The complex picture of neutron-proton pair correlations in N=Z nuclei - an experimentalist's perspective

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Reactions and Spectroscopy of Unstable Nuclei
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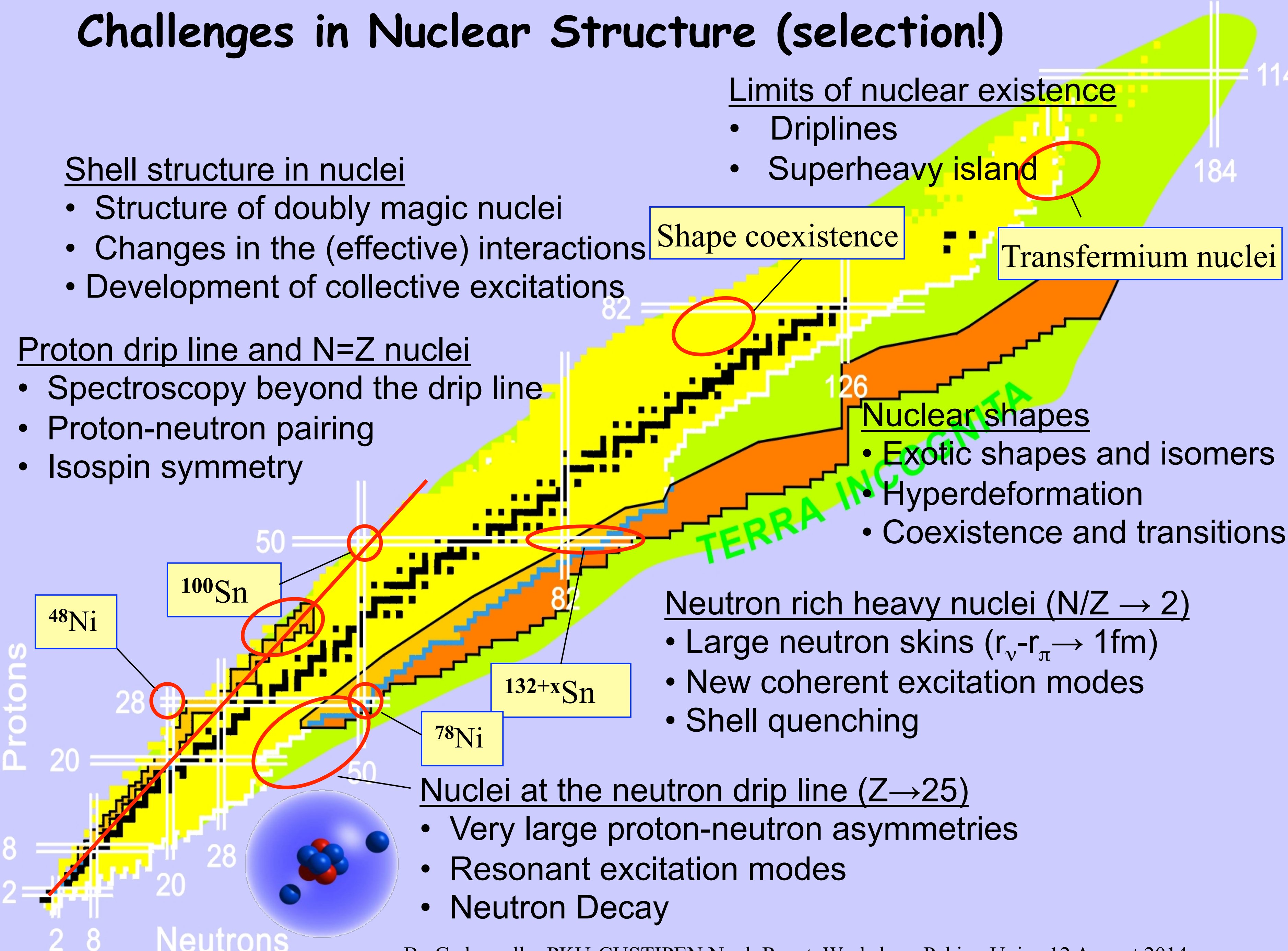
Challenges in Nuclear Structure (selection!)



Limits of nuclear existence

- Driplines
- Superheavy island

Shell structure in nuclei

- Structure of doubly magic nuclei
- Changes in the (effective) interactions
- Development of collective excitations

Proton drip line and N=Z nuclei

- Spectroscopy beyond the drip line
- Proton-neutron pairing
- Isospin symmetry

Nuclear shapes

- Exotic shapes and isomers
- Hyperdeformation
- Coexistence and transitions

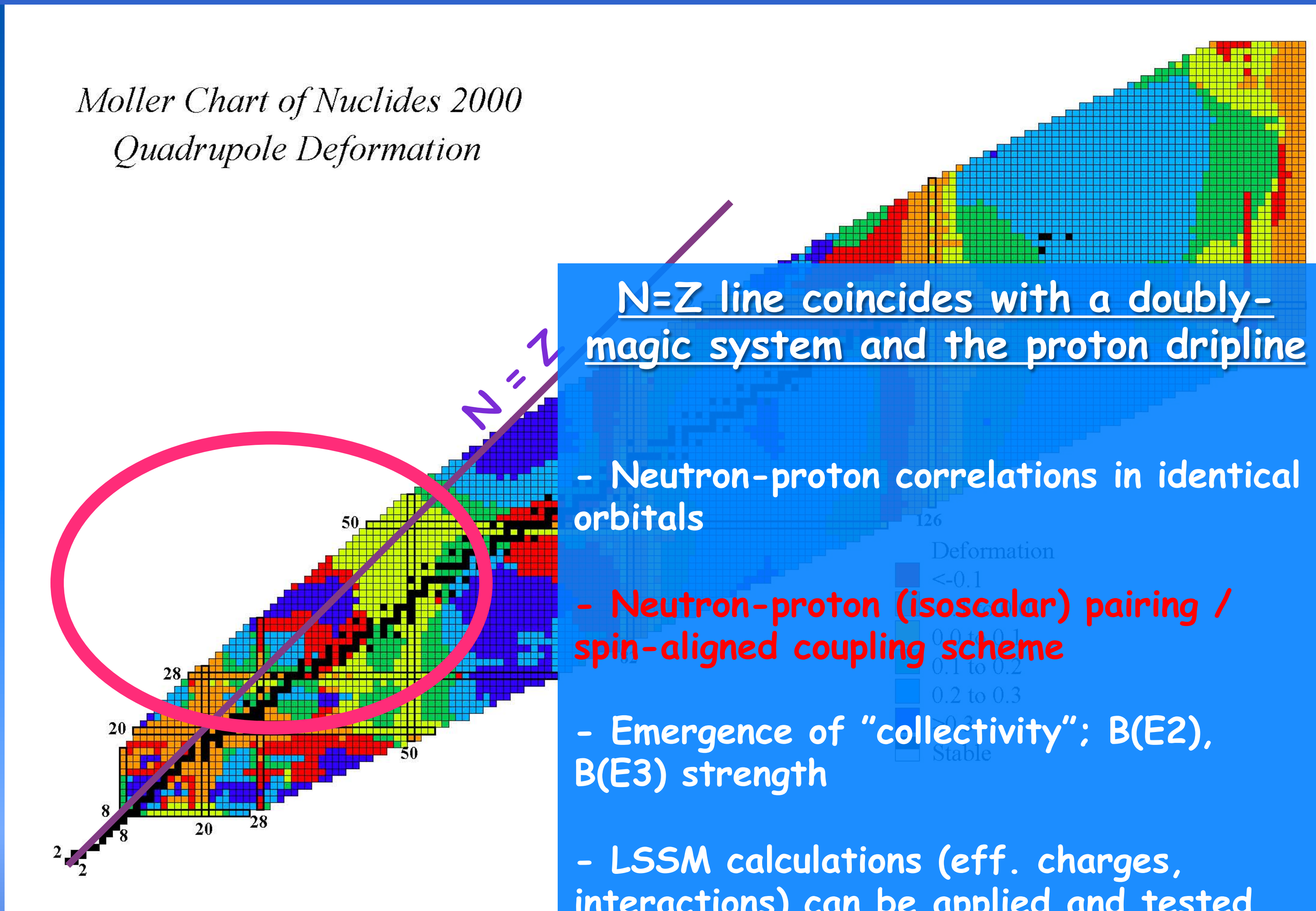
Neutron rich heavy nuclei (N/Z → 2)

- Large neutron skins (r_ν-r_π→ 1fm)
- New coherent excitation modes
- Shell quenching

Nuclei at the neutron drip line (Z→25)

- Very large proton-neutron asymmetries
- Resonant excitation modes
- Neutron Decay

Nuclear structure around ^{100}Sn – near the "top" of the N=Z line



N=Z line coincides with a doubly-magic system and the proton dripline

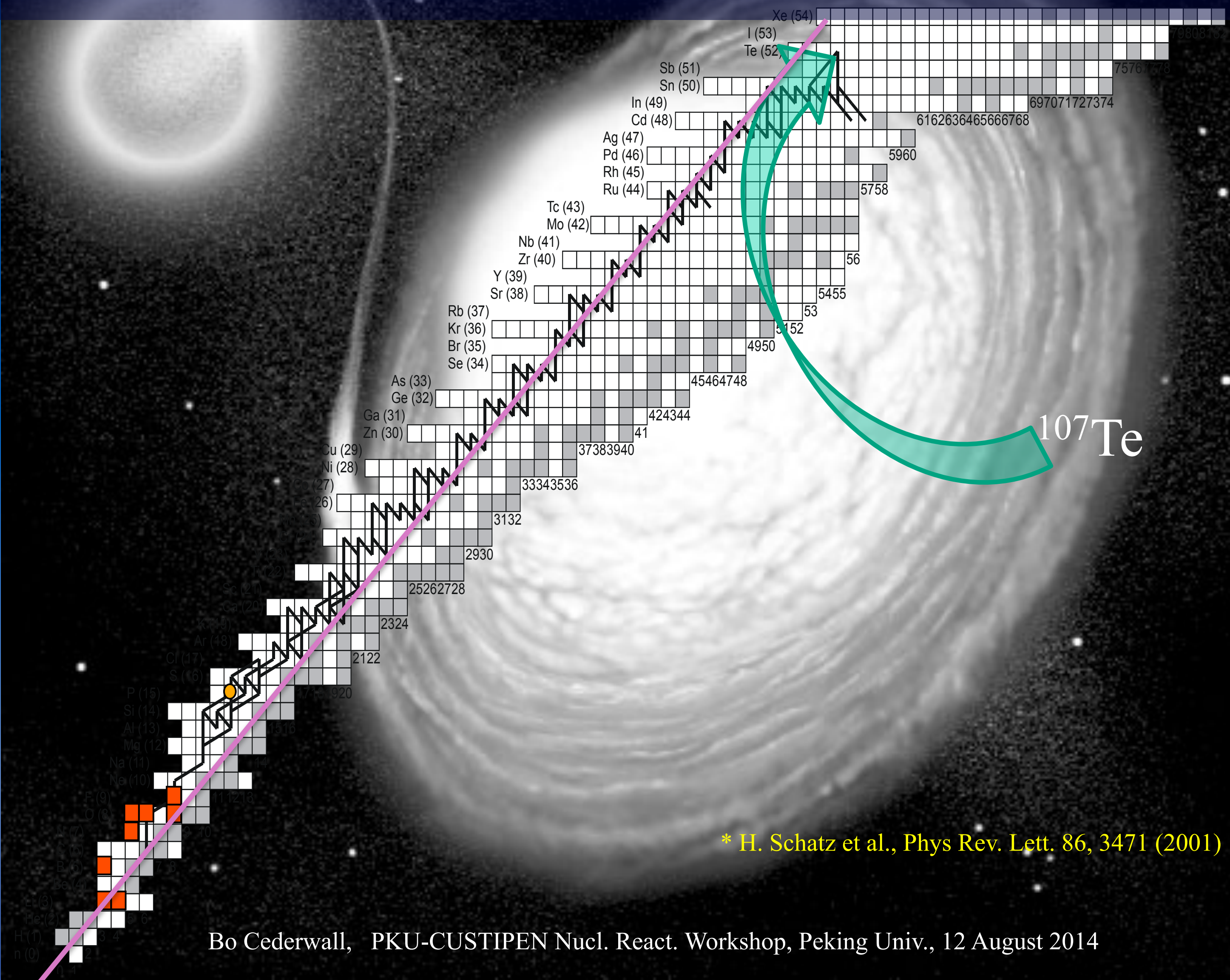
- Neutron-proton correlations in identical orbitals

- Neutron-proton (isoscalar) pairing / spin-aligned coupling scheme

- Emergence of "collectivity"; B(E2), B(E3) strength

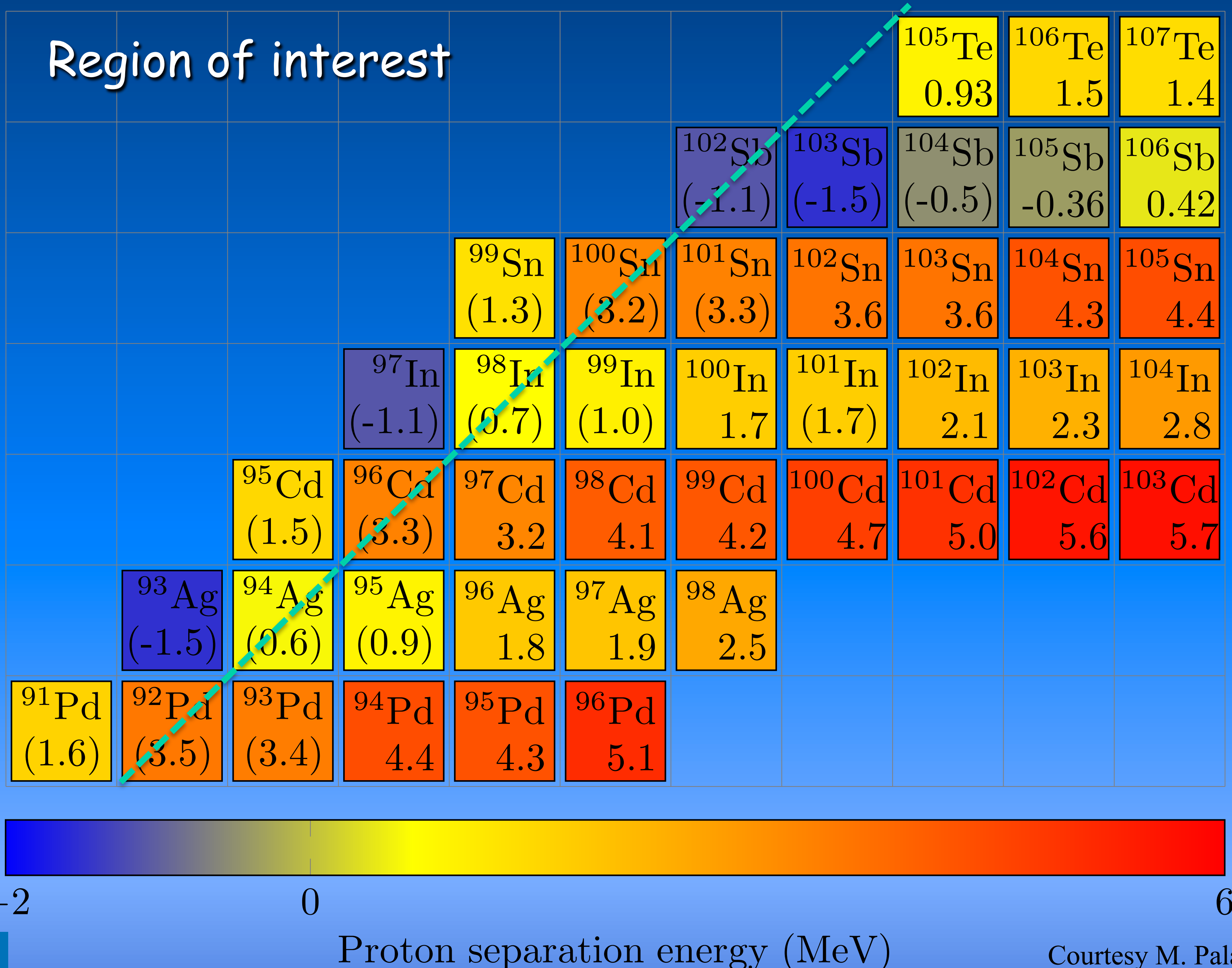
- LSSM calculations (eff. charges, interactions) can be applied and tested

Astrophysical interest:
End point of the rp-process path in X-ray bursts and steady-state hydrogen burning on accreting neutron stars*



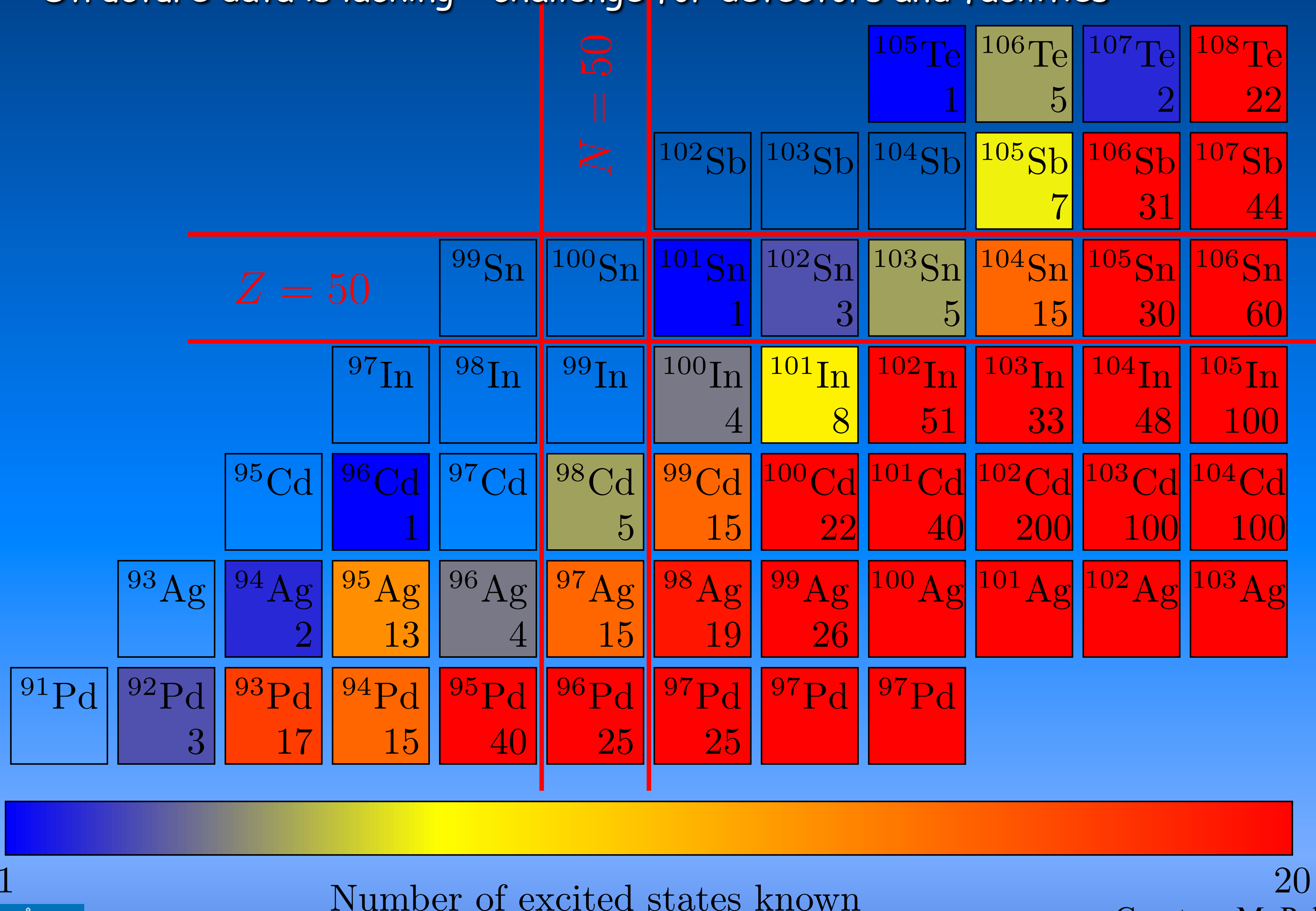
* H. Schatz et al., Phys Rev. Lett. 86, 3471 (2001)

Region of interest



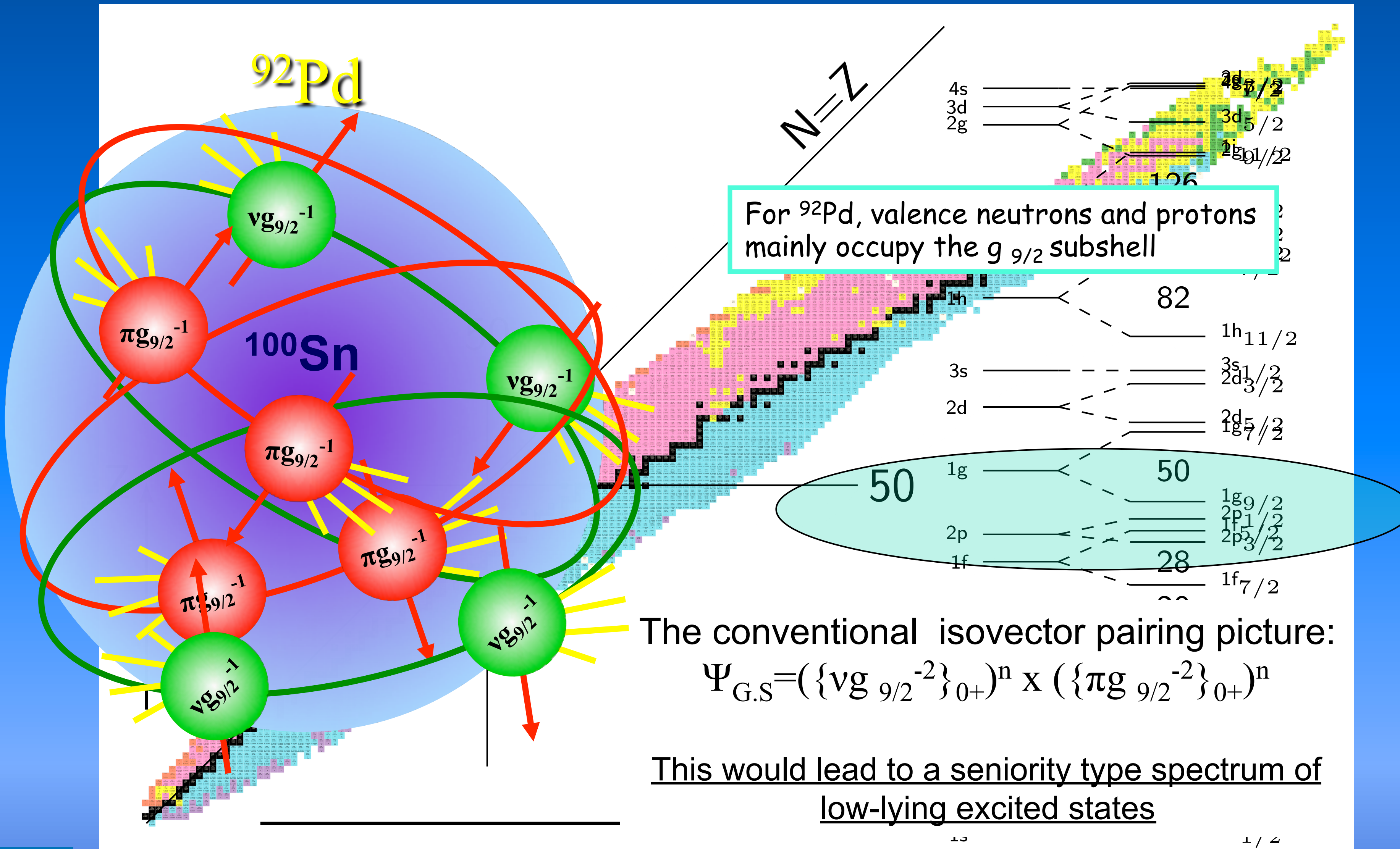
Courtesy M. Palacz

Structure data is lacking – challenge for detectors and facilities



Courtesy M. Palacz

What is the g.s. structure of the heaviest N=Z nuclei?
Spin-aligned isoscalar coupling scheme



For ^{92}Pd, valence neutrons and protons mainly occupy the g $_{9/2}$ subshell

The conventional isovector pairing picture:

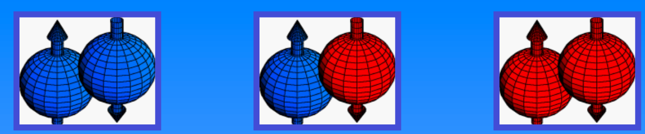
$$\Psi_{G.S}=(\{\nu g_{9/2}^{-2}\}_{0+})^n \times (\{\pi g_{9/2}^{-2}\}_{0+})^n$$

<u>This would lead to a seniority type spectrum of low-lying excited states</u>

What is the nature of nuclear pair correlations near N=Z?
- A long-standing, open question in nuclear structure physics

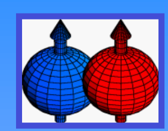
When approaching N=Z, "normal" pair correlations may remain or even be extended as neutrons and protons occupy identical quantum states:

***T*=1, *J*=0 ("isovector") nn, pp**
as well as **np** Cooper pairs (neutrons and protons occupy identical orbits)



$T = 1 \quad J = 0$

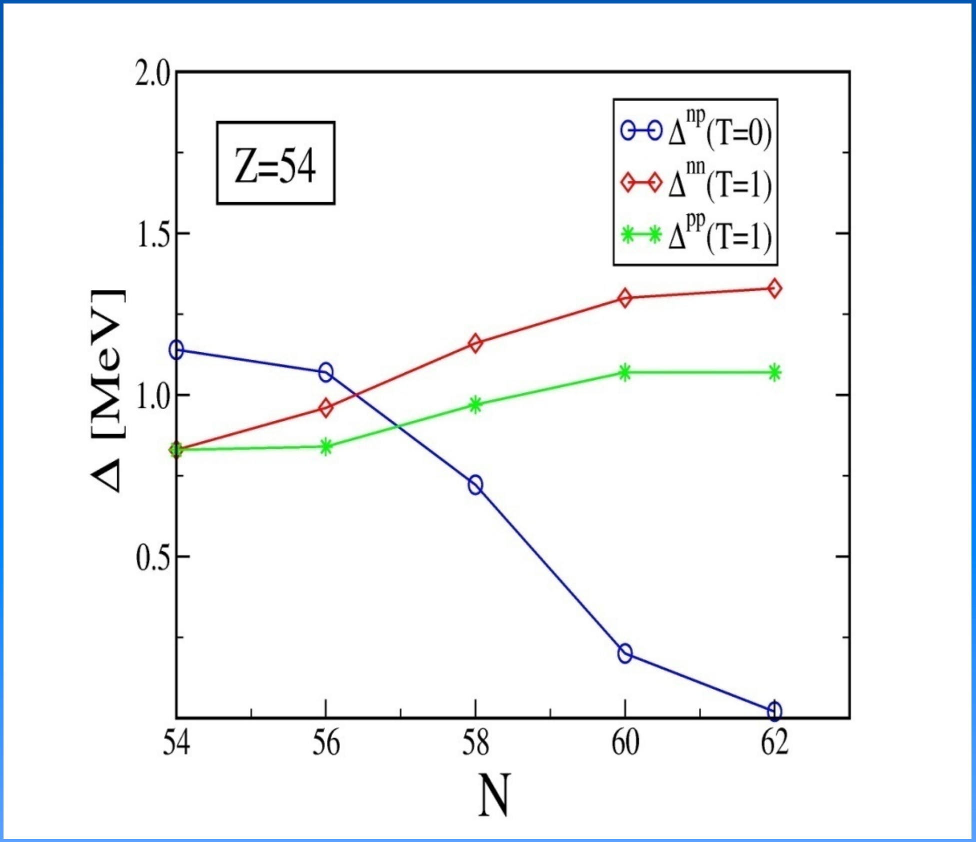
In addition: *T*=0, *J*=1... ("isoscalar") np pairing?



$T = 0 \quad J > 0$

(We know the isoscalar NN interaction is strongly attractive)

The isoscalar (np) pair gap is predicted to increase sharply as N→Z



"Isospin-generalized" BCS-type calculation by W. Satula, R. Wyss
Phys. Rev. Lett. Vol. 86, 4488 (2001)

Does isoscalar (np) pairing *in the BCS sense* exist in Nature?

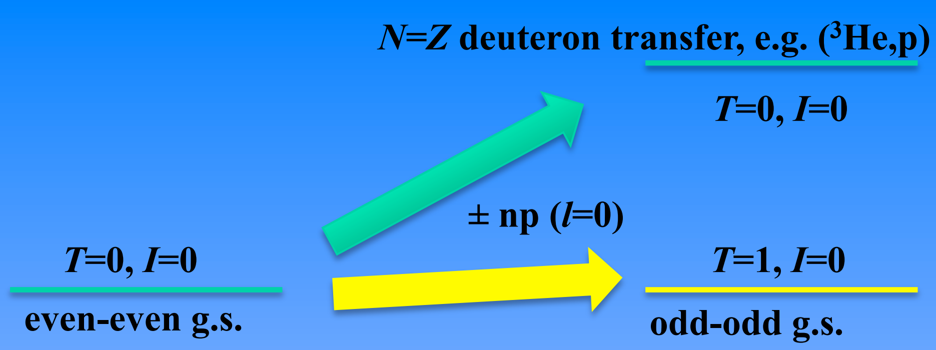
(i.e. can we find an isoscalar pairing "deuteron" condensate somewhere?)

The experimental search for *T*=0 np pairing has focused on special features:

- g.s. binding energies of N=Z (even-even vs odd-odd) nuclei

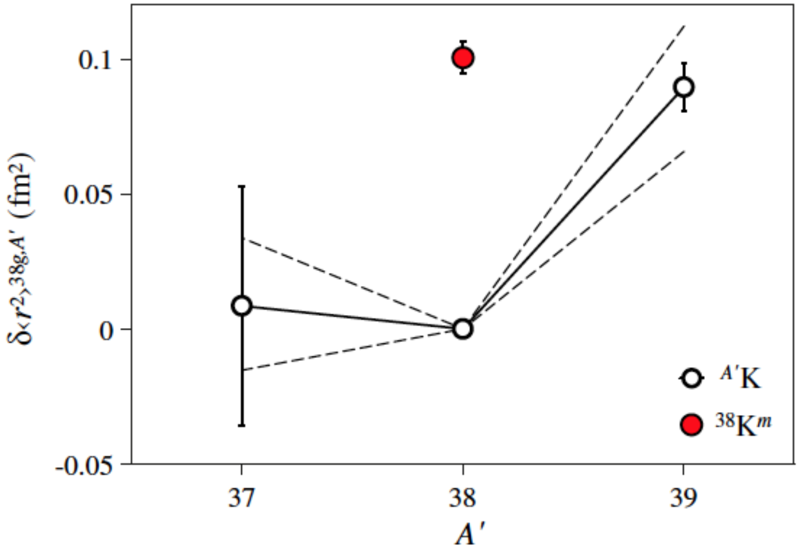
- high-spin properties of N=Z nuclei (reduced CAP, delayed alignments?)

- deuteron transfer reactions: (e.g. measure branching to T=1 and T=0 states in odd-odd N=Z nuclei)
  Need for (reaction) theory to develop sharp predictions.

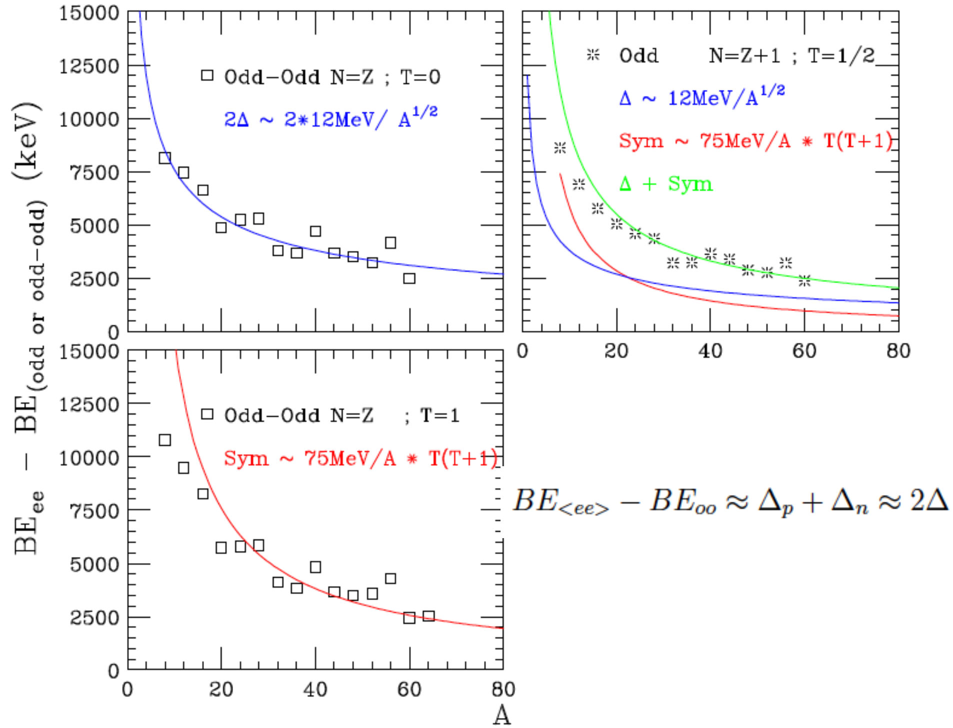


Status: No convincing evidence so far
But much more to be done …

Evidence for *isovector* np pairing is claimed from nuclear binding energies, rotational alignments, charge radii etc



"Proton-Neutron Pairing Correlations in the Self-Conjugate Nucleus ^{38}K Probed via a Direct Measurement of the Isomer Shift", Bissell et al., PRL 113, 052502 (2014) in press



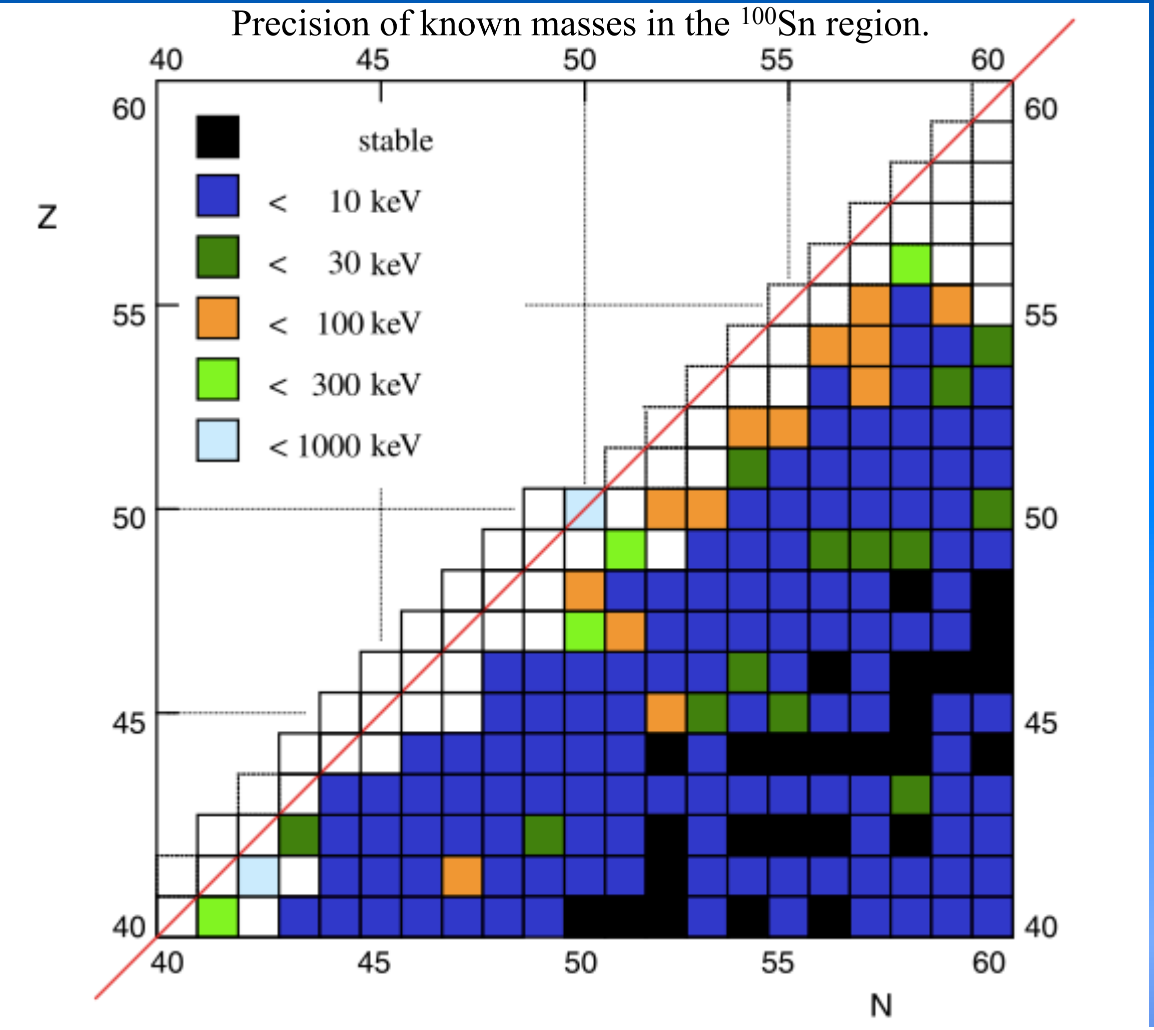
$$BE_{<ee>} - BE_{oo} \approx \Delta_p + \Delta_n \approx 2\Delta$$

Figure 25: Summary of binding energy differences for nuclei along the $N = Z$ line.

Frauendorf and Macchiavelli
arXiv:1405.1652v1 [nucl-th] 7 May 2014

"Excludes" T=0 pairing in g.s
Note: Data end at N=Z≈30
Symmetry energy?

Precison mass data is crucially lacking for N=Z!



T. Faestermann, M. Górska, and H. Grawe, Prog. Part. Nucl.Phys. 69, 85 (2013)

But strong T=0 neutron-proton (np) pair correlations may also lead to something different:

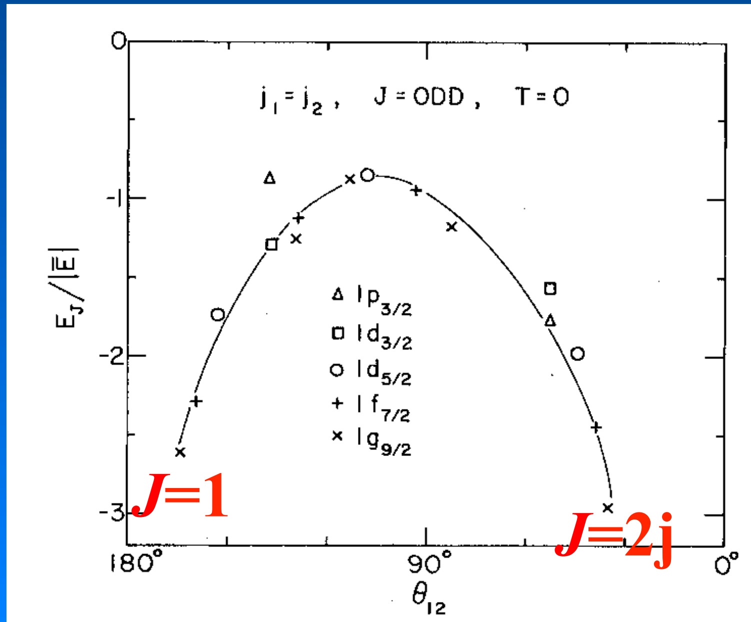
"Isoscalar spin-aligned np coupling scheme" *
predicted for N=Z nuclei close below ^{100}Sn.

- New "paired phase" different from standard (BCS) T=0 np pairing concept
- Unique signature of "vibrational-like" yrast energies and "rotational-like" B(E2) strengths. $B(E2;0^+ \rightarrow 2^+)$s develop differently compared with standard seniority scheme along isotopic chain as N→ Z
- A new manifestation of strong np-pair correlations

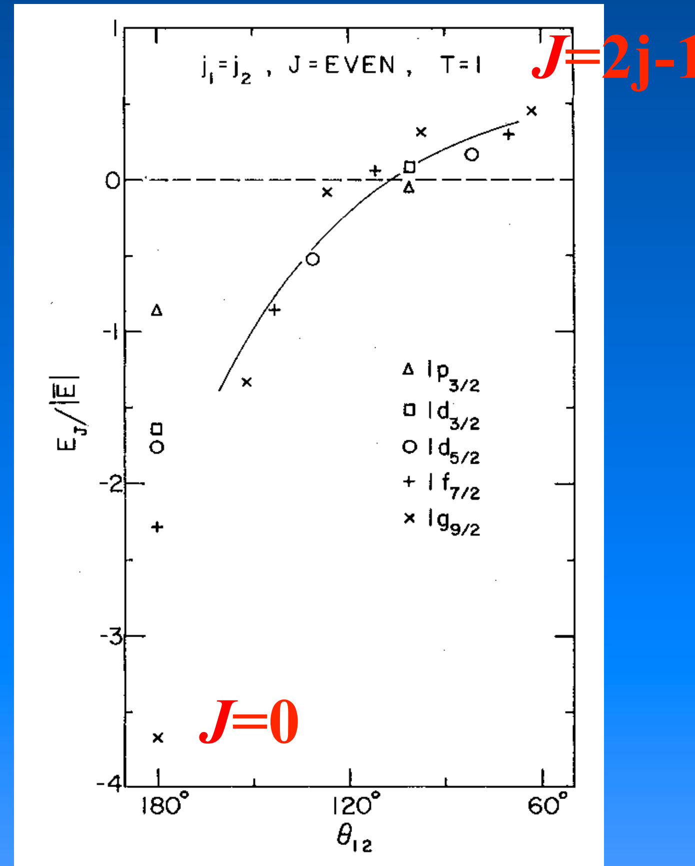
* 'Evidence for a spin-aligned neutron-proton paired phase from the level structure of ^{92}Pd'
B. Cederwall et al., Nature **469**, 68 (2011)

'Spin-aligned neutron-proton pair mode in atomic nuclei'
C. Qi, J. Blomqvist, T. Bäck, B. Cederwall, A. Johnson, R. J. Liotta, and R. Wyss
Phys. Rev. C 84, 021301 (2011)

Effective (residual) interactions between nucleons in a j-shell

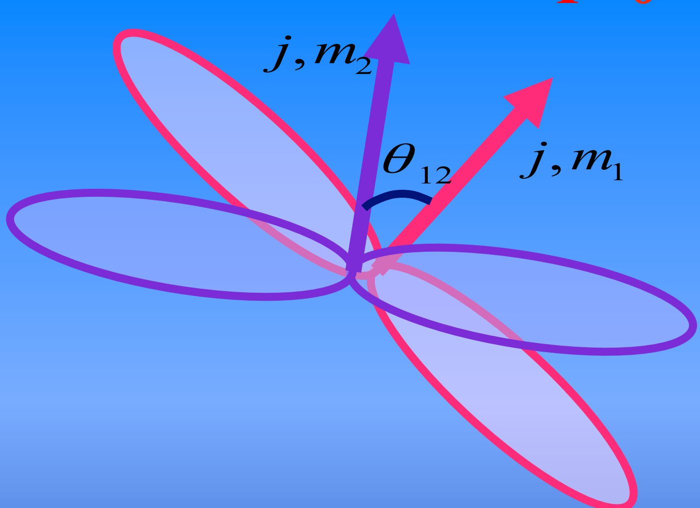


T=0



T=1

$$\cos\theta_{12} = \frac{J(J+1)}{2j(j+1)} - 1$$

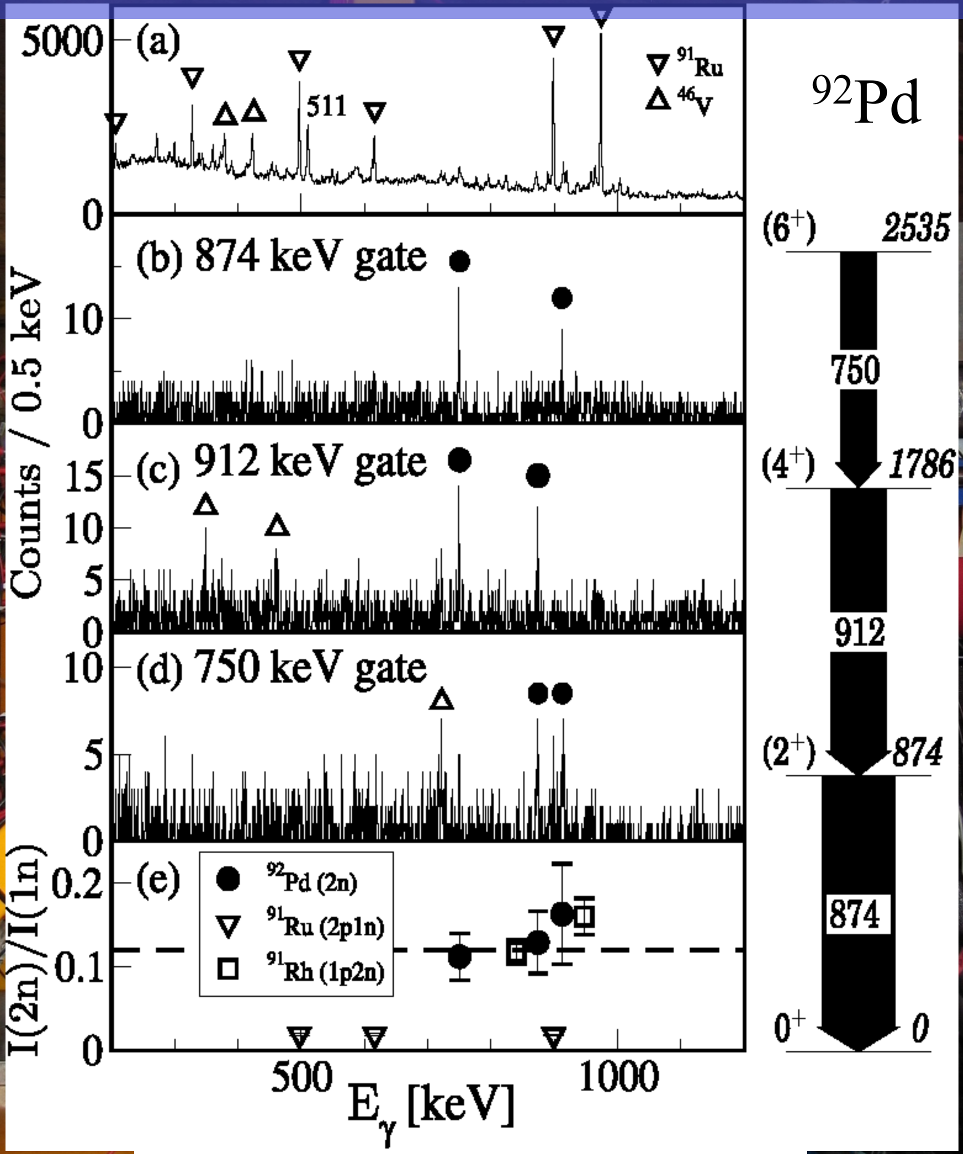


J. P. Schiffer and W. W. True
Rev. Mod. Phys., Vol. 48, No. 2, Part I, April 1976

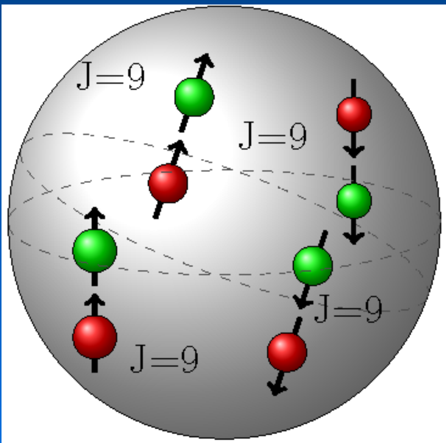
- **effective force between particles ~ <u>orbital overlap</u>**
- **Pauli principle**

Observation of excited states in the N=Z=46 nucleus ^{92}Pd

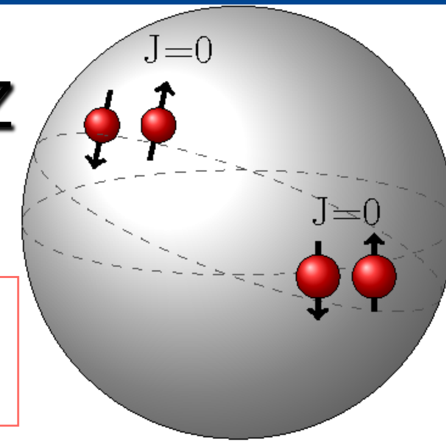
EXOGAM + Neutron Wall + Diamant experiment



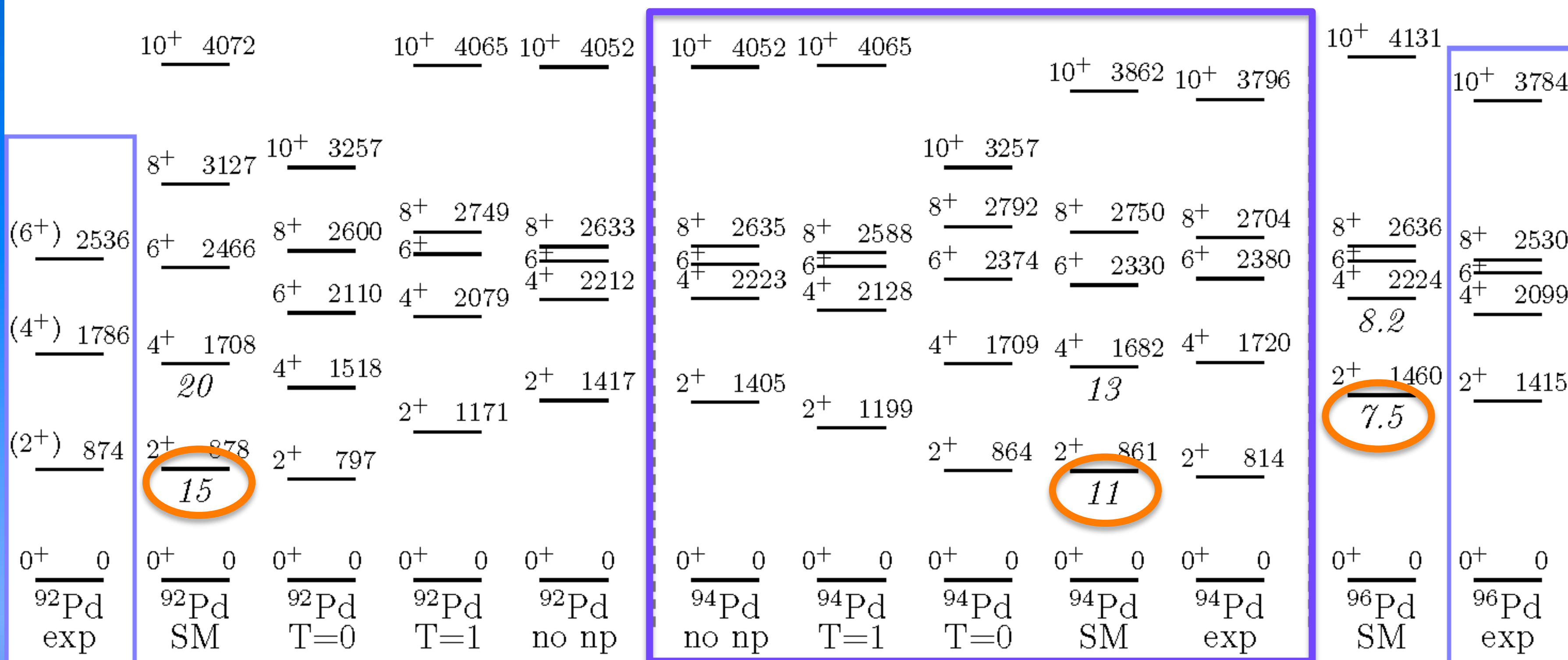
B. Cederwall et al., Nature **469**, 68 (2011)



Pd level systematics near N=Z - effects of np interactions

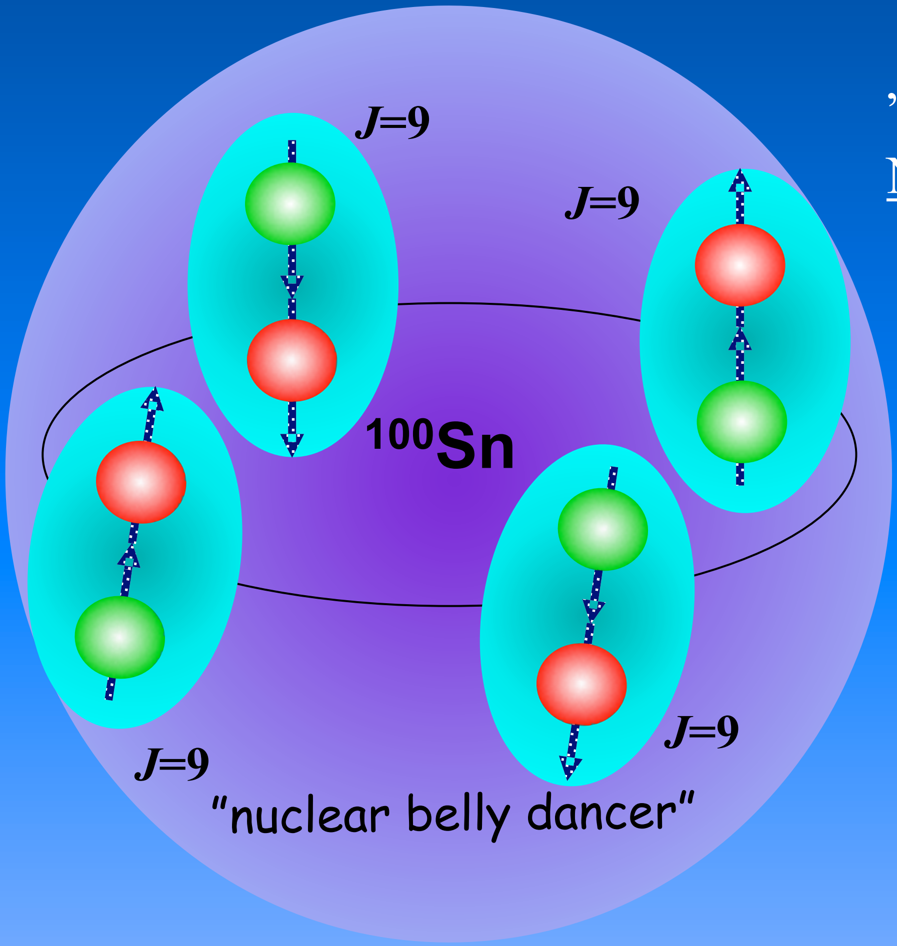


Calculations performed in several model spaces,
i.e., 0g9/2, 0g9/2-1p1/2 and 0g9/2-1p1/2-0f5/2-1p3/2
which all give very similar results .
Int. parameters determined to reproduce exp energies in ^{94,95}Pd, ^{93,94}Rh



B. Cederwall et al., Nature **469**, 68 (2011)

Strong residual np interactions → Spin-aligned T=0 np coupling scheme for N=Z nuclei below ^{100}Sn



"Spin-aligned T=0 np paired phase"

Not pairing as a BCS condensate

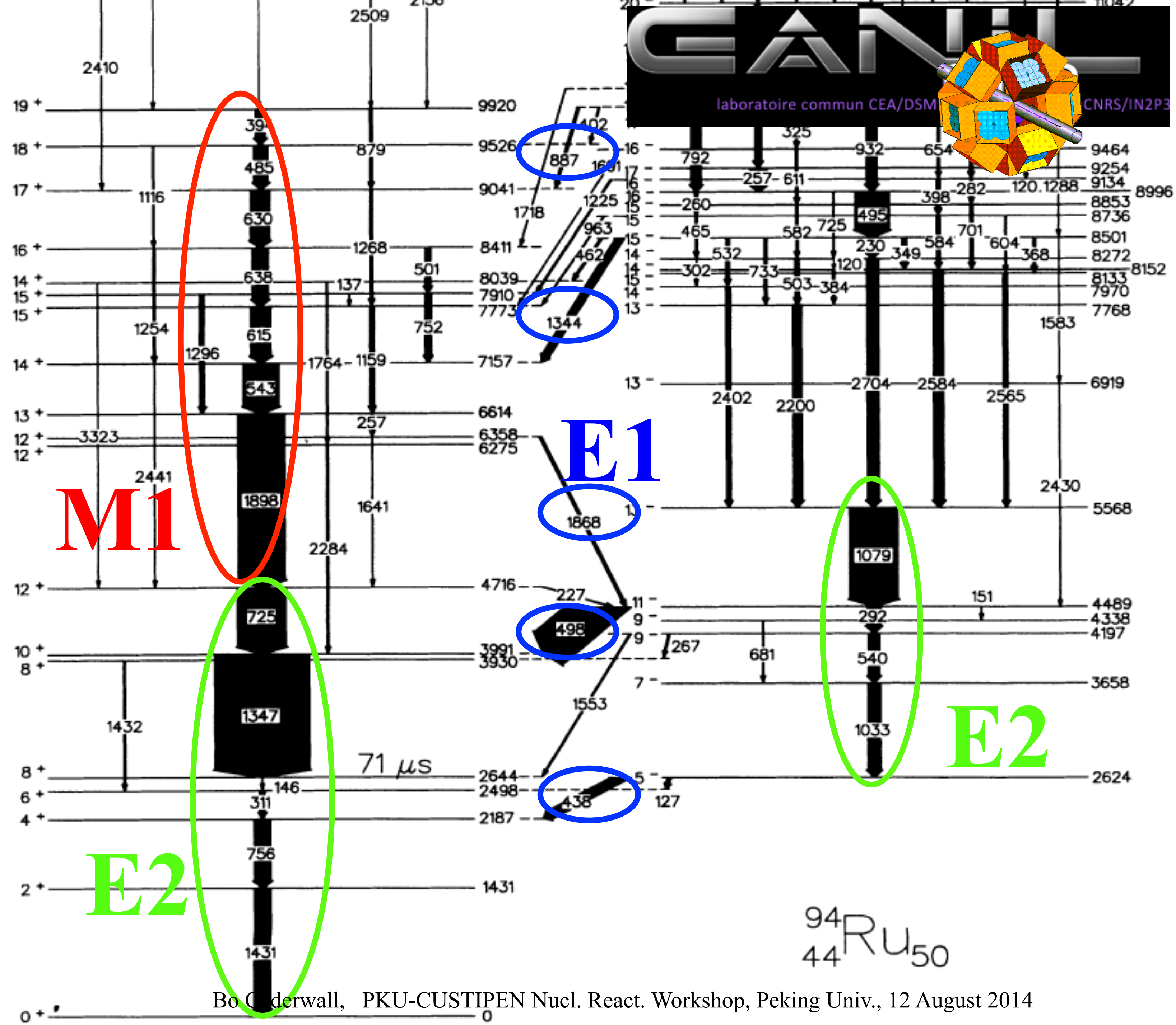
The diagonal SM interaction matrix element that corresponds to the isoscalar $\nu\pi(g_{9/2})^2$ aligned np pair ($J^\pi = 9^+$),
$V_9 = \langle g^2_{9/2}; J=9|V|g^2 9/2; J=9\rangle$,
is strongly attractive, with $V_9 \sim -2$ MeV

Aligned isoscalar np coupling:

$$\Psi_{G.S.}=[(\{\nu g_{9/2}^{-1} \times \pi g_{9/2}^{-1}\}_{9+})^2]_{0+} \times [(\{\nu g_{9/2}^{-1} \times \pi g_{9/2}^{-1}\}_{7+})^2]_{0+}$$

Critical test of LSSM interactions: Precision spectroscopy of E1 transitions in semimagic nuclei

- All low-lying states in this region are well described within the $f_{5/2}$, $p_{3/2}$, $p_{1/2}$ and $g_{9/2}$ model space.
- *E*1 transitions are "forbidden" within this space since the matrix elements $\langle f\,|E1|\,i\rangle$ vanish for all possible combinations of initial states i and final states f.
- Presence of E1 transitions → other (higher or deeper lying) single-particle states are active.
- A sensitive probe: Even a minute admixture of such configurations in the wave function may greatly increase the probability of *E*1 decay since the *E*1 single-particle matrix element is very large in comparison with any other multipole mode.
- The observed *E*1 transition strengths serve as a critical test of the shell-model wave function with respect to the model subspace from which it is constructed. In particular for core excited states.


GANIL
laboratoire commun CEA/DSM
CNRS/IN2P3
M1
E1
E2
E2
71 μs
$^{94}_{44}Ru_{50}$
1898
1347
725
1431
756
1079
1033
1868
1344
887
498
438
9920
9526
9041
8411
8039
7157
6614
6358
6275
4716
3991
3930
2644
2498
2187
1431
0
5568
4489
3658
2624

E1 hindrance factors in N=50 nucleus ^{94}Ru

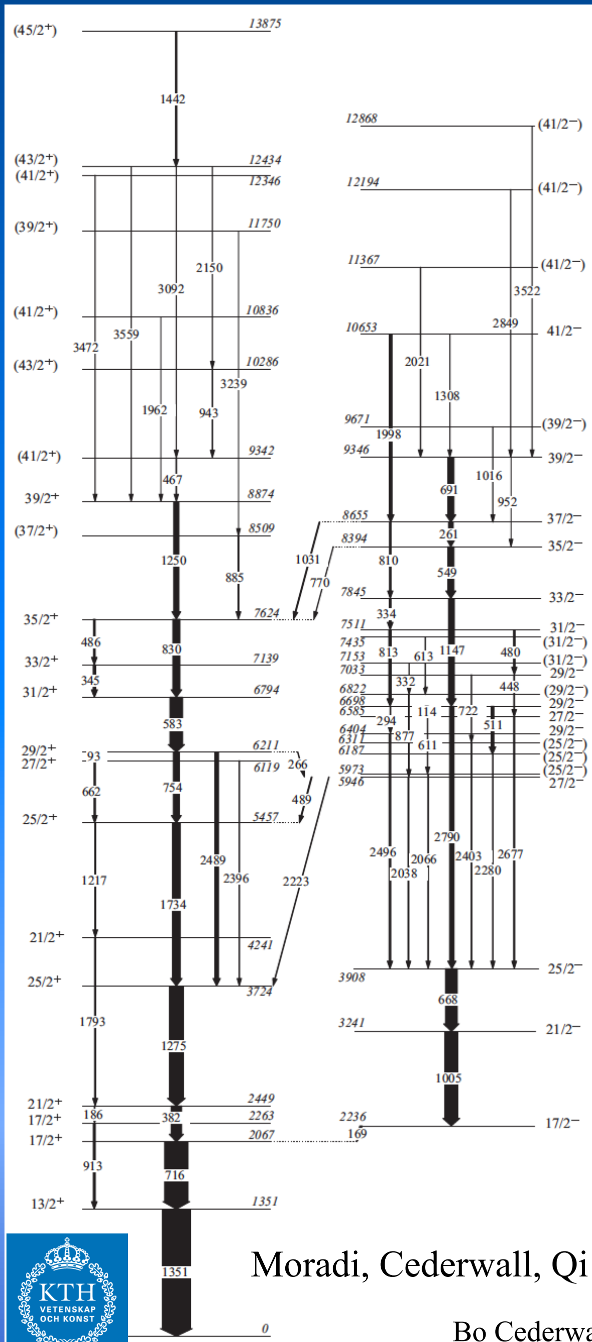
TABLE II. The hindrance factors[a] H for the observed $E1$ γ-ray transitions as deduced from the branching ratios and lifetimes [30] of the initial states. Uncertainties are given in parentheses. $\Delta E_\gamma = \pm 0.5$ keV.

E_γ (keV)	$J_i^\pi \to J_f^\pi$	$H \times 10^5$ (W.u.)$^{-1}$
257	$13^+ \to 12_1^-$	0.006 (1)
462	$15_2^- \to 14_2^+$	0.051 (5)
402	$18_1^- \to 18^+$	0.188 (25)
1344	$15_2^- \to 14_1^+$	0.451 (32)
227	$12_1^+ \to 11^-$	0.57 (27)
887	$18_1^- \to 17^+$	1.09 (12)
438	$5^- \to 4^+$	1.90 (17)
498	$11^- \to 10^+$	4.27 (19)

[a] $H = \frac{A^{2/3}}{15.5 \times B(E1)}$.

Moradi, Qi, Cederwall et al., PRC, 014301 (2014)

E1 hindrance in ^{95}Rh



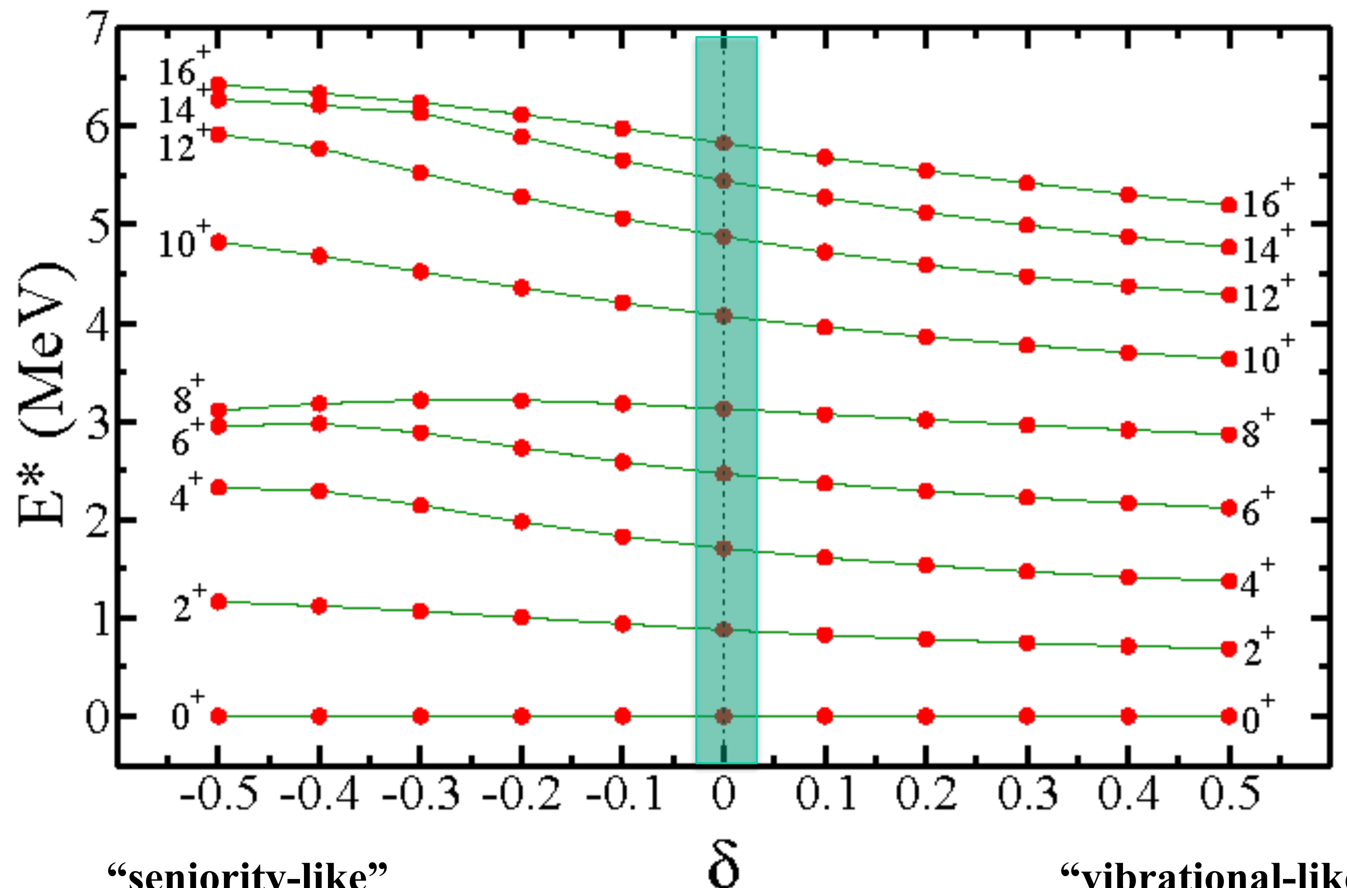
E_γ (keV)	$J_i^\pi \rightarrow J_f^\pi$	$H \times 10^5$ (W.u.)$^{-1}$
266	$29/2^+ \rightarrow 27/2^-$	0.11(1)
1031	$37/2^- \rightarrow 35/2^+$	0.29(1)
770	$35/2^- \rightarrow 35/2^+$	0.35(1)
169	$17/2^- \rightarrow 17/2_1^+$	2.8(2)

$^{a}H = \frac{A^{2/3}}{15.5 \times B(E1)}$

Table II of this work, there are a number of weak $E1$ transitions present, even at low excitation energies (below 5 MeV). We evaluated all possible $E1$ transitions among states within the expanded shell model space. Considering first the $E1$ decay from the first $17/2^-$ state to the yrast $17/2_1^+$ state, these states are predominantly of $\pi(1p_{1/2}^{-1}0g_{9/2}^{-4})$ and $\pi(0g_{9/2}^{-5})$ character, respectively, as discussed above; i.e., without possibility of $E1$ decay. This transition has the largest hindrance, 2.8×10^5 W.u.$^{-1}$ among the $E1$ decays observed in ^{95}Rh which is reflected by the long (∼19 ns) half-life of the $17/2^-$ state [2]. The core-excitation components in these two states are mainly of a one-neutron character. In our calculation the contribution to the transition in terms of occupation probability from the high lying shells $1d_{5/2}$ and $0g_{7/2}$ is 0.02, while the corresponding contribution from the deep-lying shells $1p_{3/2}$ and $0f_{5/2}$ is approximately 10^{-4}. Therefore the $E1$ hindrance factor is of the order 5×10^5 W.u.$^{-1}$, which is consistent with the value given in Table II. The absence of $E1$ transitions depopulating the following negative-parity states up to $25/2^-$ indicates that the influence of the core excited configurations is limited in these states as predicted in Ref. [8]. $E1$ decays observed from the higher-lying negative-parity states as well as from the $29/2_1^+$ state signal significant contributions from core-excited configurations with one neutron being excited from below the $N = 50$ shell closure to the $1d_{5/2}$ or $0g_{7/2}$ orbits, in agreement with the calculations presented in Ref. [20].

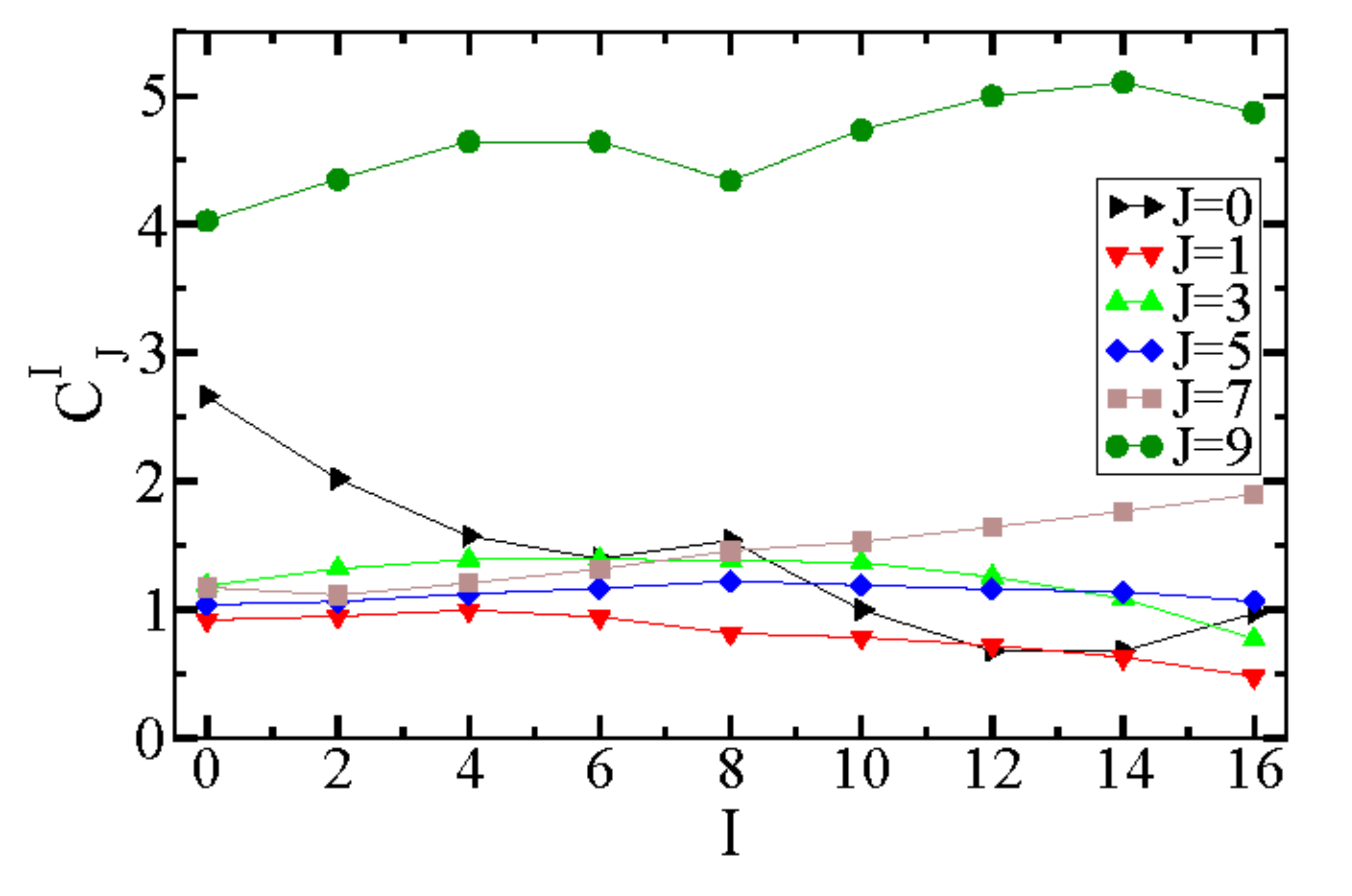
Moradi, Cederwall, Qi et al., PRC, 044310 (2014)

Exposing the $\pi\nu((g_{9/2})^2)_{9^+}$ interaction



"seniority-like" **"vibrational-like"**

Shell model spectrum of ^{92}Pd calculated in the $1p_{1/2}0g_{9/2}$ space as a function of a controlling parameter , i.e., (we take as interaction matrix element the value V9(δ) = V9(1 + δ)
C.Qi, J.Blomqvist, T.Bäck, B. Cederwall, A. Johnson, R. J. Liotta, and R. Wyss, PRC 84, 021301(R) (2011)

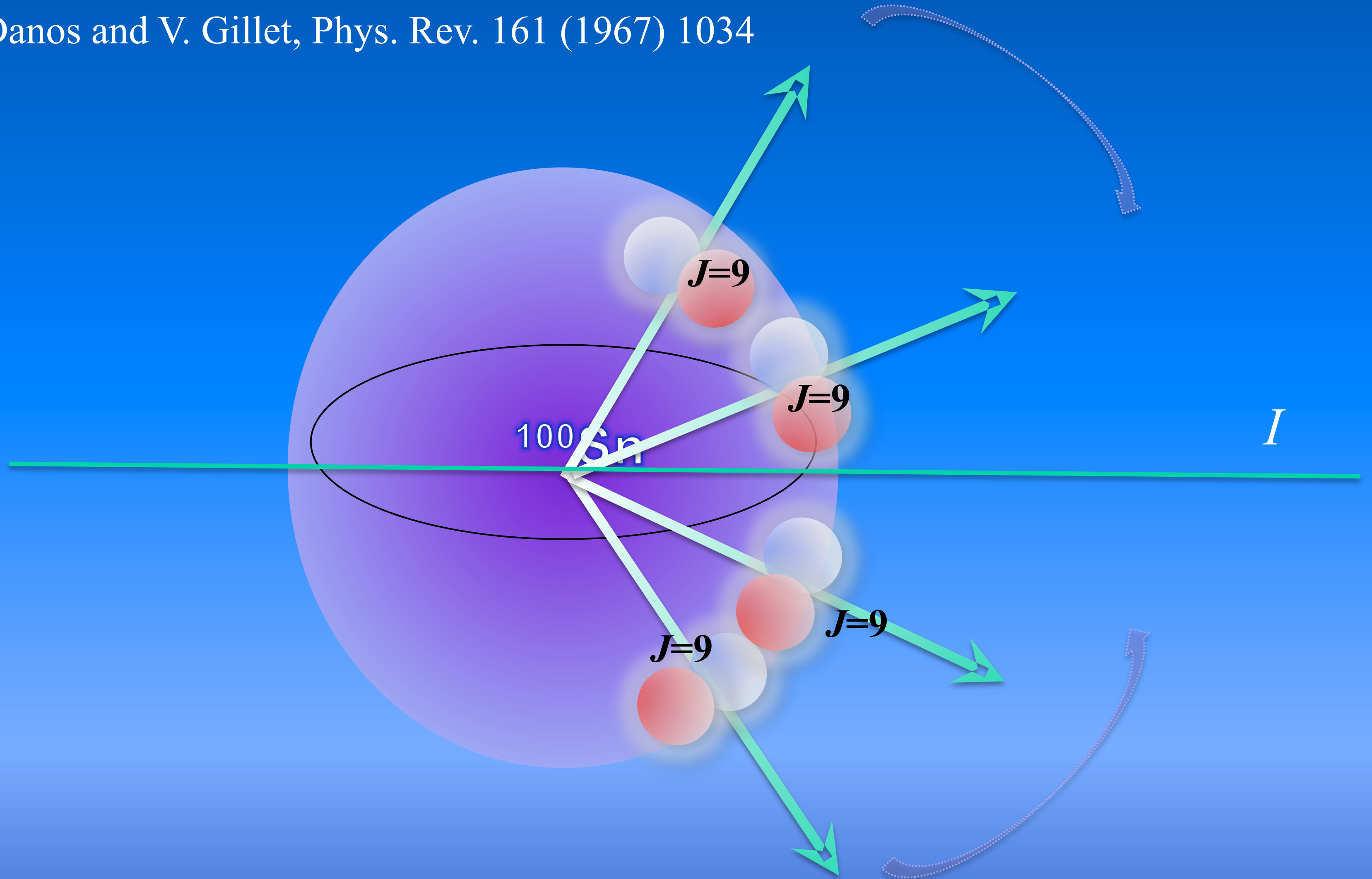


Average number of $(0g^2_{9/2})$J pairs,C^I_J, as a function of spin I for the wave functions of the yrast states of ^{92}Pd.
C.Qi, J.Blomqvist, T.Bäck, B. Cederwall, A. Johnson, R. J. Liotta, and R. Wyss, PRC 84, 021301(R) (2011)

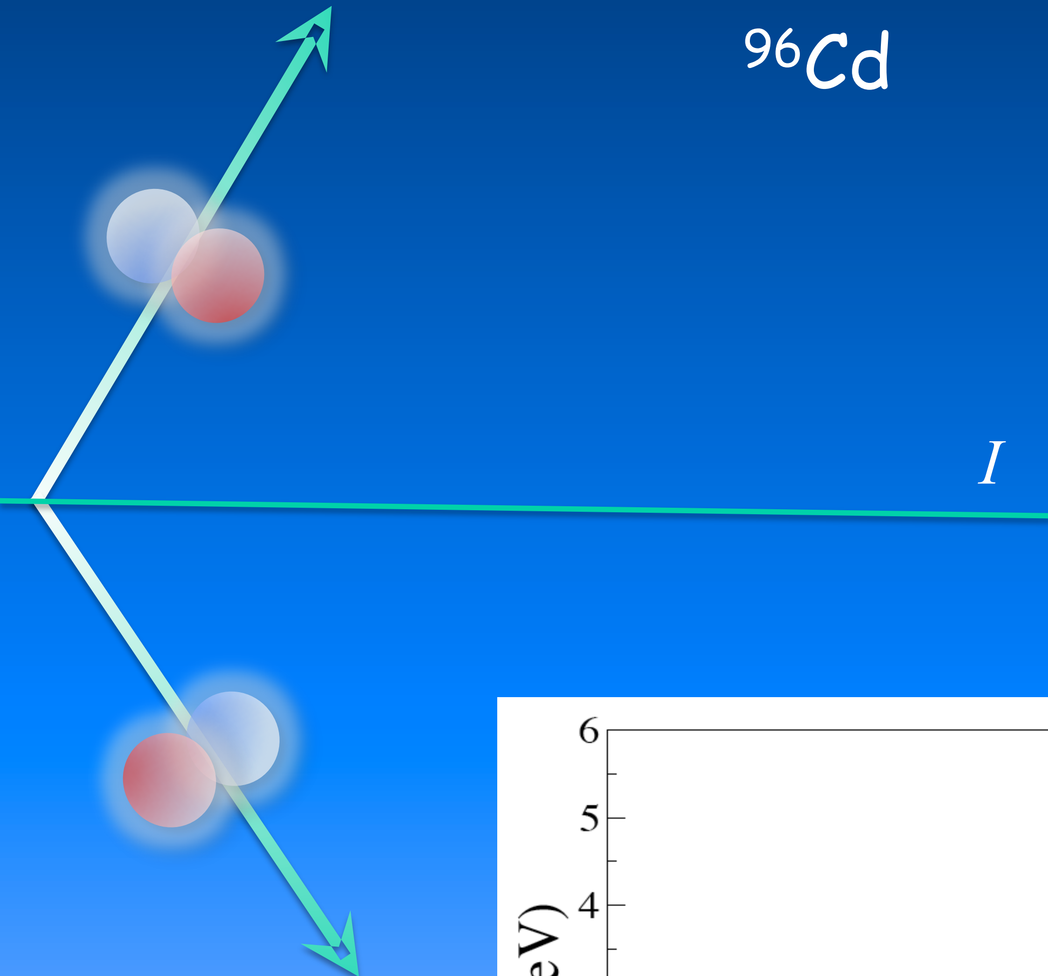
Generation of angular momentum in the isoscalar spin-aligned coupling scheme (^{92}Pd)

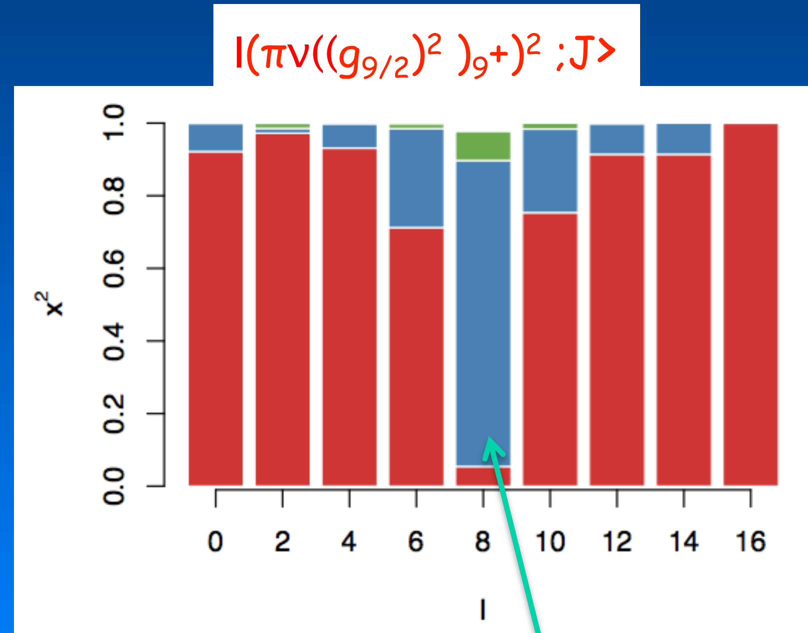
Similarities with "stretch scheme"

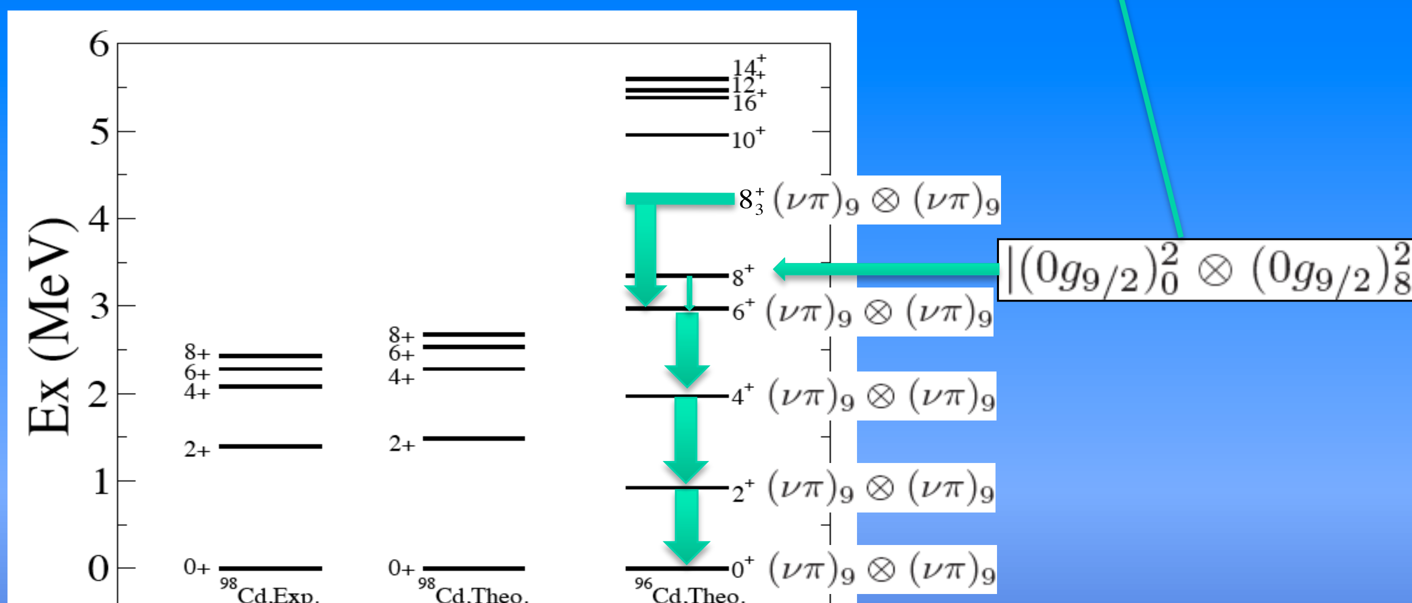
M. Danos and V. Gillet, Phys. Rev. 161 (1967) 1034



^{96}Cd





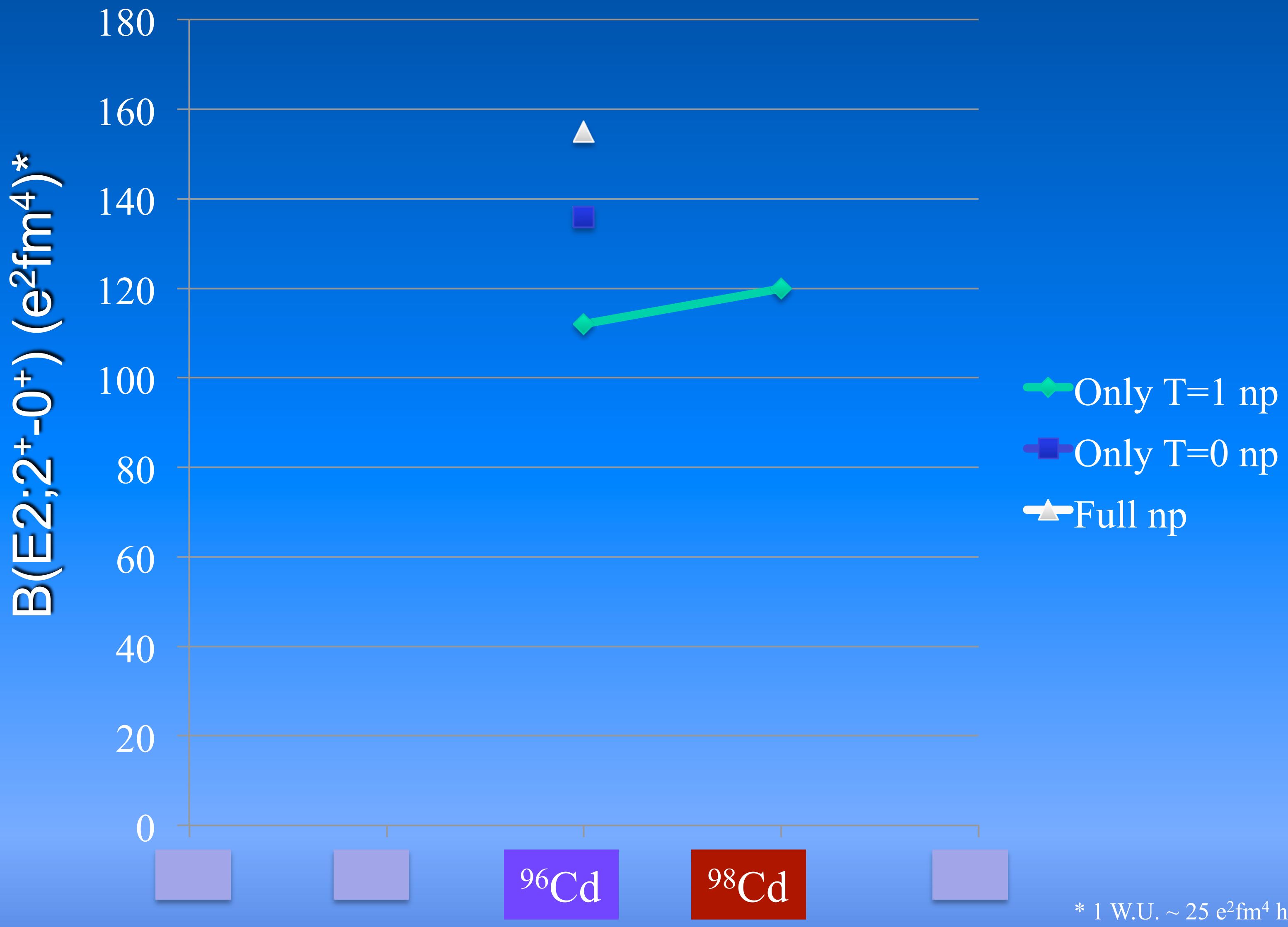


C. Qi, priv. comm., Z.X. Xu et al., Nuclear Physics A 877 (2012) 51–58

LSSM calculation, fpg (f5/2, p3/2,p1/2, g9/2) (all shells between 28 and 50) C. Qi

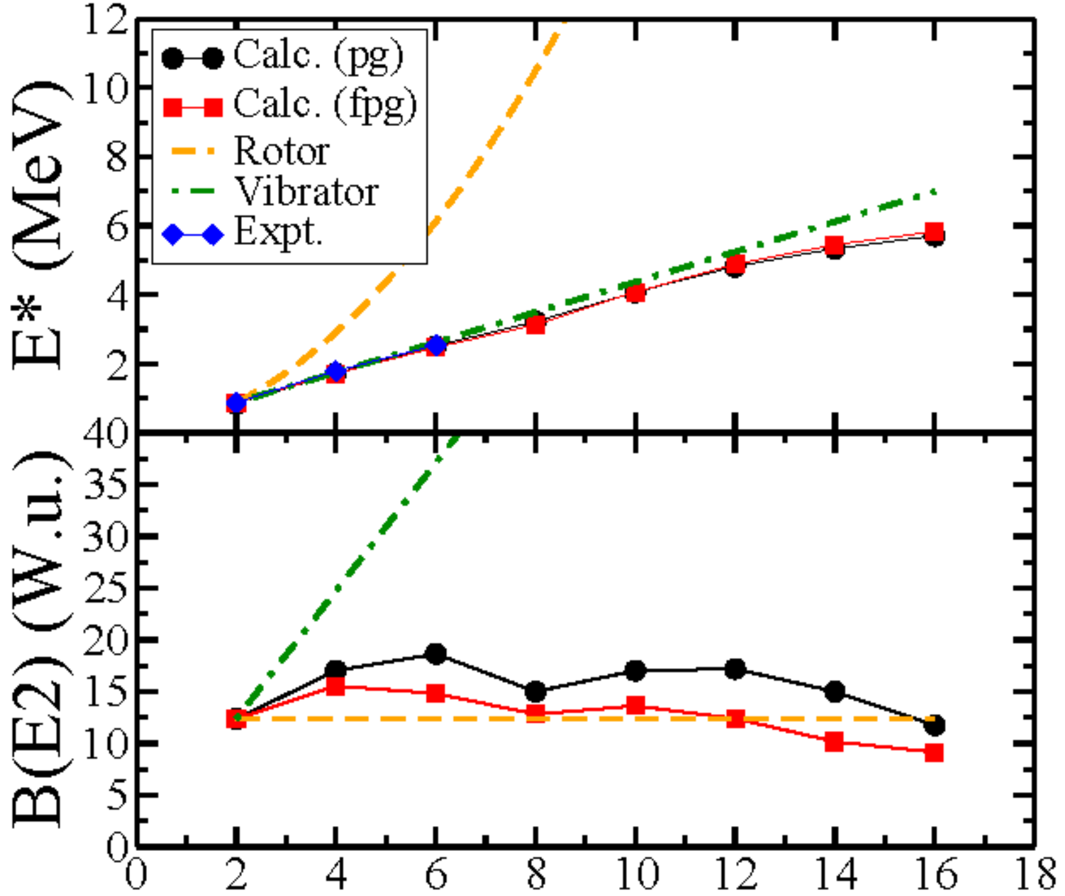
* 1 W.U. ~ 25 e^2fm^4 here

LSSM calculation, fpg (f5/2, p3/2,p1/2, g9/2) (all shells between 28 and 50) C. Qi



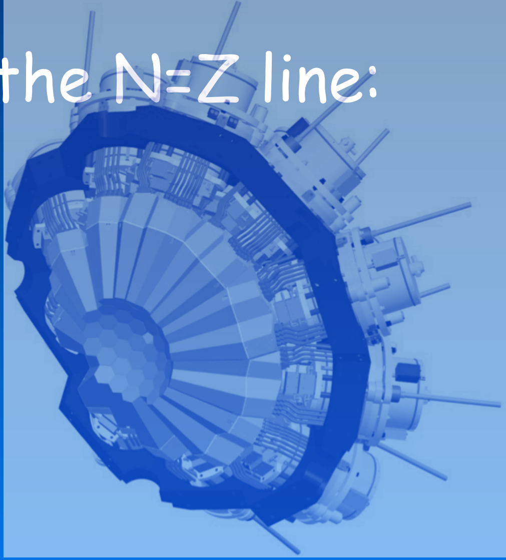
* 1 W.U. ~ 25 e^2fm^4 here

“Unique” signature of spin-aligned T=0 coupling scheme



Upper: Shell model spectra of ^{92}Pd
calculated within the $1p_{3/2}0f_{5/2}1p_{1/2}0g_{9/2}$ space [10] (fpg) and the $1p_{1/2}0g_{9/2}$ space (pg).
Lower: B(E2; I → I − 2) values in ^{92}Pd calculated within the fpg and pg spaces. The two dashed lines show the predictions of the geometric collective model normalized to the 2^+_1 state
C.Qi, J.Blomqvist, T.Bäck, B. Cederwall, A. Johnson, R. J. Liotta,
and R. Wyss, PRC 84, 021301(R) (2011)

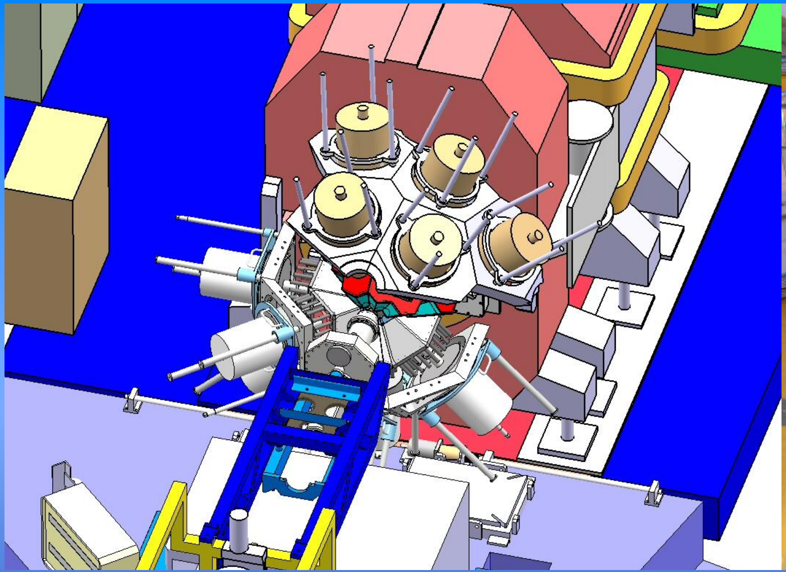
Experimental opportunities at the end of the N=Z line:



AGATA @ GANIL (until now, EXOGAM) …
- RDT/RDDS using VAMOS in gas-filled mode
- L.E. Coulex
- Spectroscopy
- np-transfer

RIKEN (DALI2+ZDS) ?
AGATA-HISPEC @ FAIR
- H.E. Coulex, knockout

Theory: Need sharper predictions for reactions & structure



Thank You