Mass Measurements and Nuclear Structure: Isolating Key Physics

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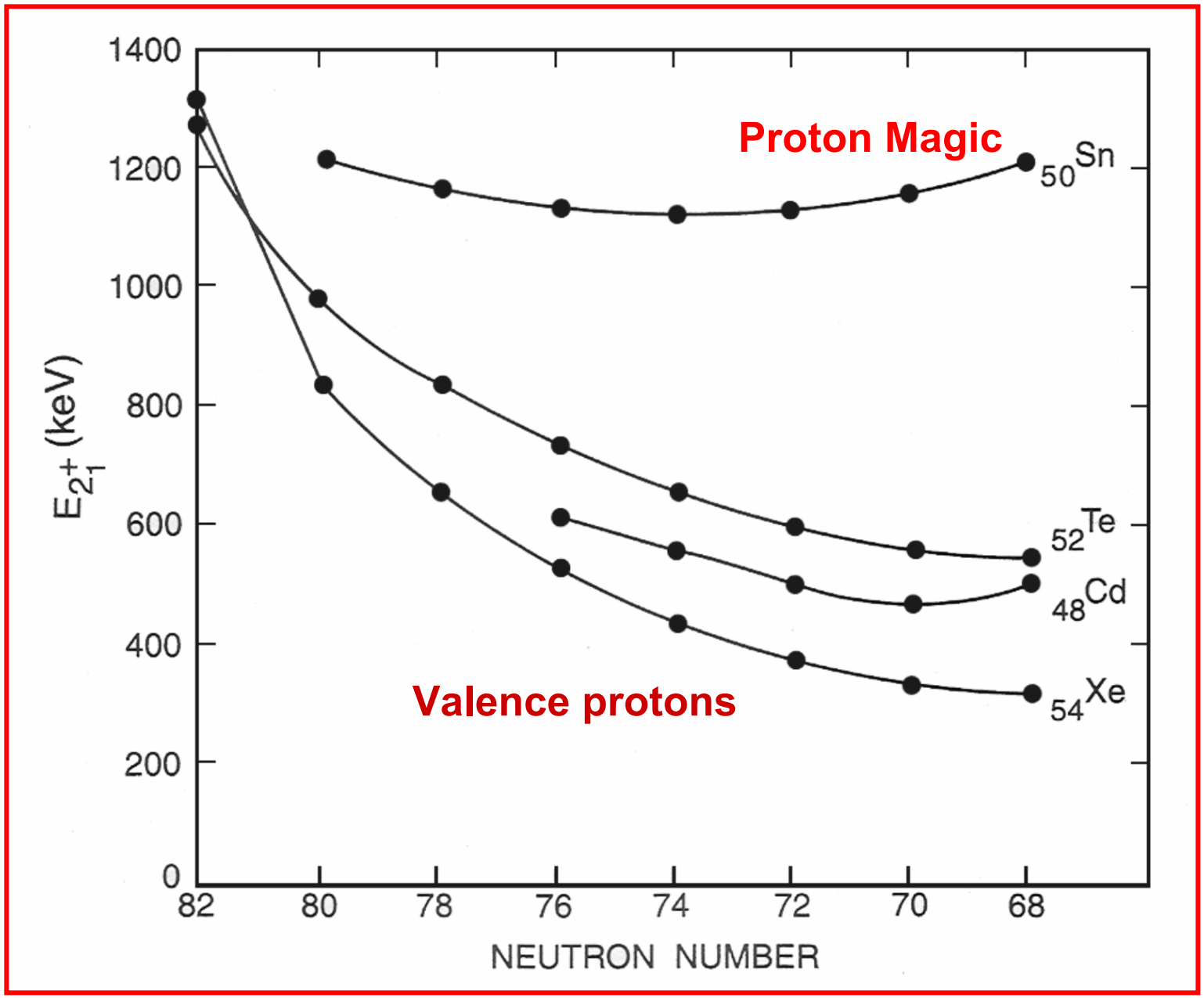
The Valence Proton-Neutron Interaction A Key to the Evolution of Structure and Collectivity

Microscopic origins of phase transitional behavior

Changes in single particle energies, magic numbers and shell structure – Monopole p-n

Growth and growth rates of configuration mixing, collectivity, and deformation

Valence p-n interactions--key to collectivity



Can we *measure* the p-n interaction?

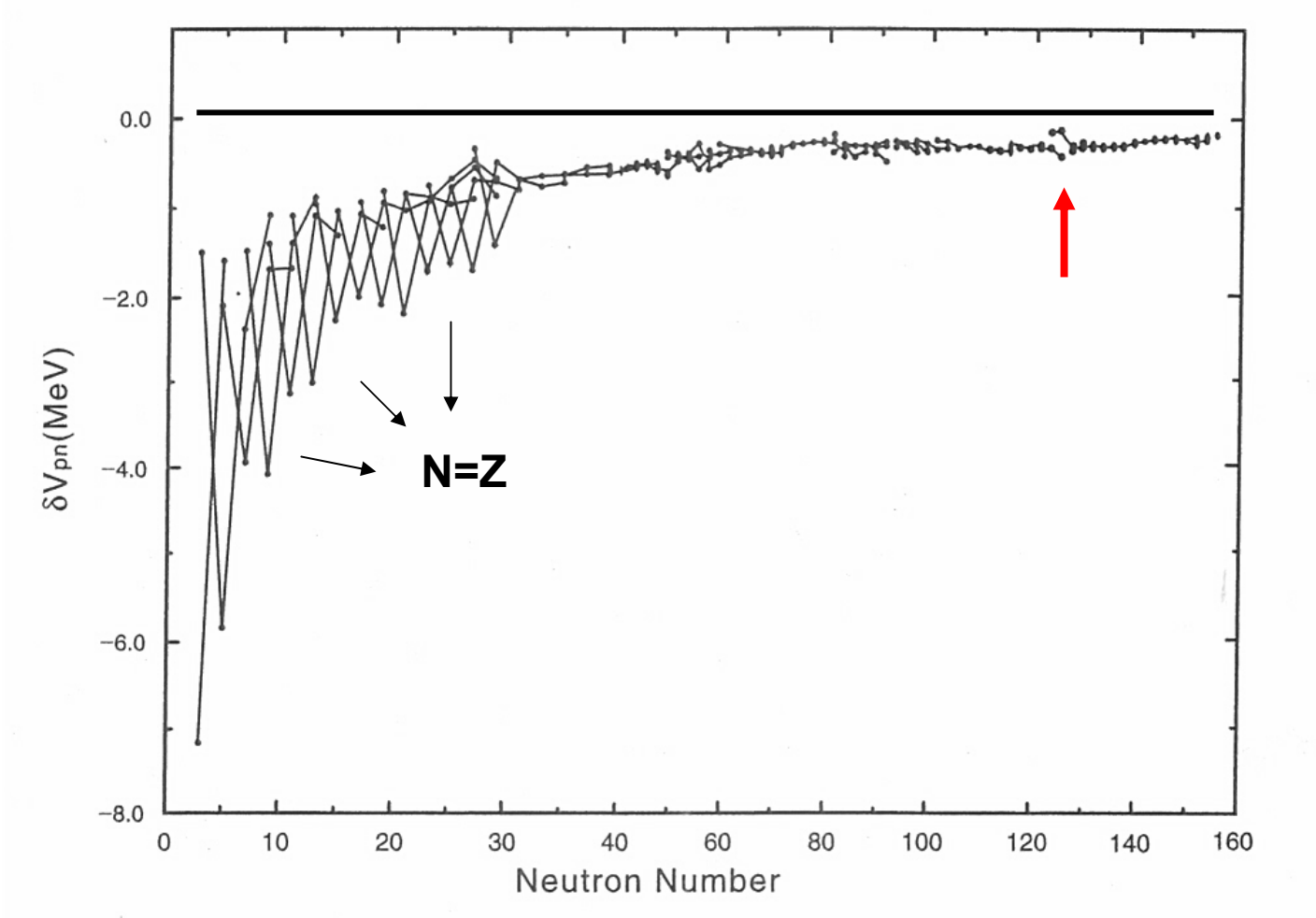
Empirical average *p-n* interaction of the last proton and neutron — δV_{pn}

Double difference of binding energies

$$\delta V_{pn}(Z,N) = \tfrac{1}{4}\,[\,\{B(Z,N) - B(Z,N-2)\} - \{B(Z-2,N) - B(Z-2,N-2)\}\,]$$

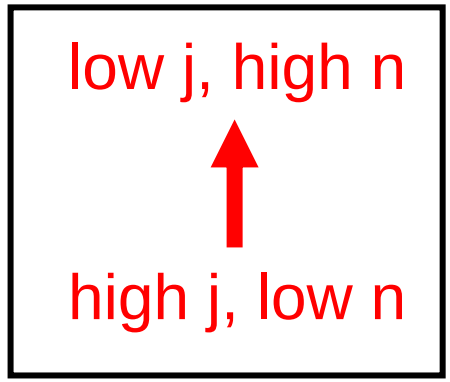
- studied about 15 years ago
- with new 2003 Mass evaluation, many more masses available and hence δV_{pn} values.

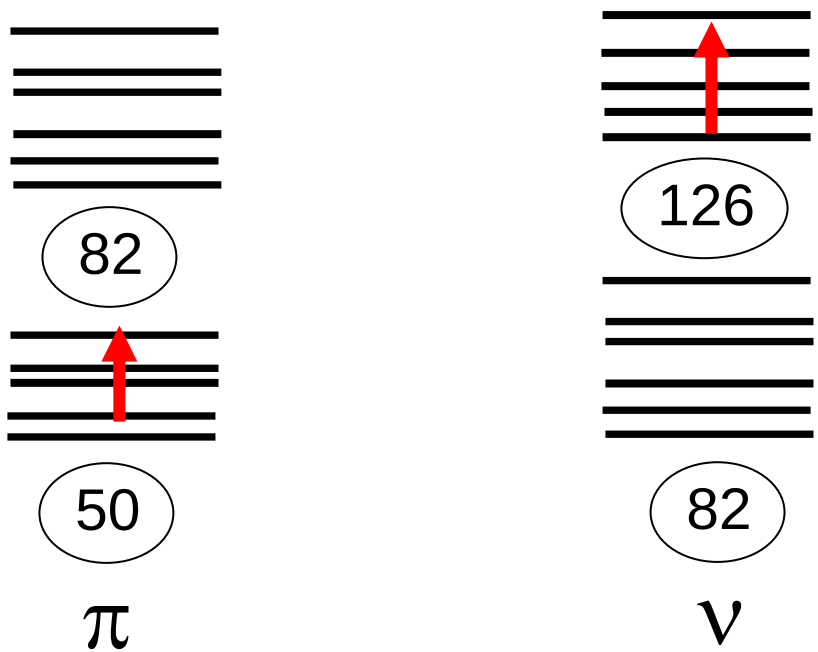
Empirical interactions of the last proton with the last neutron

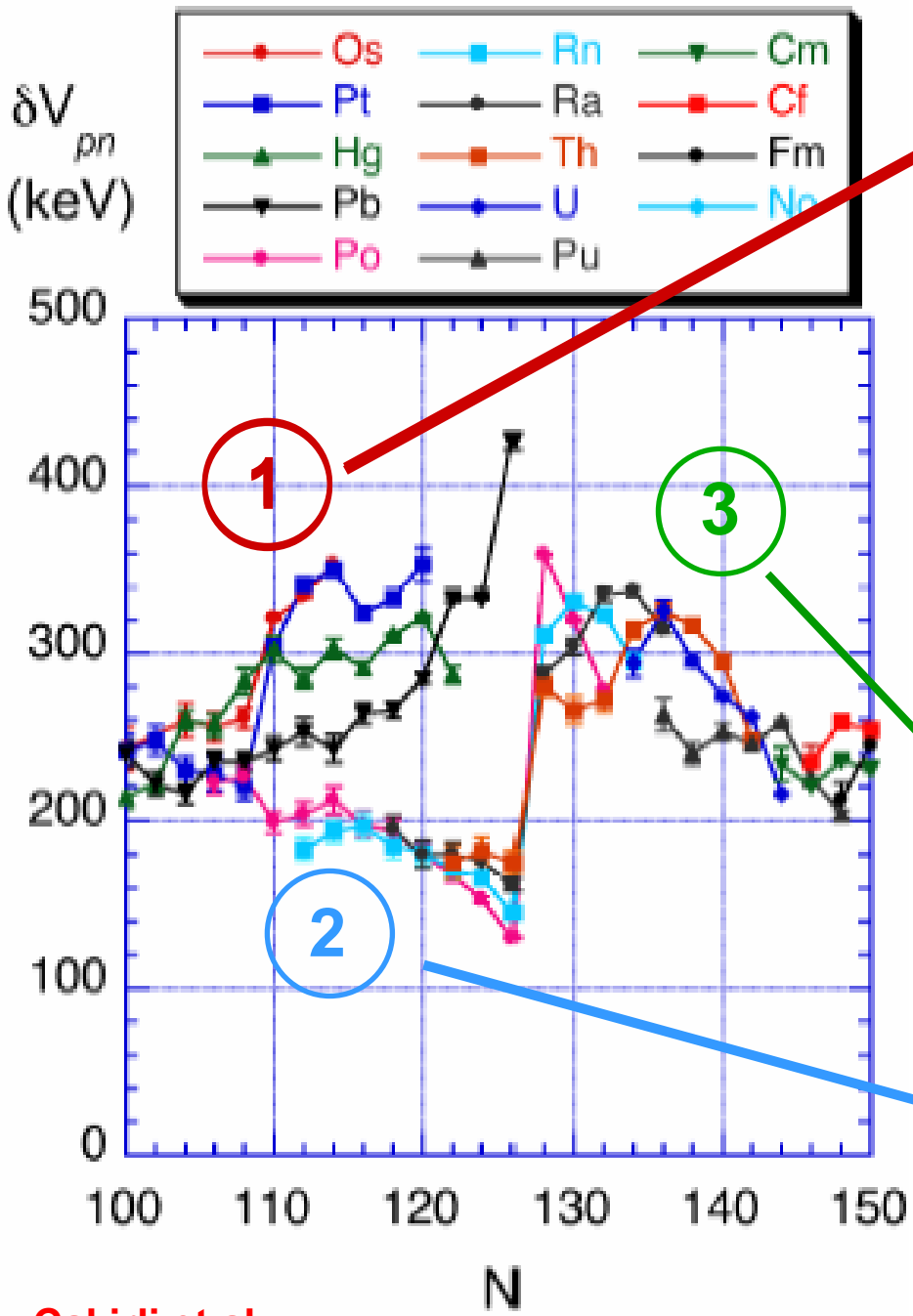


Concept of proton-neutron spatial overlaps

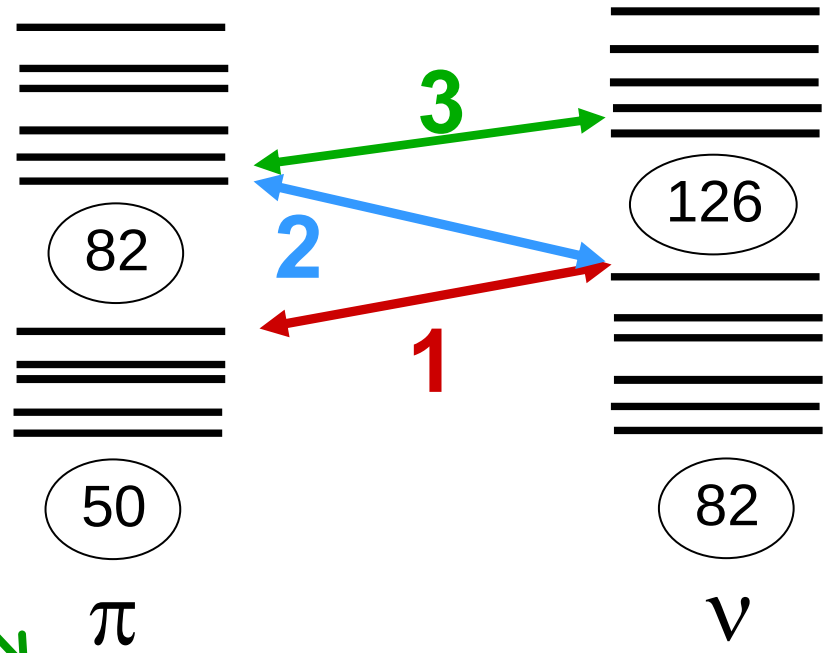
Generic
sequencing of shell
model orbits







Z ≤ 82 , N < 126



Z > 82 , N > 126

Z > 82 , N < 126

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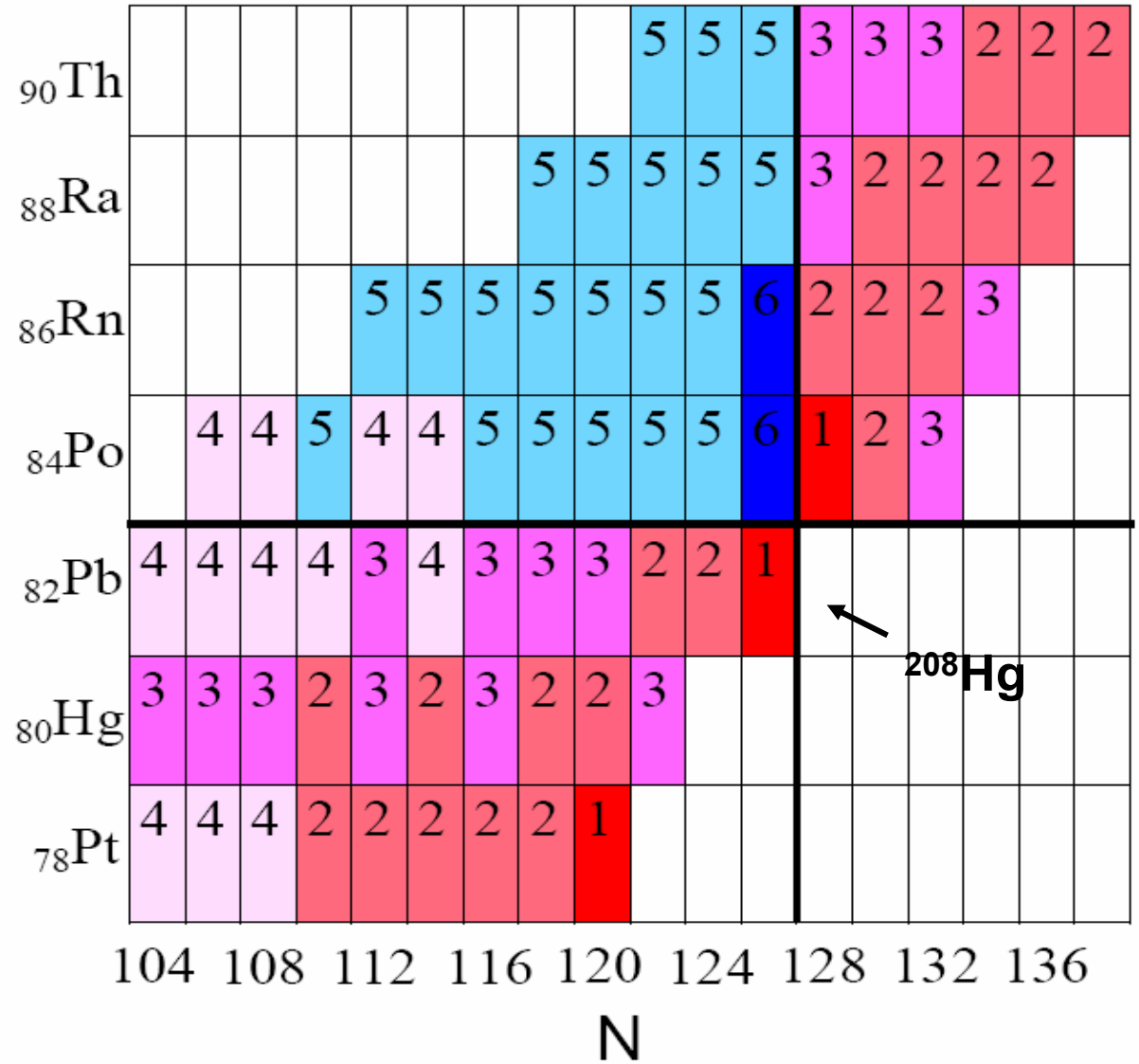
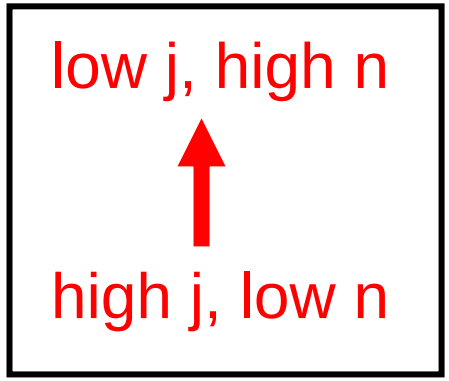
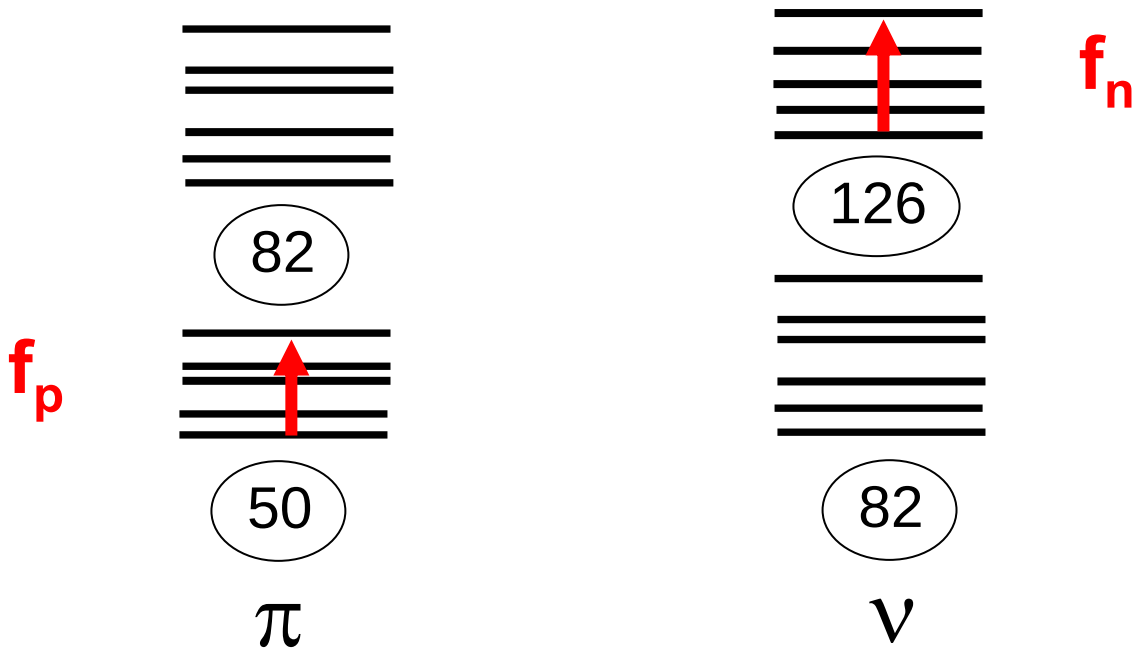


1	> 350 keV	4	250 – 200 keV
2	350 – 300 keV	5	200 – 150 keV
3	300 – 250 keV	6	150 – 100 keV

Generic sequencing of shell model orbits

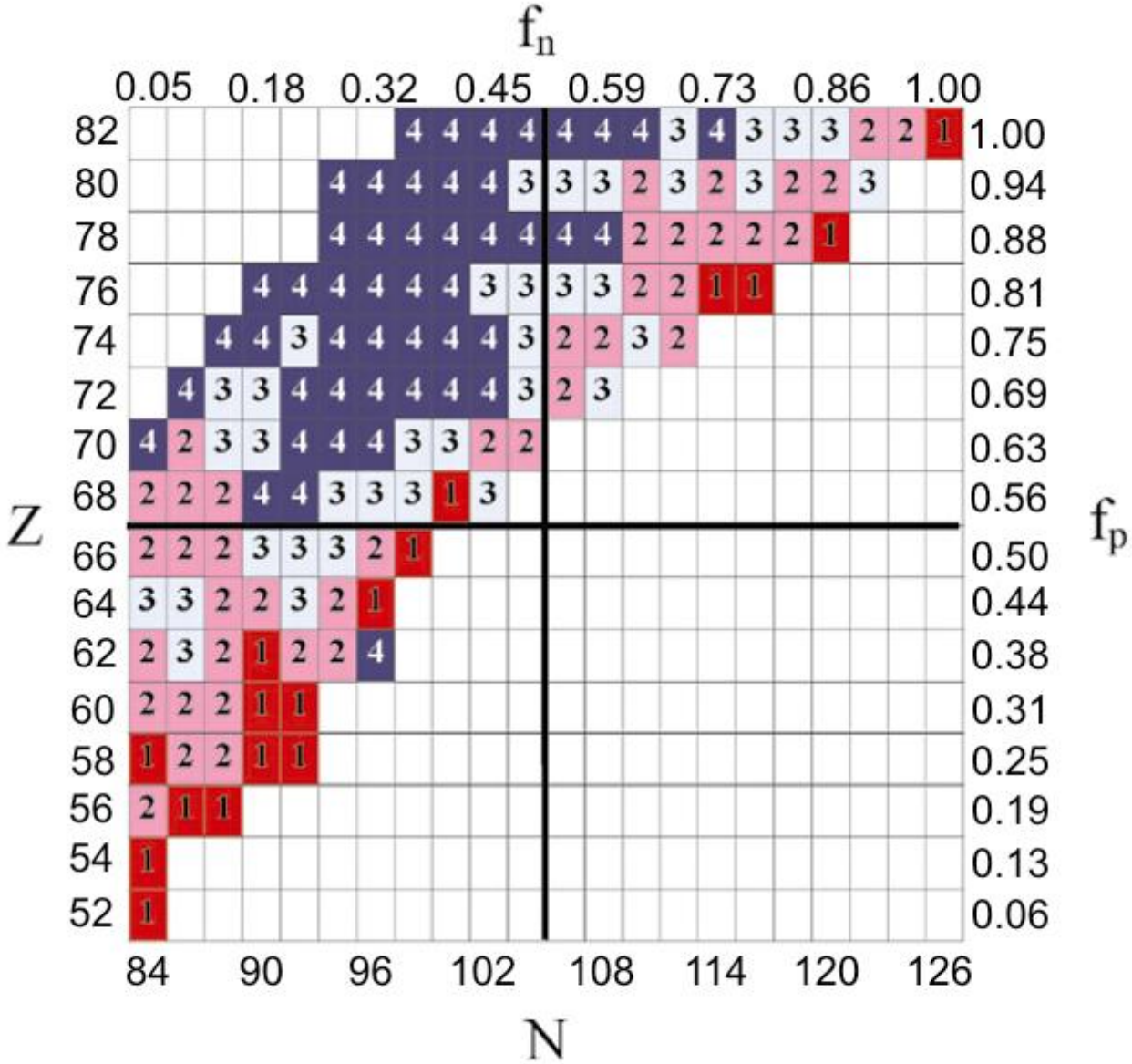




Hence, if the protons and neutrons are filling similarly, p-n interaction should be largest. We introduce the concept of **fractional filling**

Fractional Filling of major shells and the p-n interaction

Strongest along diagonal where highest p-n overlaps occur



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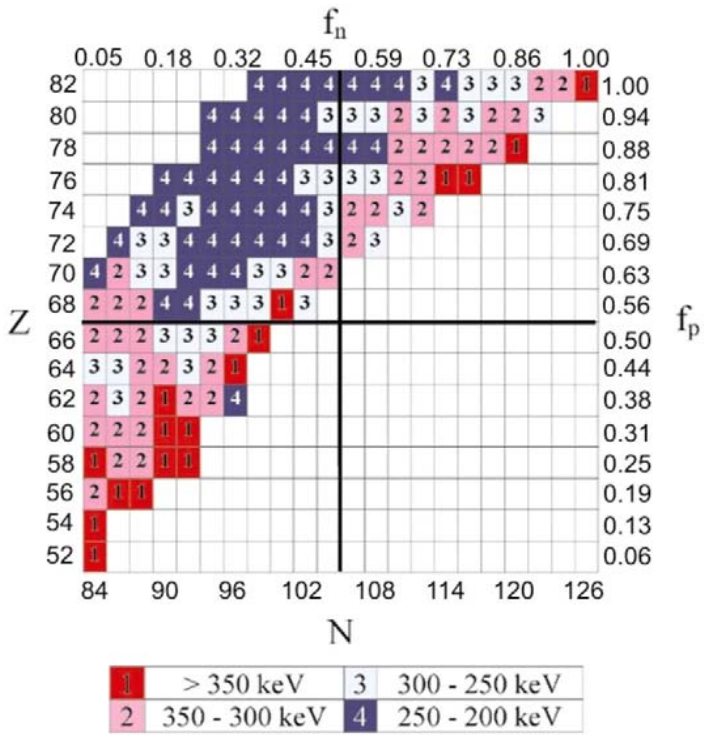
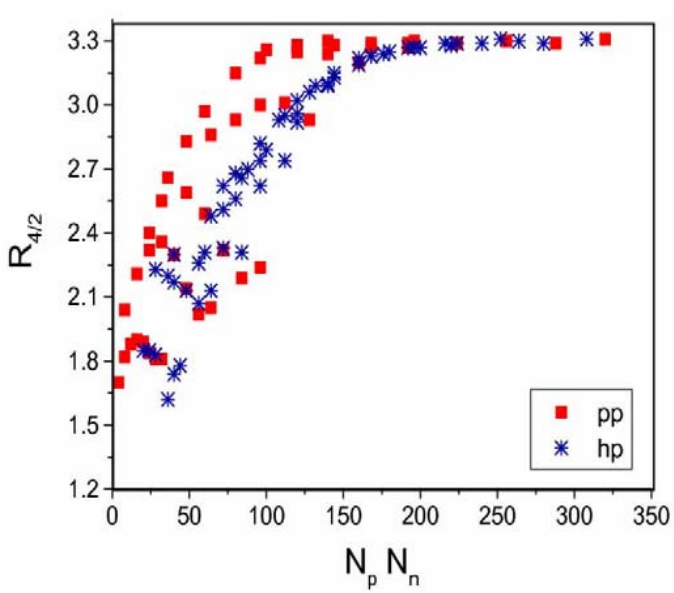
Empirical p-n interactions

Strongest along diagonal where highest p-n overlaps occur



Empiririical $R_{4/2}$



First direct correlation of *empirical* p-n interaction strengths with *empirical* growth rates of collectivity

Qualitative – needs microscopic underpinnings

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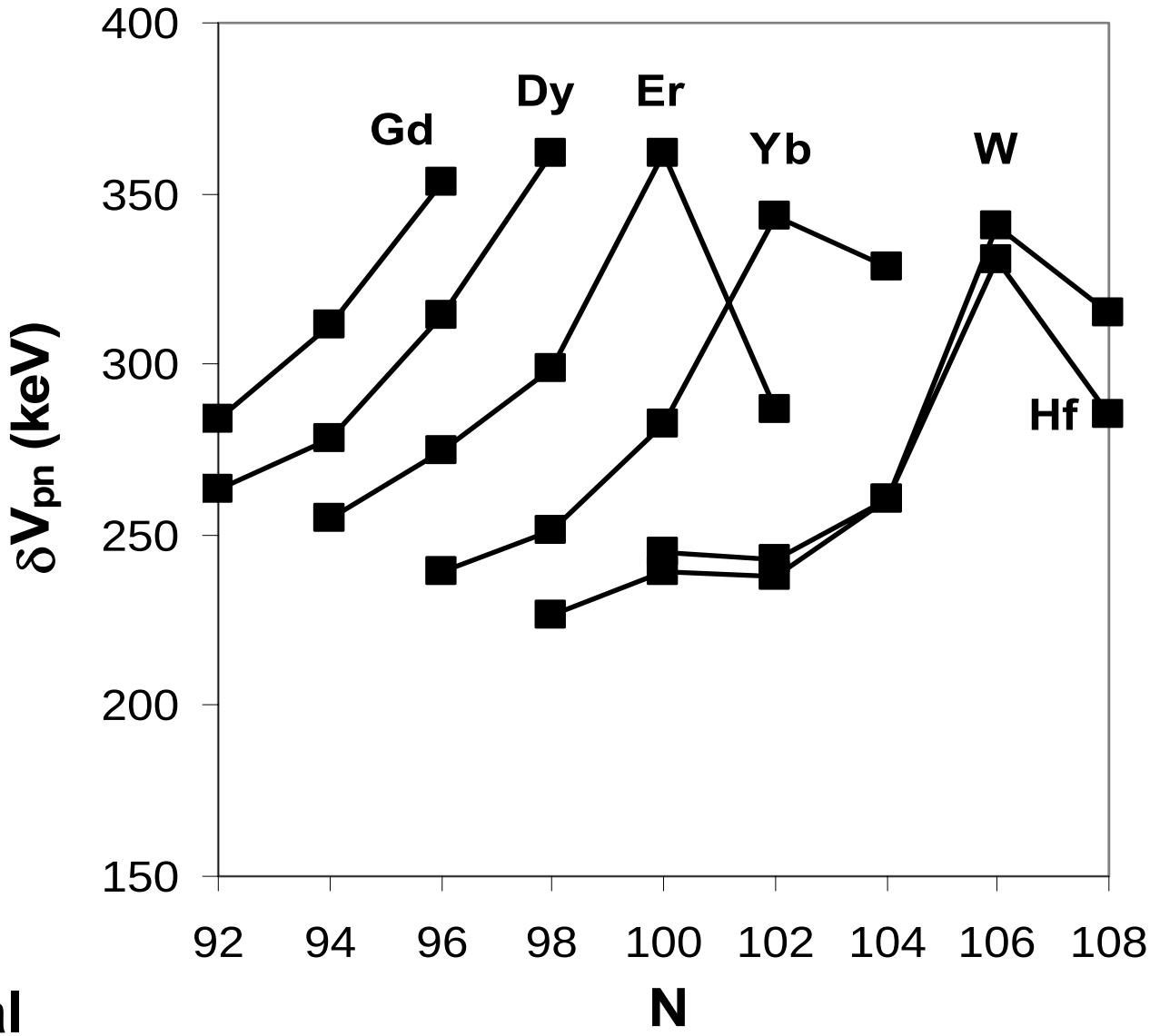
Specific Regions – an example

- **Rare earth nuclei from Gd-W**
- **Remarkably regular pattern of p-n interaction strengths**

Rare earth region



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"Theorem" (still to be proved): If it looks simple, it has a simple explanation !

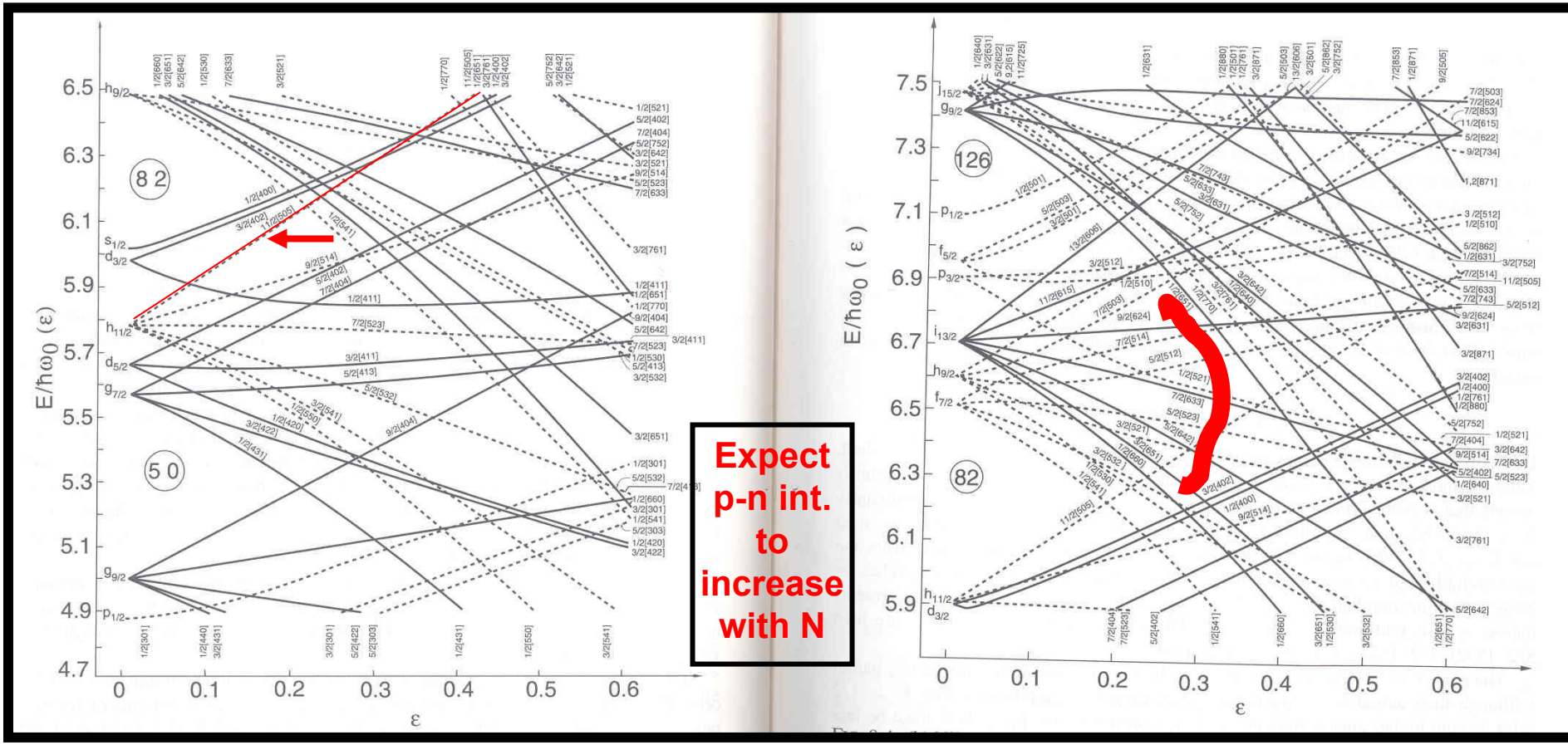
Calculating proton-neutron interactions in deformed nuclei

- How to do it?
- Deformed – hence nucleons occupy Nilsson orbits
- Each Nilsson wave function can be expanded in a basis of spherical shell model wave functions. The C_j coefficients give the relative amplitudes of each *nlj* orbit

Simple approach: Consider Nilsson diagrams

Protons

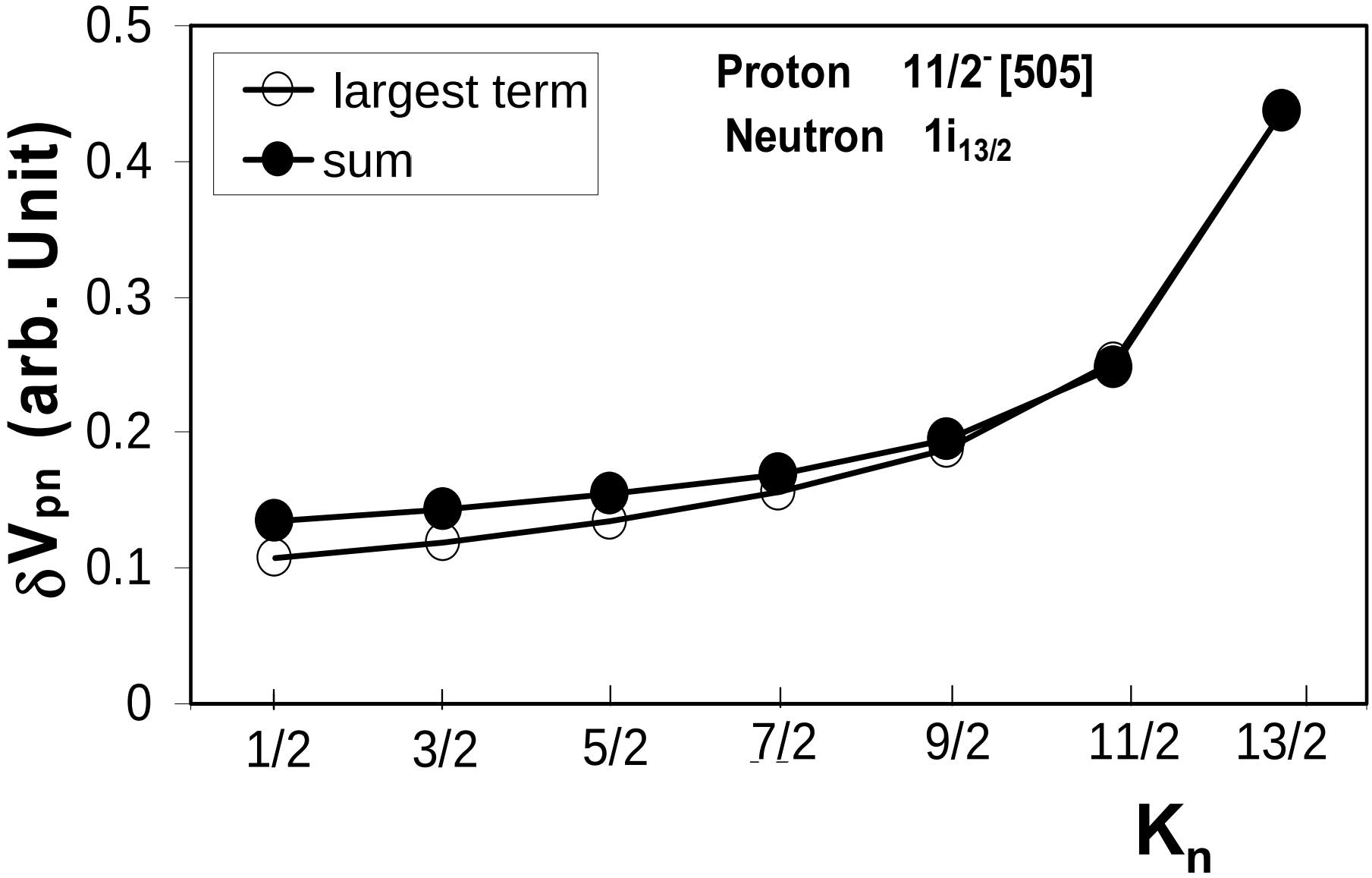
Neutrons



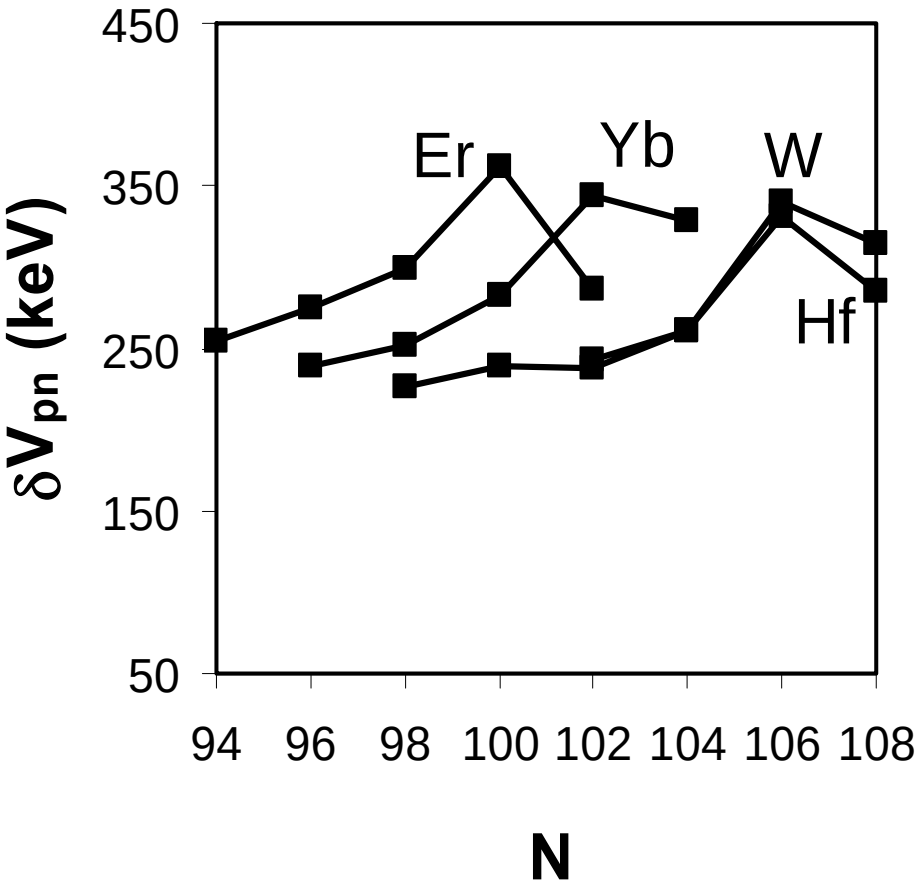
Downsloping orbits: equatorial

Flat orbits: ~ 45°

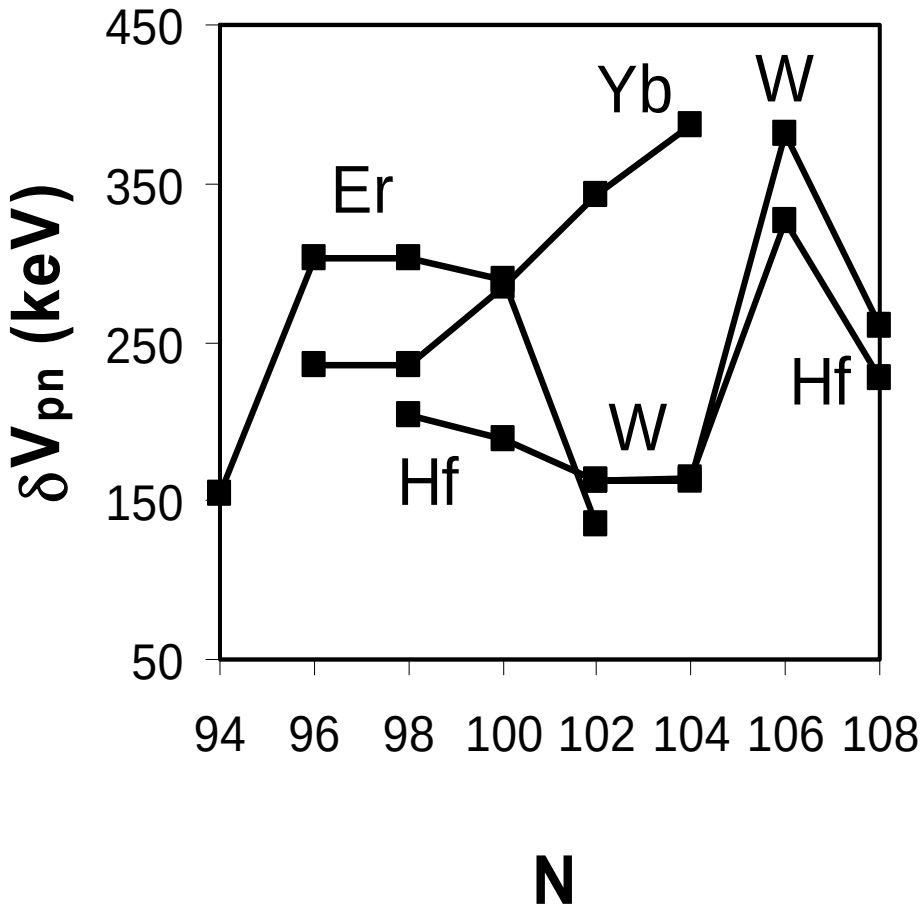
Upsloping orbits: polar


largest term
sum
Proton 11/2⁻ [505]
Neutron 1i13/2
δVpn (arb. Unit)
0.5
0.4
0.3
0.2
0.1
0
1/2
3/2
5/2
7/2
9/2
11/2
13/2
Kn

Experiment



Calculation



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But now for something much more realistic

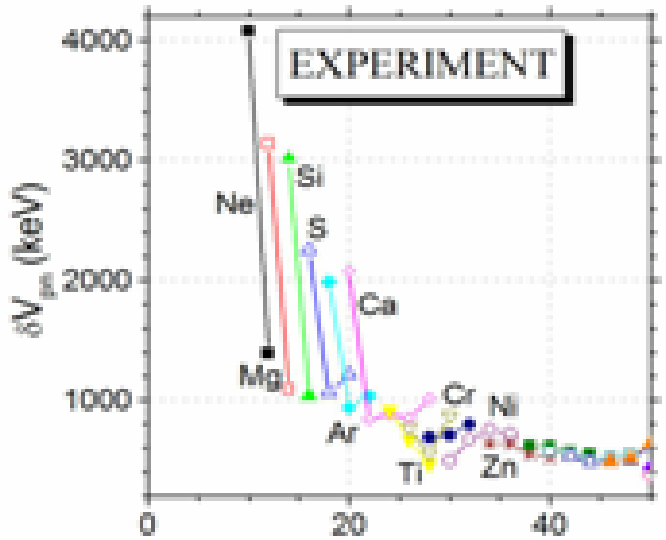
Microscopic Density Functional Calculations

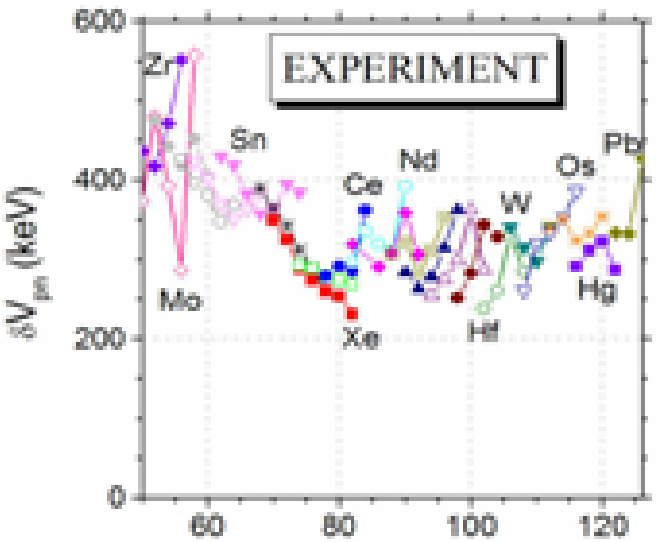
- Witek Nazarewicz and Mario Stoitsov

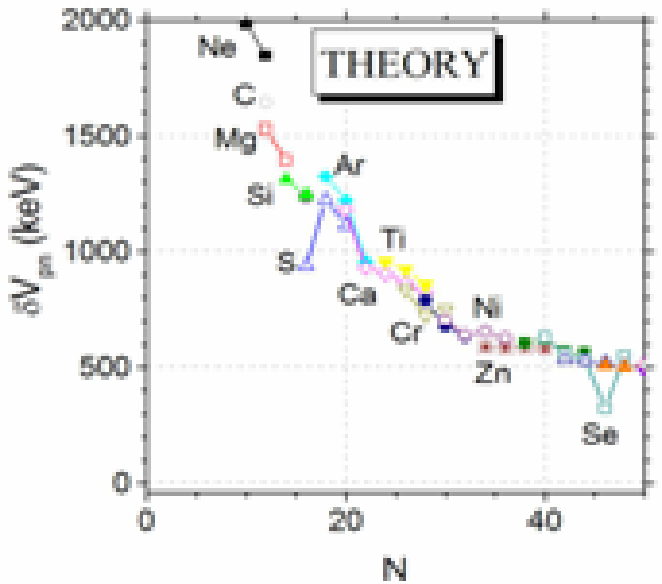
- Density Functional Theory with Skyrme forces and different treatments of pairing

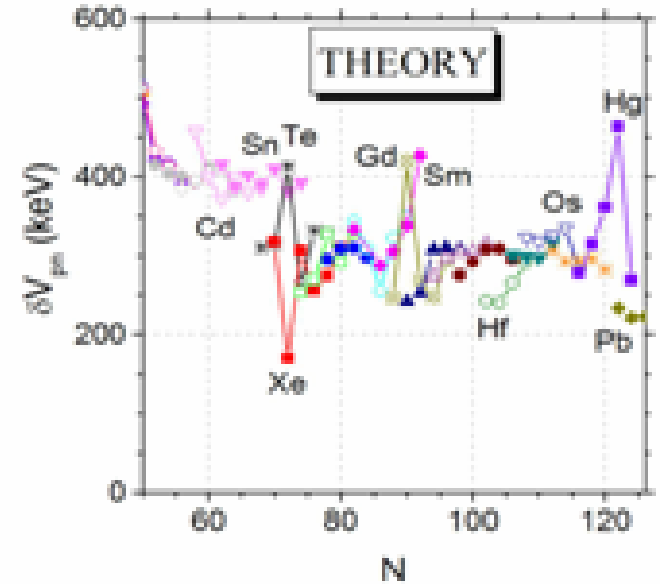
Preliminary results

FOR STABLE NUCLEI

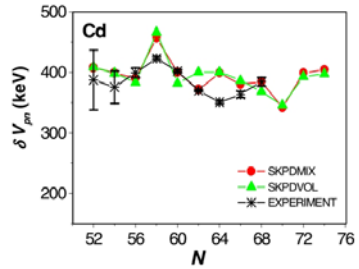


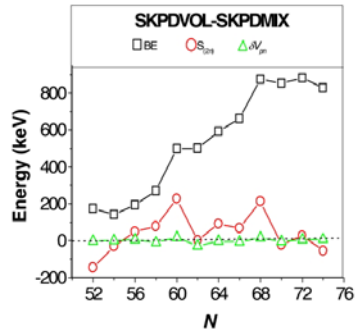


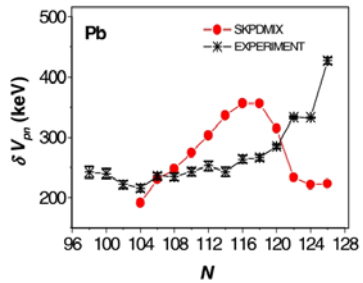


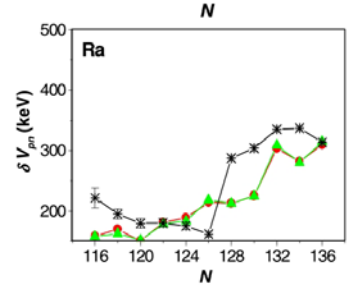


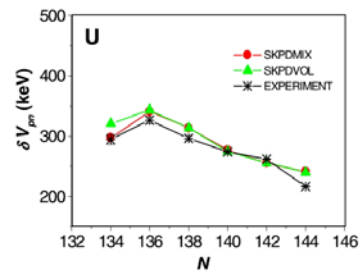
Tentative











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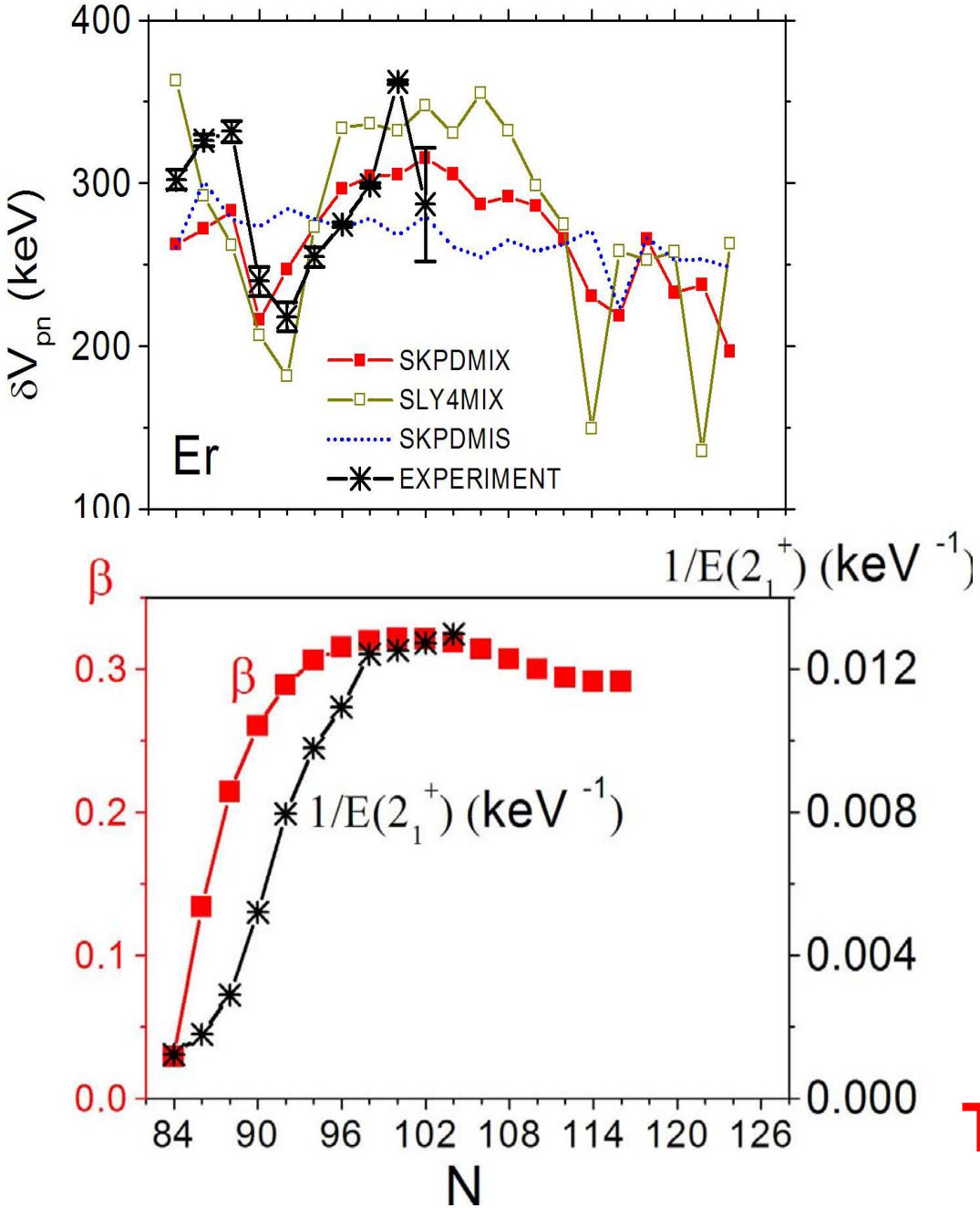
Tentative



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Tentative

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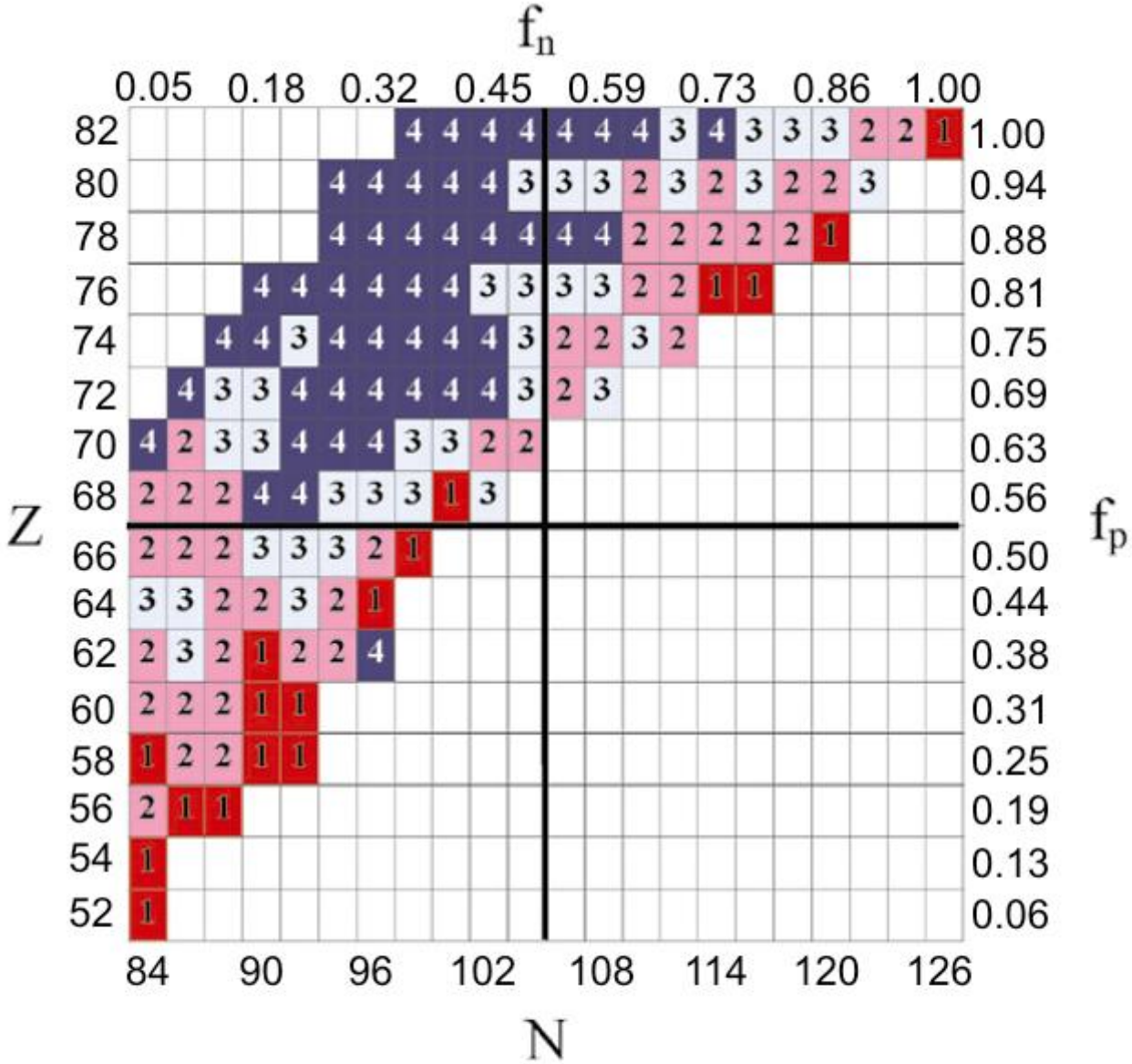

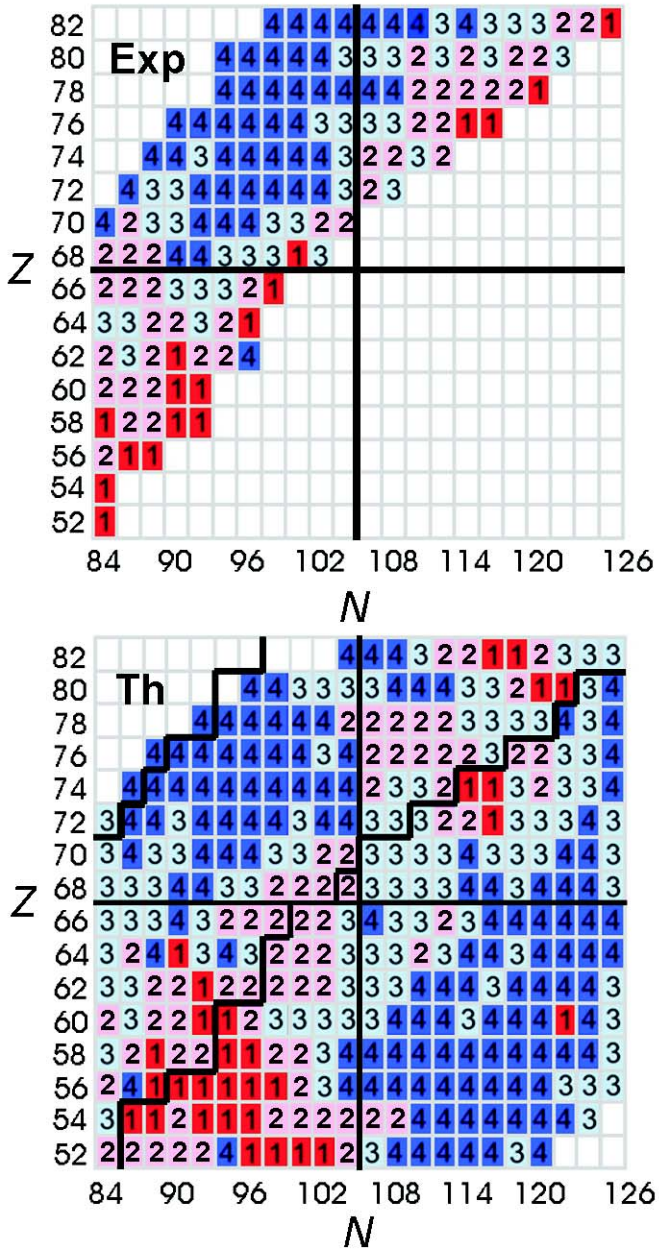

DFT reproduces general trends, including the particle-particle vs. particle-hole classification, and predicts low values in the lower right quadrant

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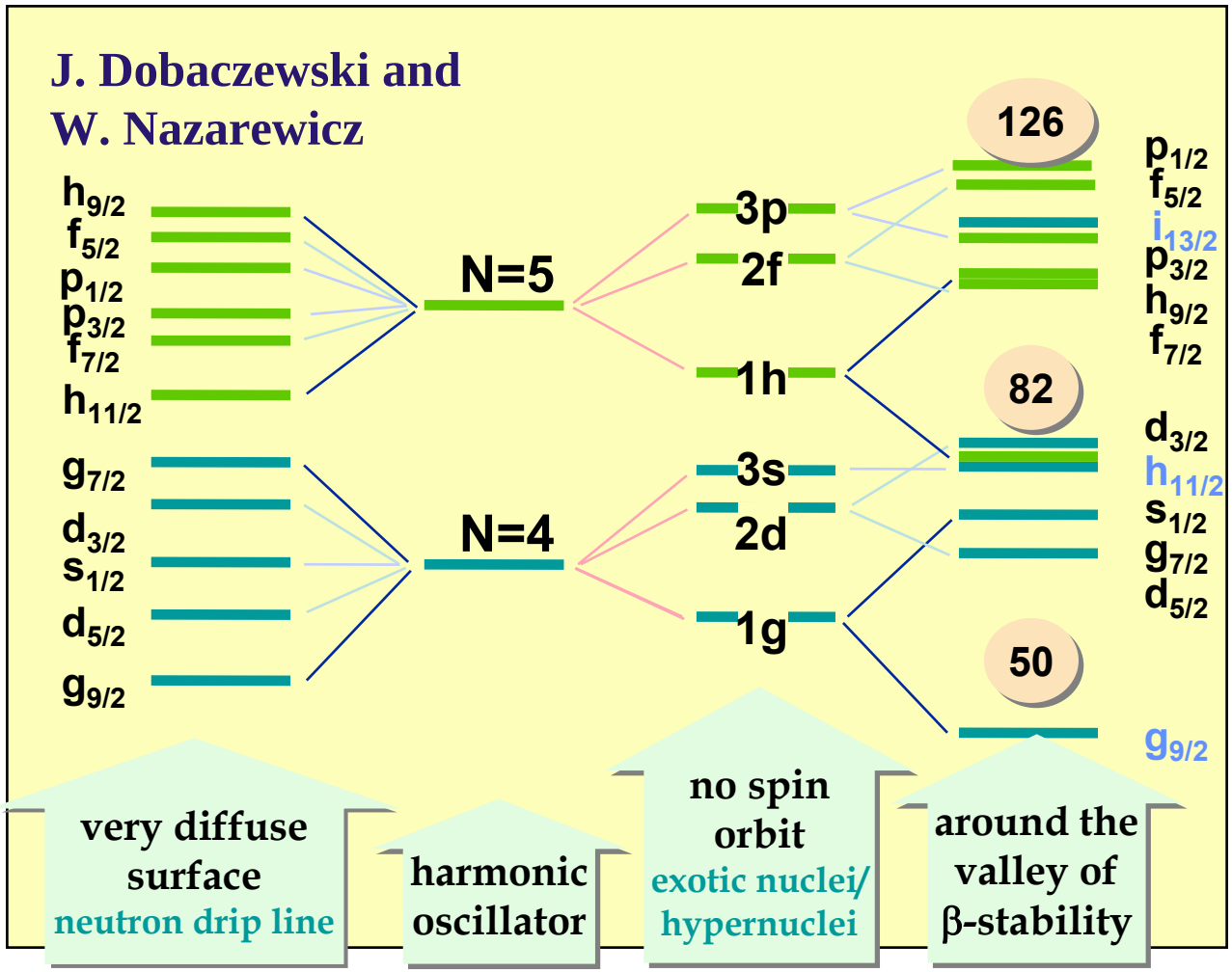
Tentative

What happens far off Stability

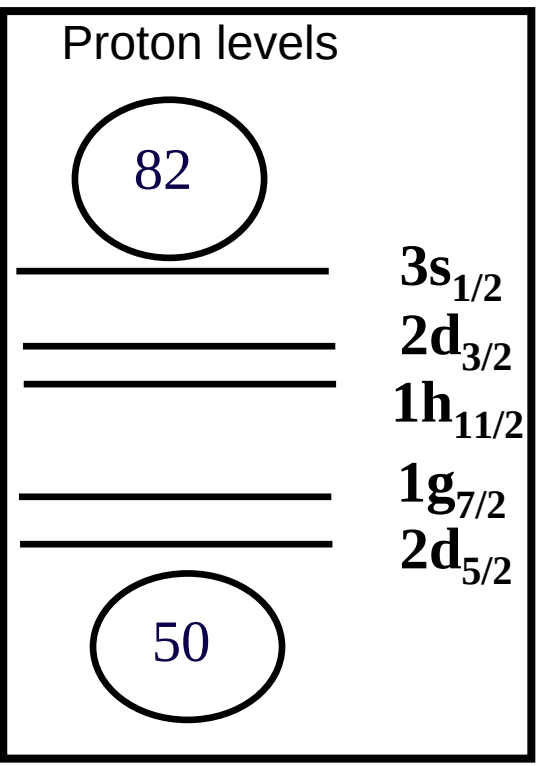
- Fragility of Magicity
- Can masses, p-n interaction filters give clues to shell structure?

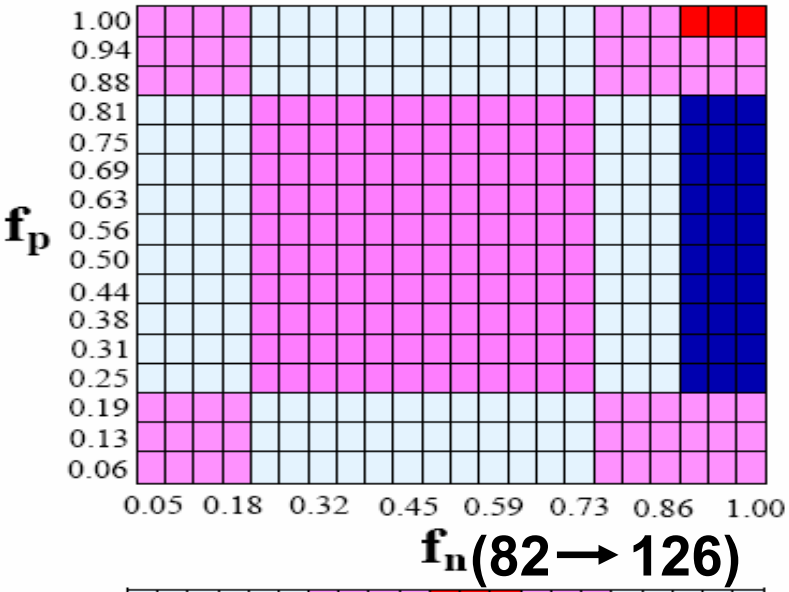
Possible Changes in Structure for Skin Nuclei

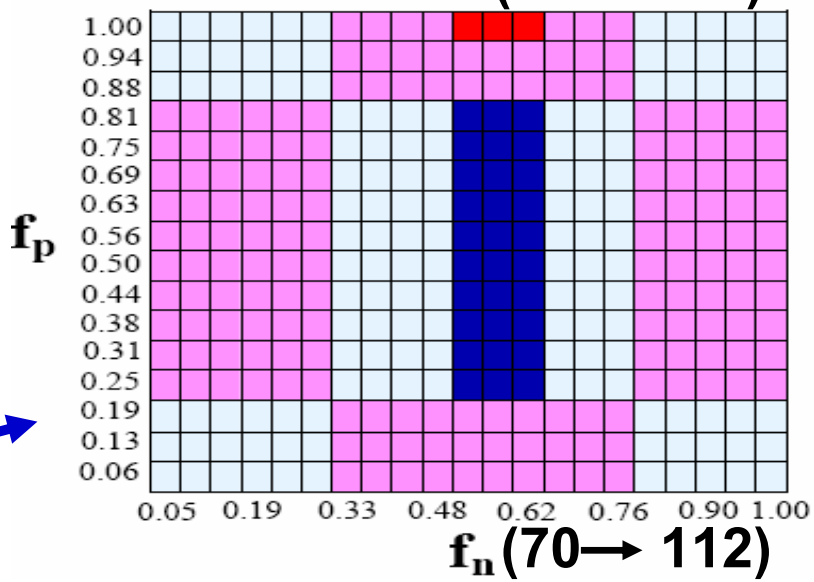


CALCULATED δV_{pn}

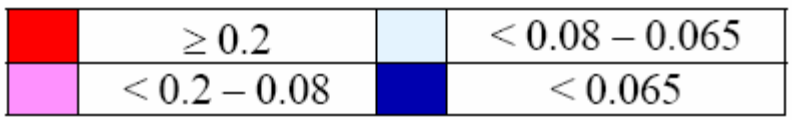
For Normal Nuclei

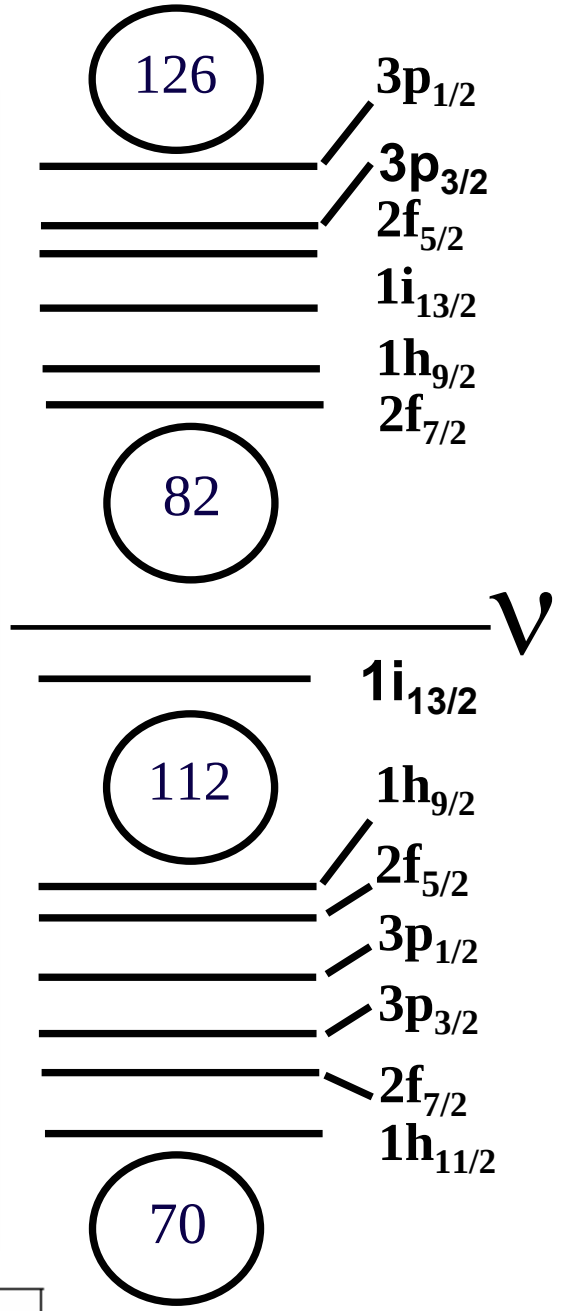






For Exotic Nuclei





Region of Interest	To compute dV_{pn}	Mass Measurements Needed
Self Conjugate	^{64}Ge	^{62}Ge
	^{68}Se	^{66}Se
	^{72}Kr	^{70}Kr
	^{76}Sr	^{74}Sr
	^{80}Zr	^{80}Zr, ^{78}Zr
N~50	^{72}Zn	^{70}Ni
	^{74}Zn	^{72}Ni,^{70}Ni
	^{84}Se	^{82}Ge
	^{86}Se	^{84}Ge, ^{82}Ge
	^{97}Zr, ^{95}Mo	^{97}Zr, ^{96}Zr
	^{98}Mo	^{98}Mo, ^{96}Mo, ^{96}Zr ^{94}Zr
	^{100}Mo	^{100}Mo, ^{98}Mo, ^{98}Zr ^{96}Zr
	^{102}Mo	^{102}Mo, ^{100}Mo, ^{100}Zr ^{98}Zr
N~82	^{125}In	^{124}Cd, ^{122}Cd
	^{126}Sn	^{124}Cd, ^{122}Cd
	^{128}Sn	^{126}Cd, ^{124}Cd
	^{130}Sn	^{128}Cd, ^{126}Cd
	^{132}Sn	^{130}Cd, ^{128}Cd

Region of Interest	To compute dV_{pn}	Mass Measurements Needed
N~82	^{134}Sn	^{134}Sn, ^{134}Cd, ^{132}Cd
	^{118}Cd	^{116}Pd
	^{120}Cd	^{118}Pd, ^{116}Pd
	^{122}Cd	^{122}Cd, ^{120}Pd, ^{118}Pd
	^{124}Cd	^{124}Cd, ^{122}Cd, ^{122}Pd, ^{120}Pd
	^{126}Cd	^{126}Cd, ^{124}Cd, ^{124}Pd, ^{122}Pd
	^{152}Nd	^{150}Ce
N~126	^{209}Pb	^{207}Hg
	^{210}Pb	^{208}Hg
	^{211}Pb	^{209}Hg, ^{208}Hg
	^{212}Pb	^{210}Hg, ^{208}Hg
	^{204}Hg	^{202}Pt
	^{206}Hg	^{204}Pt, ^{202}Pt
	^{200}Pt	^{198}Os
	^{202}Pt	^{202}Pt, ^{200}Os, ^{198}Os
	^{225}Ra	^{223}Rn
	^{227}Ra	^{225}Rn, ^{224}Rn

Mass Measurements: Scales of Accuracy

- **Phase transitions:** **~10's - 100's keV**
- **Interaction filters (δV_{pn}) :** **~10 – 20 keV**
  - **Except $N = Z$ nuclei** **~100 keV**
- **Tests of Fundamental Symmetries:** **< < 10 keV**

Mass Measurements: Where?

- **Neutron-rich nuclei**
- **Heavier $N = Z$ nuclei**
- **Z = 50-66, N = 106-126**
- **Specific selected nuclei (see Table)**

Summary

- p-n interactions – key to collectivity
- Empirical interactions of last protons and neutrons. Remarkable patterns.
- Link to shell structure – closed shells, major shells (fractional filling)
- Correlation to empirical growth rates of collectivity.
- Simple patterns in special regions – calculations with δ force
- Extensive, realistic, Density Functional Theory calculations work extremely well and point to missing ingredients
- Phase transitional regions
- Scales of needed measurements

Collaborators

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Franco Iachello

Thanks to Kris Heyde and Anneleen De Maesschalk