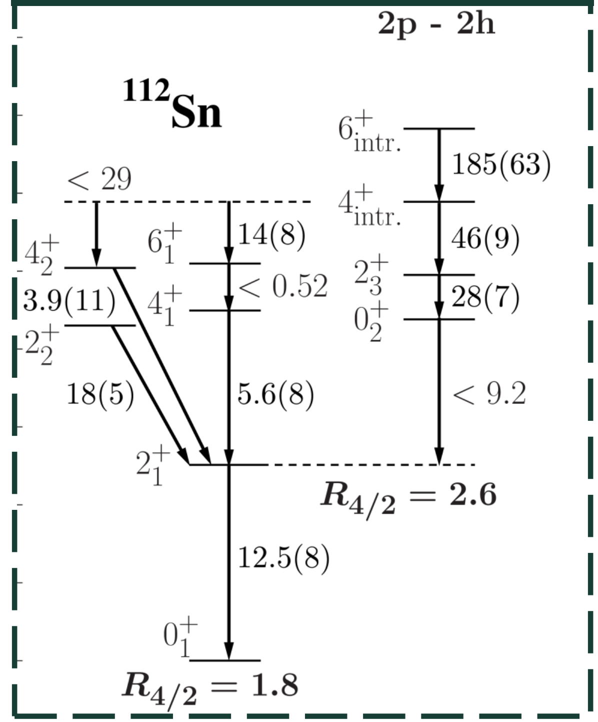
- Second 2^+ is now the "intruder"
- "Intruder" 0^+ E2 decay is more collective than in ^{112}Sn

Shape coexistence in ^{114}Sn

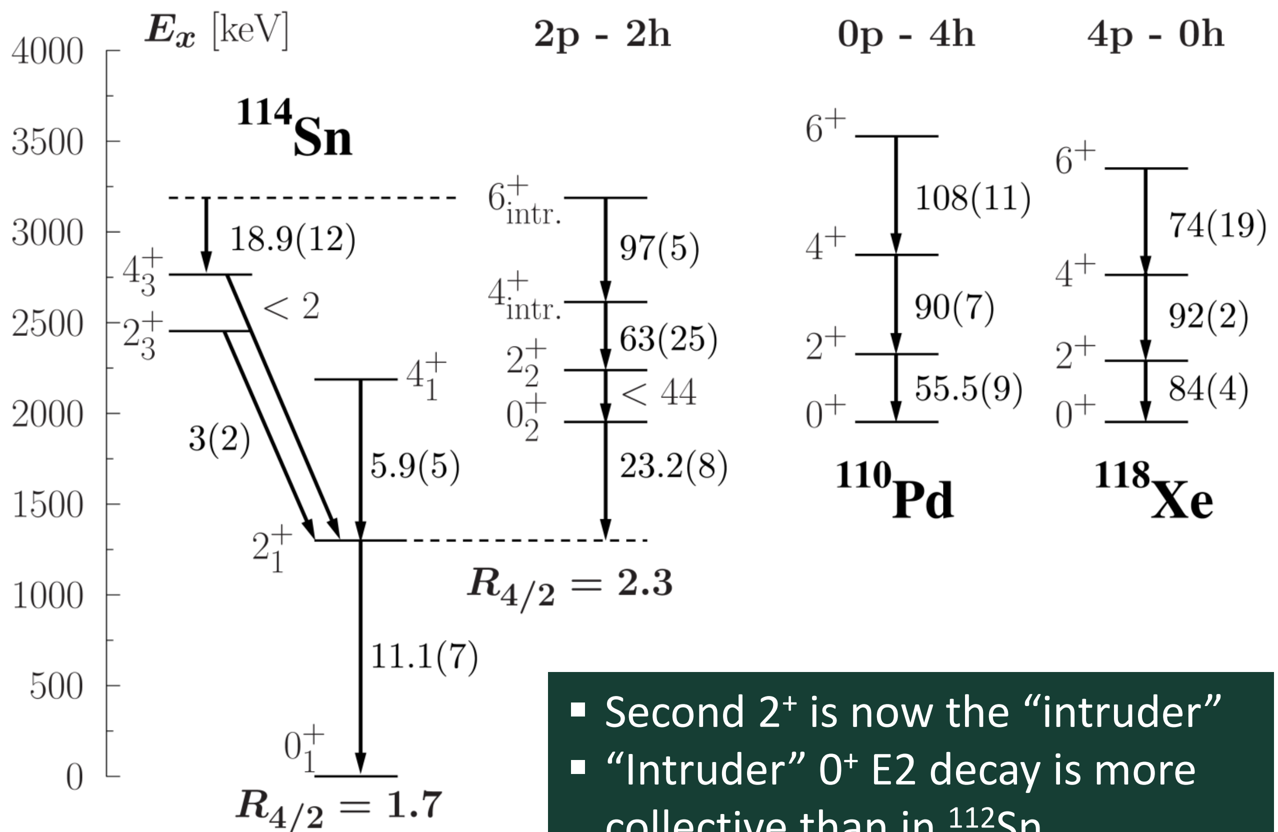


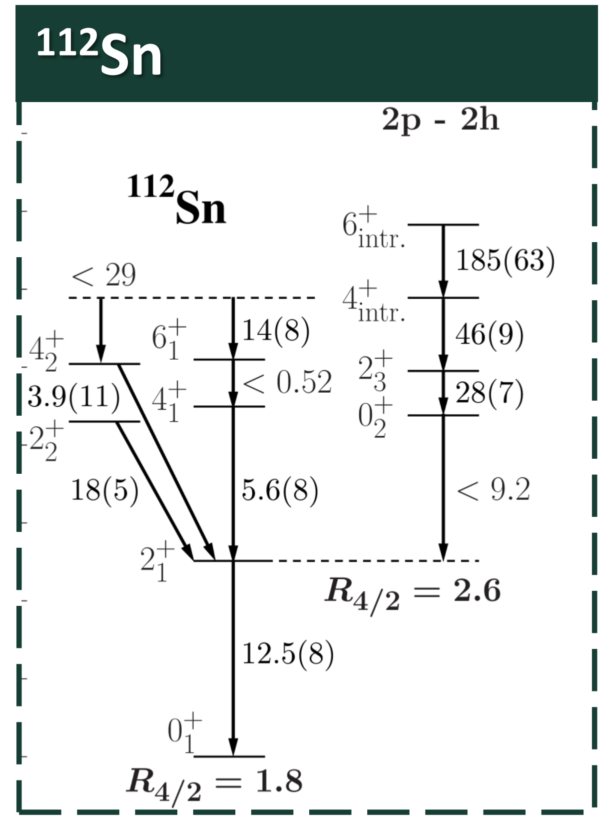
- Second 2⁺ is now the "intruder"
- "Intruder" 0⁺ E2 decay is more collective than in ^{112}Sn
- "Normal" 2⁺ (3rd) E2 decay less collective than in ^{112}Sn

^{112}Sn



Shape coexistence in ^{114}Sn





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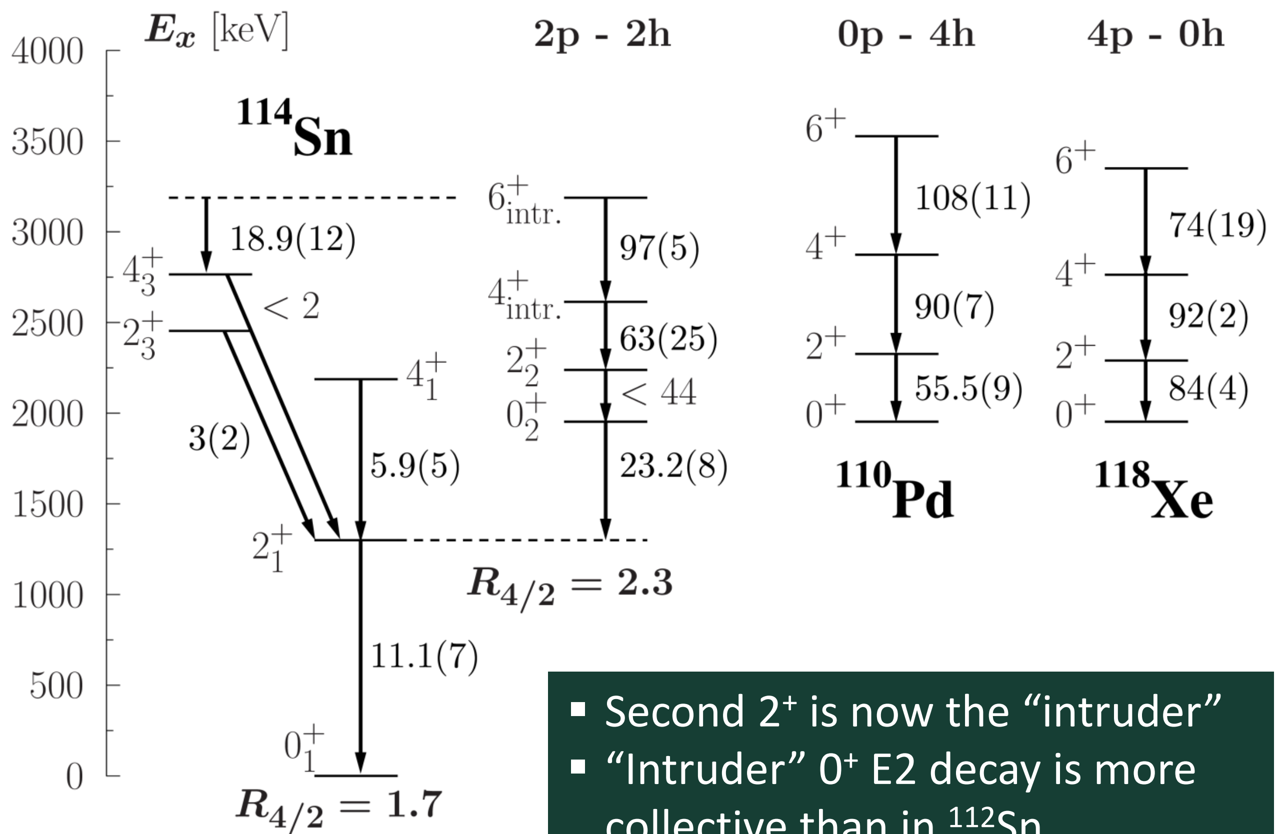

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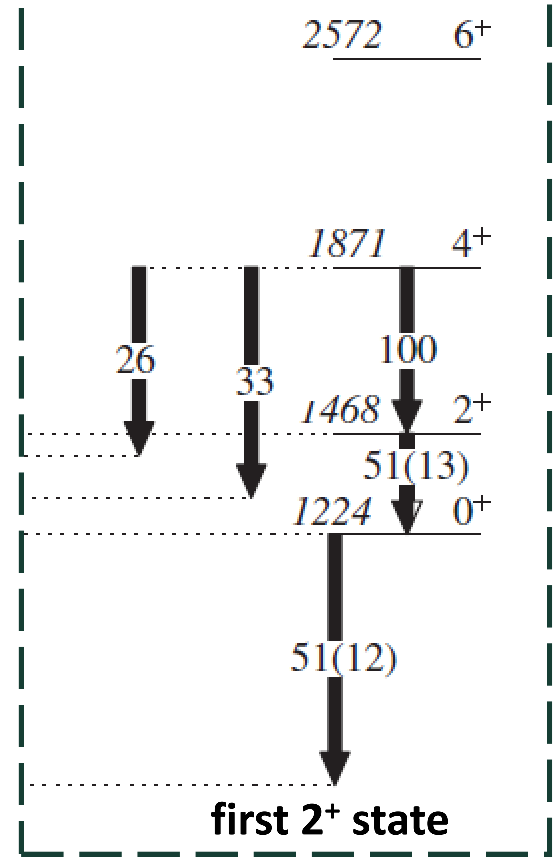
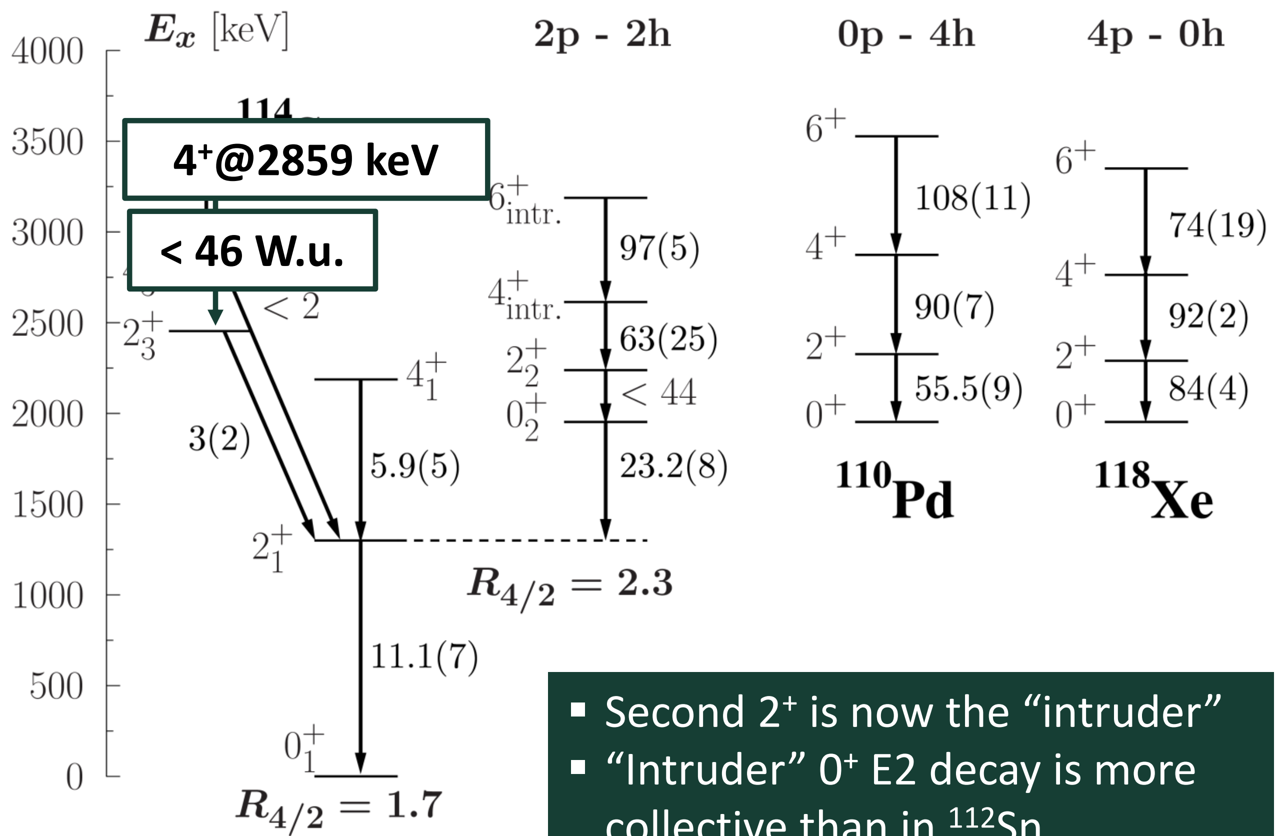
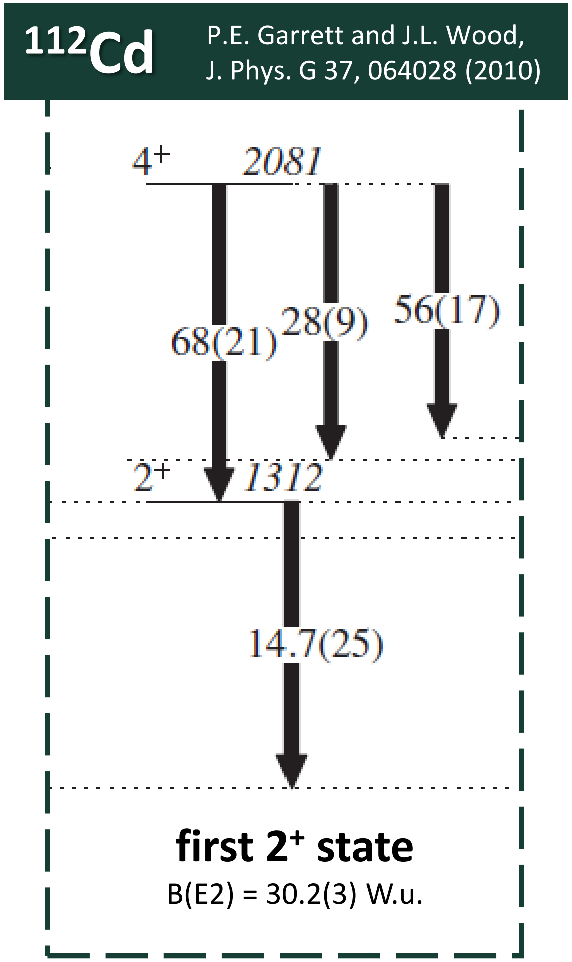


Shape coexistence in ^{114}Sn





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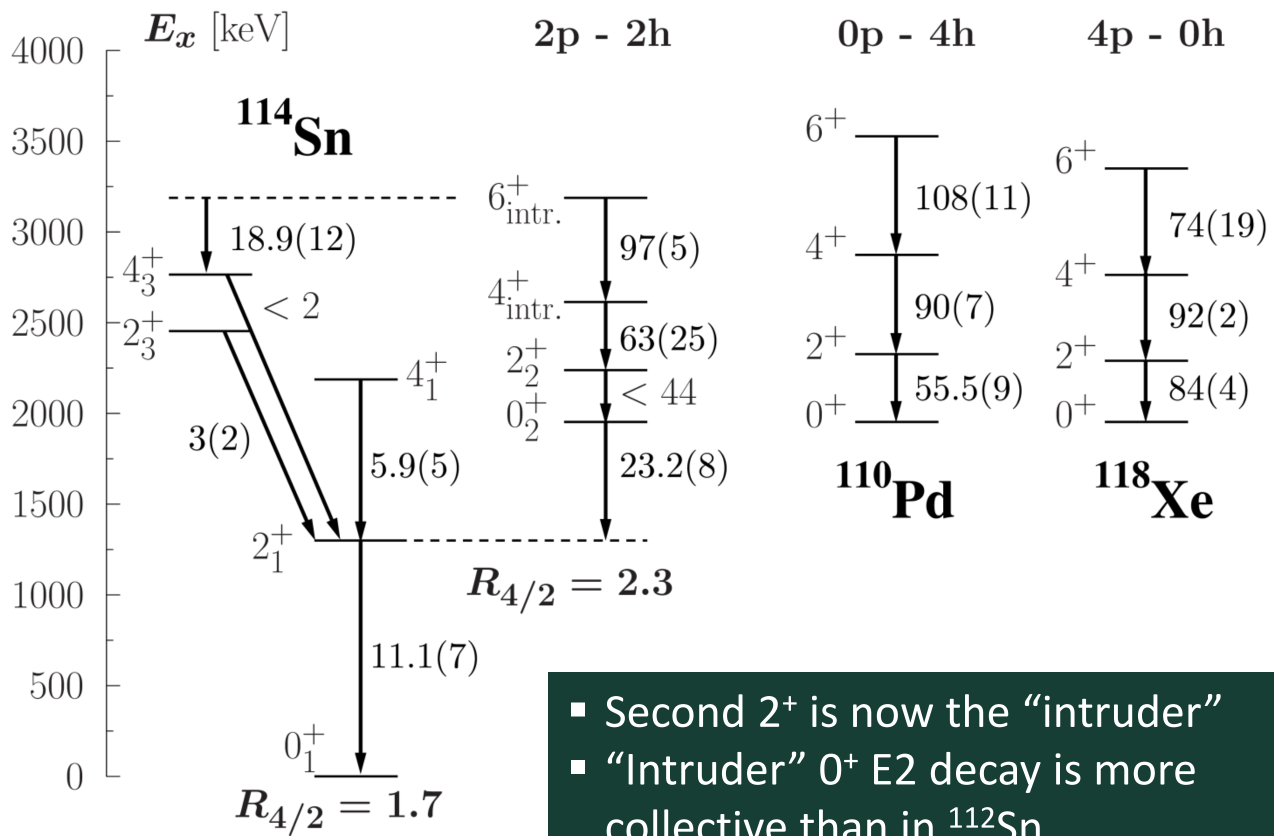
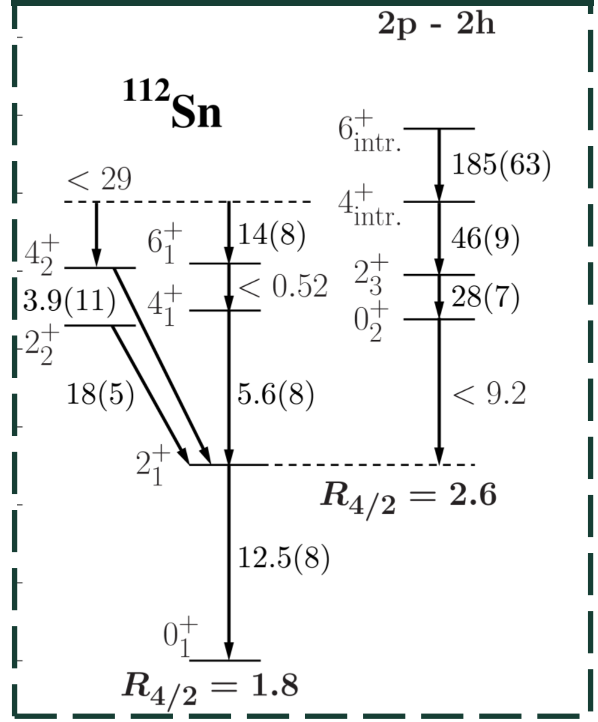
Shape coexistence in ^{114}Sn



^{112}Sn



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- “Intruder” 0⁺ E2 decay is more collective than in ^{112}Sn
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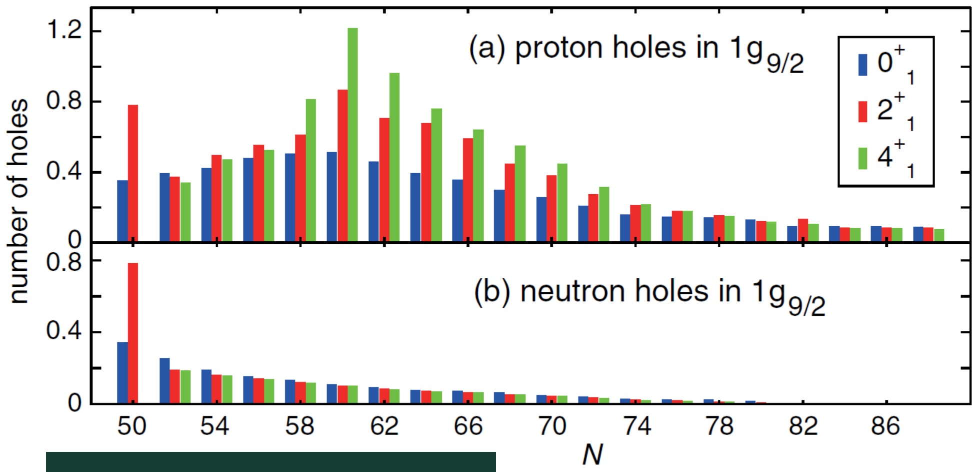
Influence of underlying single-particle structure or overall structure change?

Different influence of neutron single-particle states?

Changing shell structure from ^{114}Sn to ^{112}Sn?

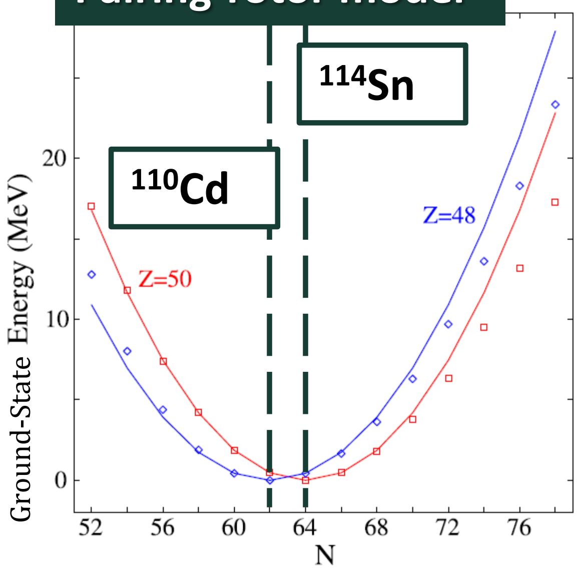
[T. Togashi, Y. Tsunoda, T. Otsuka, *et al.*, PRL **121**, 062501 (2018)]



Number of proton holes in ground state increases!

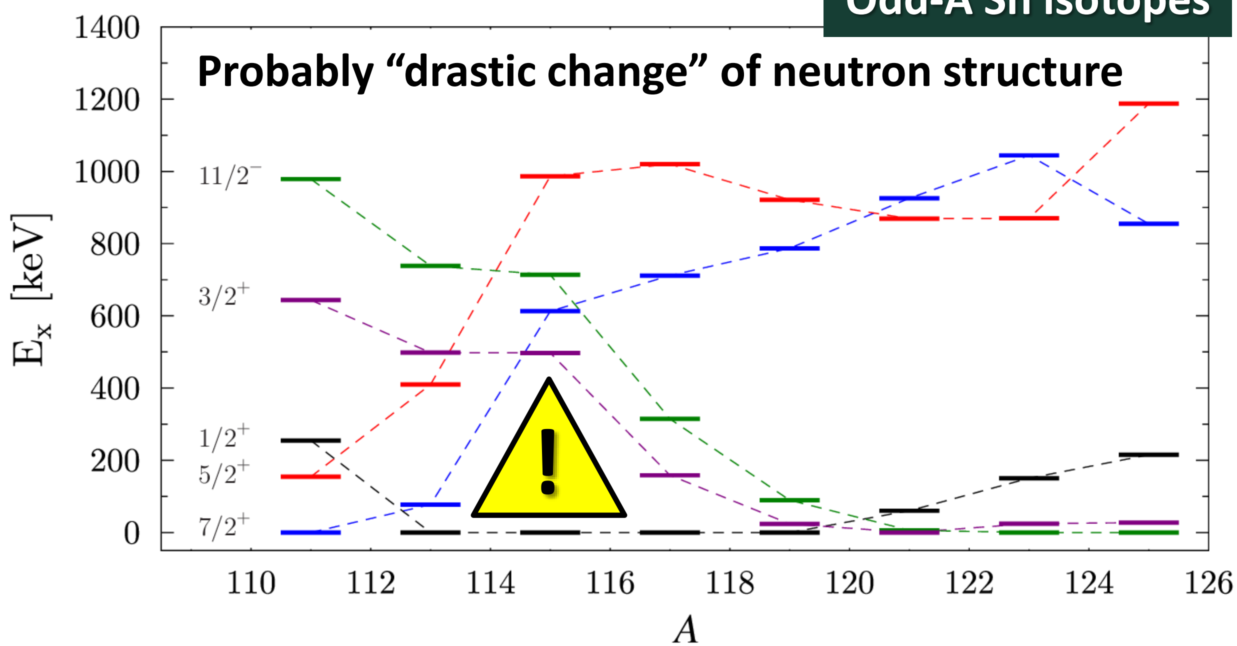
… in some sense ^{112,114}Sn are transitional nuclei (modestly deformed to pairing phase).

Pairing-rotor model



[P.E. Garrett, J. Phys. G **43**, 084002 (2016)]

Odd-A Sn isotopes

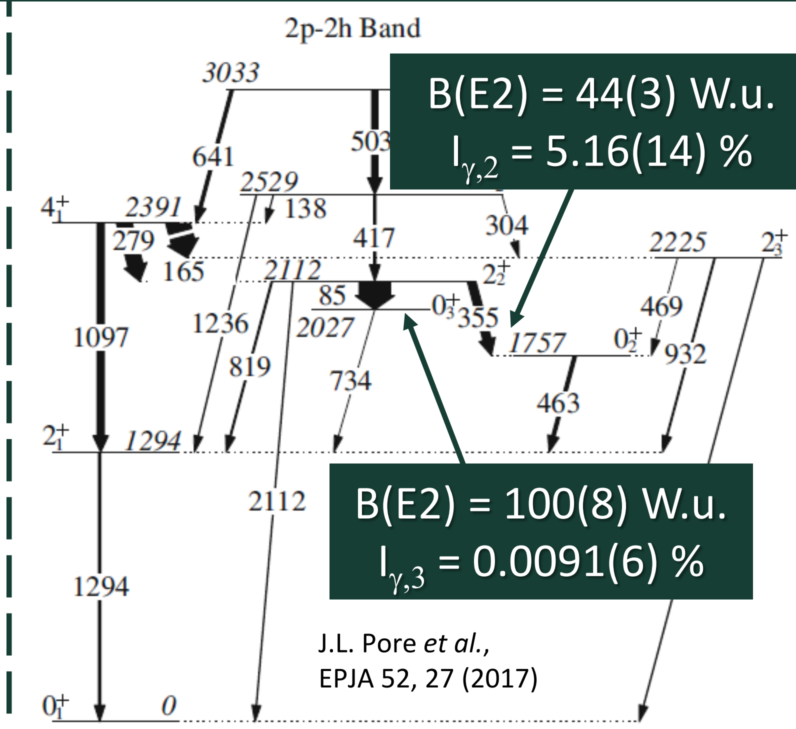


Shape coexistence in ^{114}Sn

Comparison to IBM-2 mixing calculations
(assuming ^{110}Pd to cause intruder structure)

J_i^π	E_x [MeV]	$E_{x,\mathrm{IBM}}$ [MeV]	J_f^π	$B(E2)_{\mathrm{exp.}}\downarrow$ [W.u.]	$B(E2)_{\mathrm{IBM}}\downarrow$ [W.u.]
normal configuration					
2_1^+	1.30	1.30	0_1^+	11.1(7)	11
4_1^+	2.19	2.28	2_1^+	5.9(5)	19
0_2^+	1.95	1.99	2_1^+	23.2(8)	21
2_3^+	2.45	2.54	0_1^+	0.023(9)	0.004
			2_1^+	3(2)	17
			2_2^+	-	8
intruder configuration					
0_3^+	2.16	2.15	2_1^+	≤ 5	2
2_2^+	2.24	2.46	0_1^+	≤ 0.12	0.04
			2_1^+	≤ 8	2
			0_2^+	≤ 44	31
			0_3^+	-	27
4_2^+	2.61	3.00	2_1^+	6.6(10)	0.2
			4_1^+	1.6(10)	0.06
			2_2^+	62(25)	85
6^+	3.19	3.63	4_1^+	1.68(9)	1.5
			4_2^+	97(5)	93
			4_3^+	18.9(12)	0.7

^{116}Sn – Is 3rd 0$^+$ bandhead?



J.L. Pore *et al.*,
EPJA 52, 27 (2017)

Shape coexistence in ^{114}Sn

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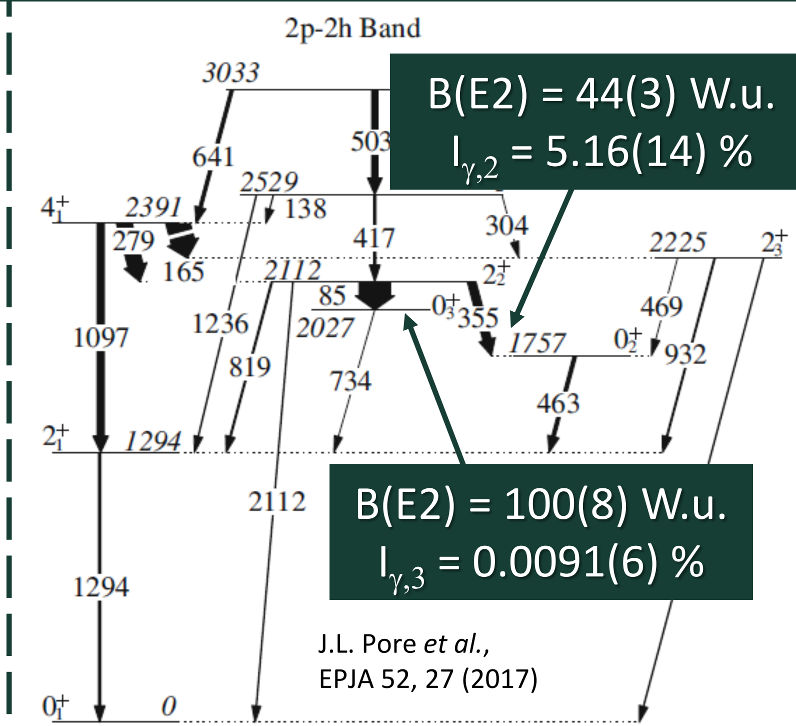
$I_{\gamma,2}$ = 0.9(3) % (Exp.)
$I_{\gamma,3}$ ≈ 0.002 % (IBM)

B(E2) = 55.5(9) W.u. in ^{110}Pd

^{116}Sn – Is 3rd 0$^+$ bandhead?



B(E2) = 44(3) W.u.
$I_{\gamma,2}$ = 5.16(14) %

B(E2) = 100(8) W.u.
$I_{\gamma,3}$ = 0.0091(6) %

J.L. Pore *et al.*,
EPJA 52, 27 (2017)

Shape coexistence in ^{114}Sn

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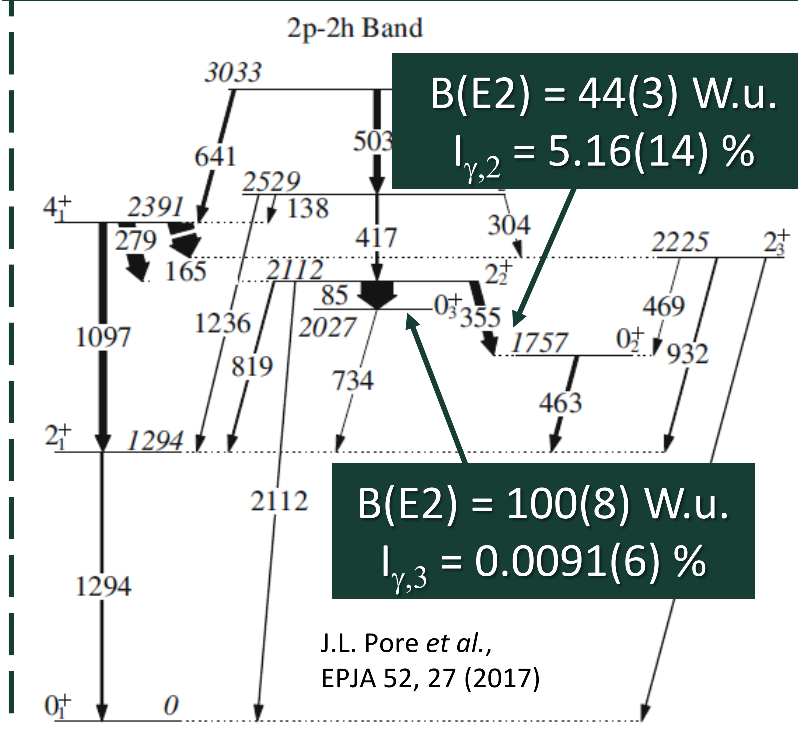

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J.L. Pore *et al.*,
EPJA 52, 27 (2017)

B(E2) = 40(7) W.u. in ^{112}Pd

How could this large B(E2) in ^{116}Sn be explained?

Shape coexistence in ^{114}Sn

Comparison to IBM-2 mixing calculations
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J_i^π	E_x [MeV]	$E_{x,\mathrm{IBM}}$ [MeV]	J_f^π	$B(E2)_{\mathrm{exp.}}\downarrow$ [W.u.]	$B(E2)_{\mathrm{IBM}}\downarrow$ [W.u.]
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0_3^+	2.16	2.15	[illegible]	[illegible]	[illegible]
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6^+	3.19	3.63	4_1^+	1.68(9)	[illegible]
			4_2^+	97(5)	[illegible]
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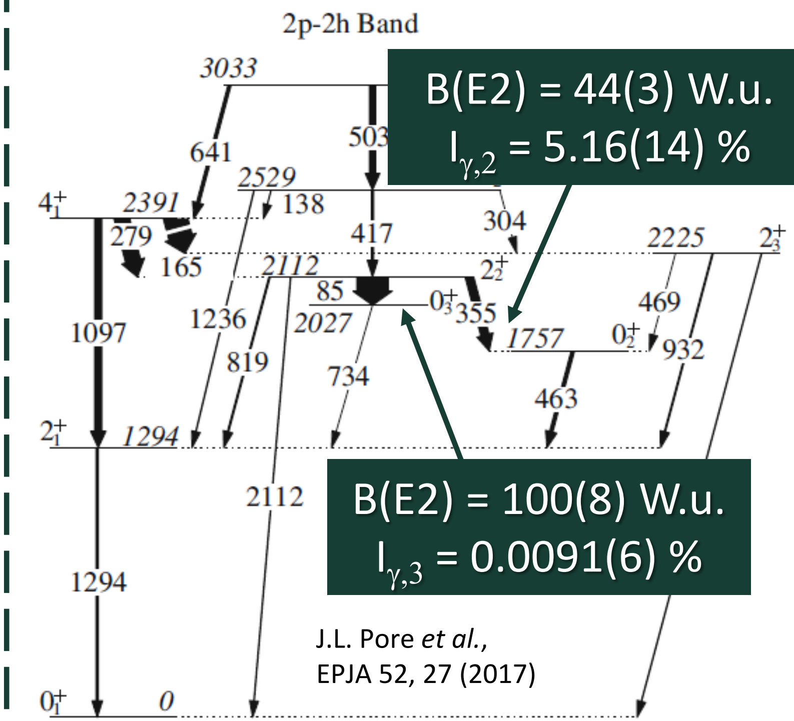
$I_{\gamma,2}$ = 0.9(3) % (Exp.)
$I_{\gamma,3} \approx$ 0.002 % (IBM)

B(E2) = 55.5(9) W.u. in ^{110}Pd

^{116}Sn – Is 3rd 0+ bandhead?



B(E2) = 44(3) W.u.
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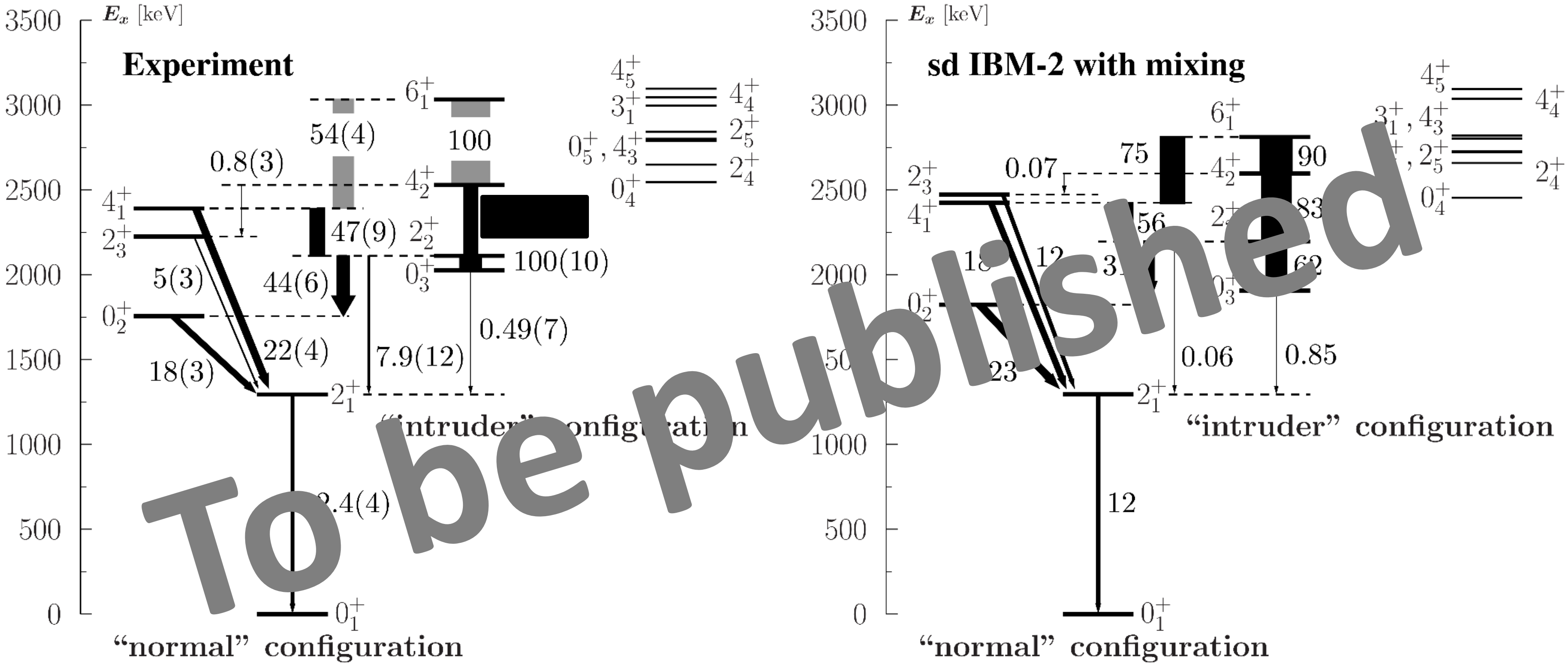
J.L. Pore *et al.*,
EPJA 52, 27 (2017)

B(E2) = 40(7) W.u. in ^{112}Pd

How could this large B(E2) in ^{116}Sn be explained?

B(E2) = 101(5) W.u. in ^{120}Xe

Shape coexistence in ^{116}Sn



[C. Petrache, J.-M. Régis, C. Andreoiu, MS, *et al.*, submitted for publication]

- **Strong mixing between normal and intruder configuration**
  → Observation of two collective decay branches with "band" structure
- **IBM-2 can provide reasonable to good description of experimental data**
  → Discrepancies can be explained by imposed selection rules

(further adjustment would be possible; maybe mix O(6)-like with O(6)-like)

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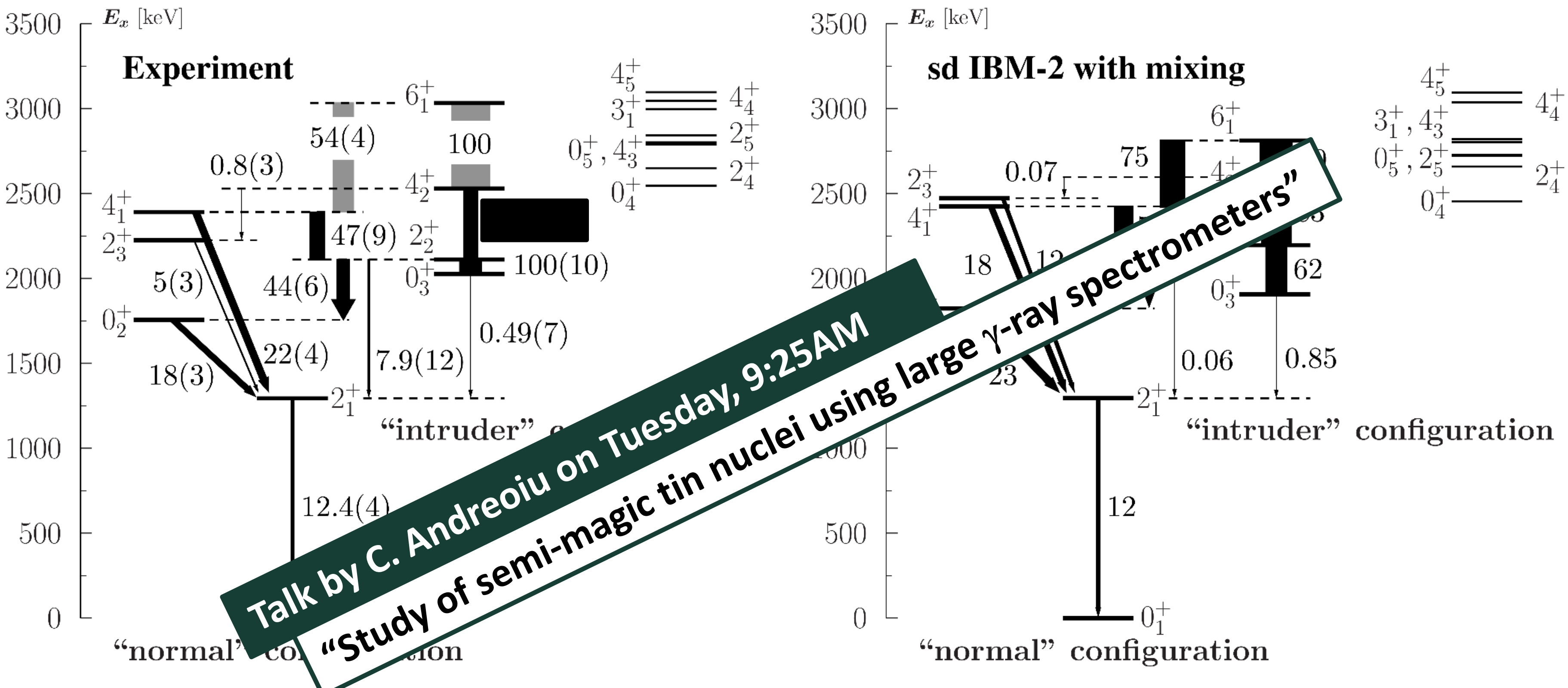
Shape coexistence in ^{116}Sn



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Summary

- **SONIC@HORUS** to determine lifetimes and γ-decay behavior of low-spin states via (p,p'γ) DSA coincidence technique

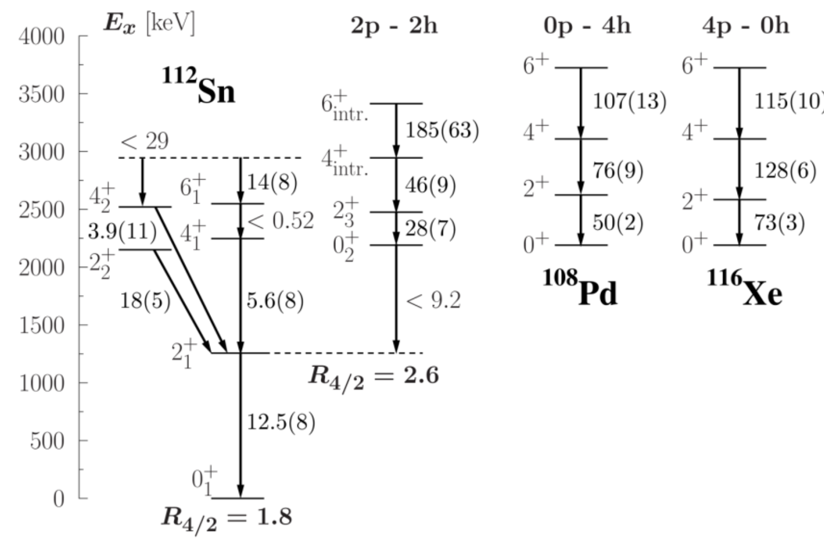
  [A. Hennig *et al.*, NIM **794**, 171 (2015)]

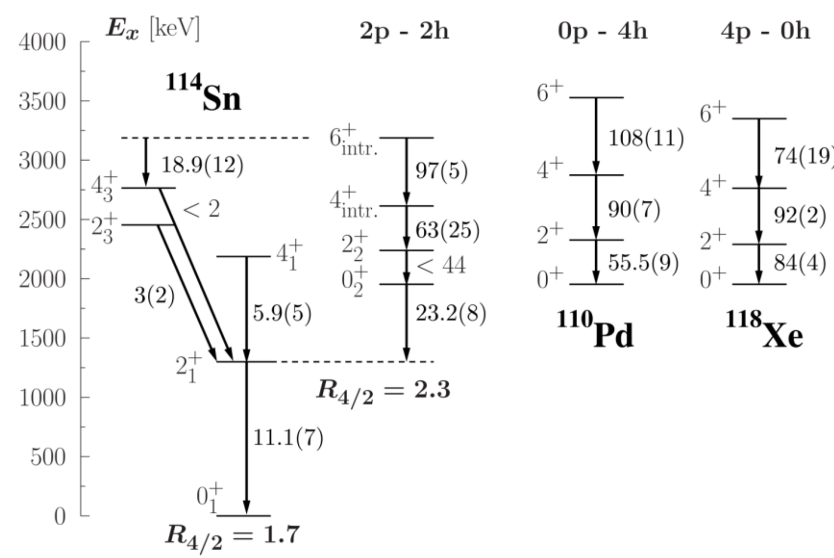
  [S.G. Pickstone *et al.*, NIM **875**, 104 (2017)]

- **Collectivity of low-spin "intruder" states** studied in $^{112,114}Sn$

- **Mixing hypothesis between normal and intruder configuration** tested via schematic IBM-2 mixing calculations

- No clear hints at quadrupole multiphonon structures in $^{112,114}Sn$





[M. Spieker *et al.*, PRC **97**, 054319 (2018)]