Valence proton-neutron interactions, shell structure, and structural evolution

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Truth in advertising: Most of this work is primarily due to R. Burcu Cakirli

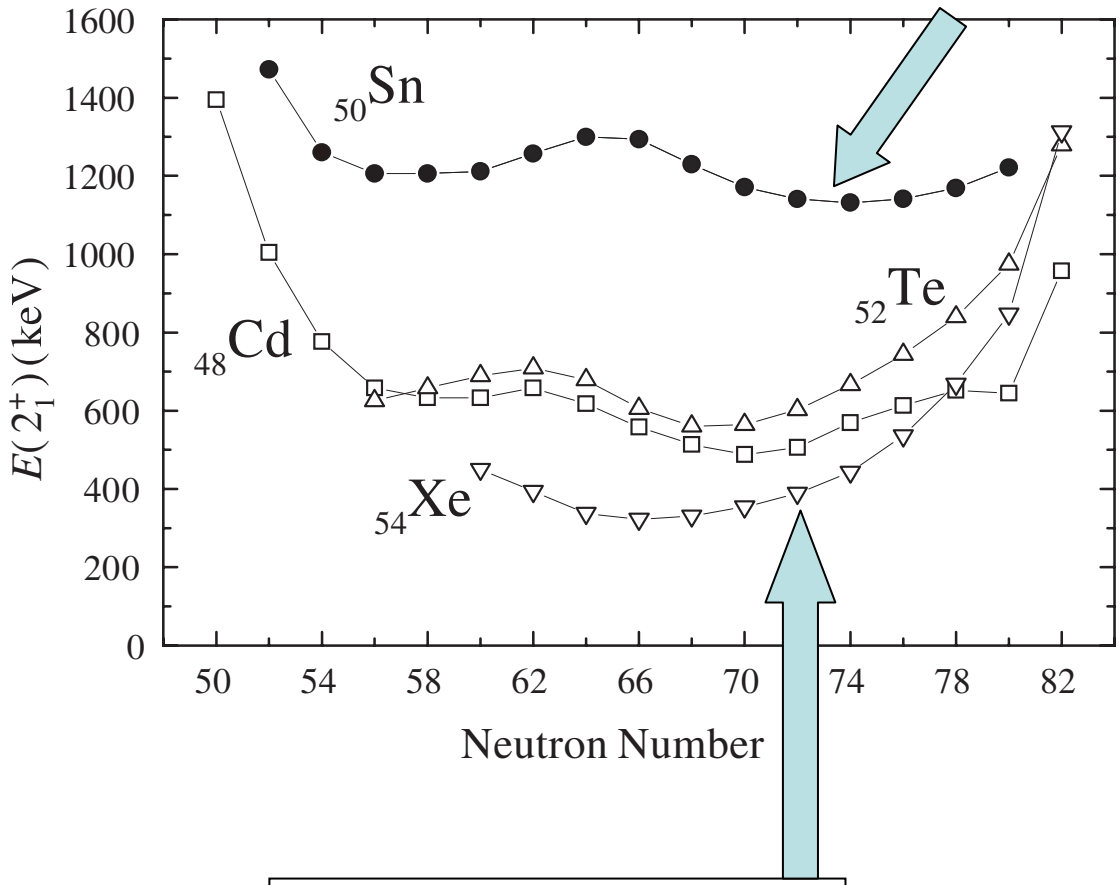
Valence Proton-Neutron Interaction and Structural Evolution

Development of configuration mixing

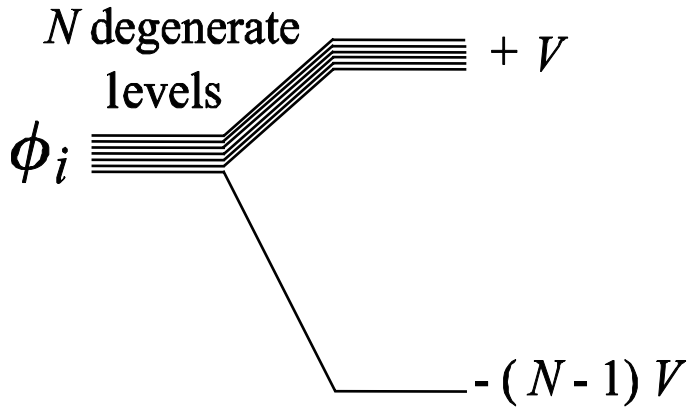
Key role in the onset of collectivity and deformation in nuclei

Changes in single particle energies and magic numbers

Sn – Magic: no valence p-n interactions



Both valence protons and neutrons

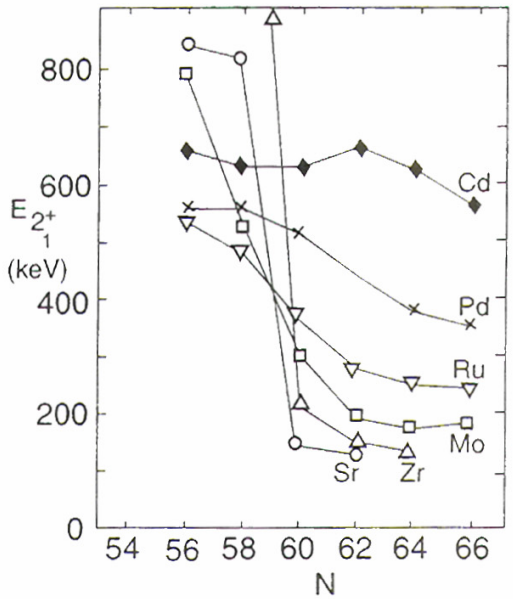


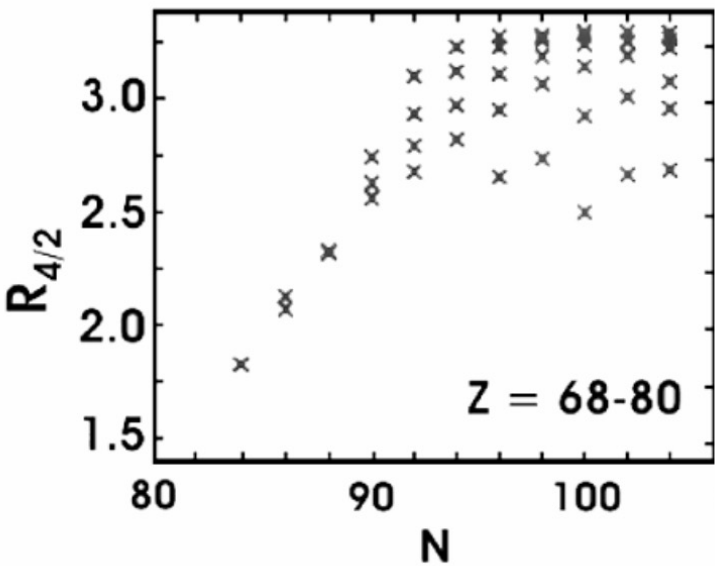
$$H = H_o + H_{pert}$$

$$\psi_{lowest} = \frac{1}{\sqrt{N}} [\, \phi_1 + \phi_2 + \phi_3 + \ldots]$$

Valence Proton-Neutron Interactions

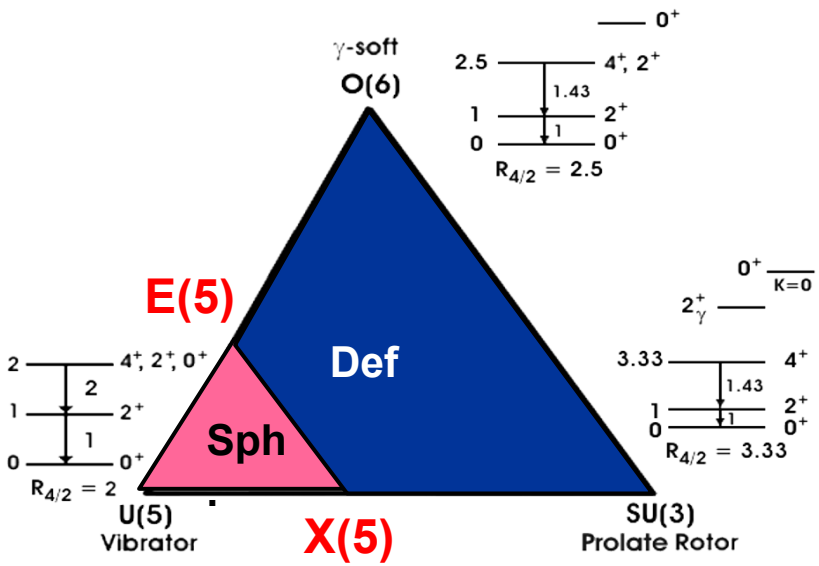
Correlations, collectivity, deformation. Sensitive to magic numbers.





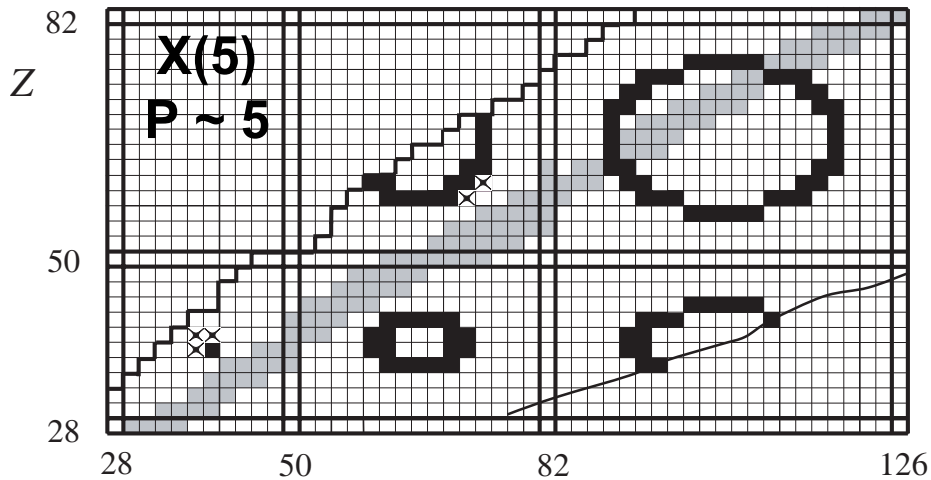
N_pN_n Scheme

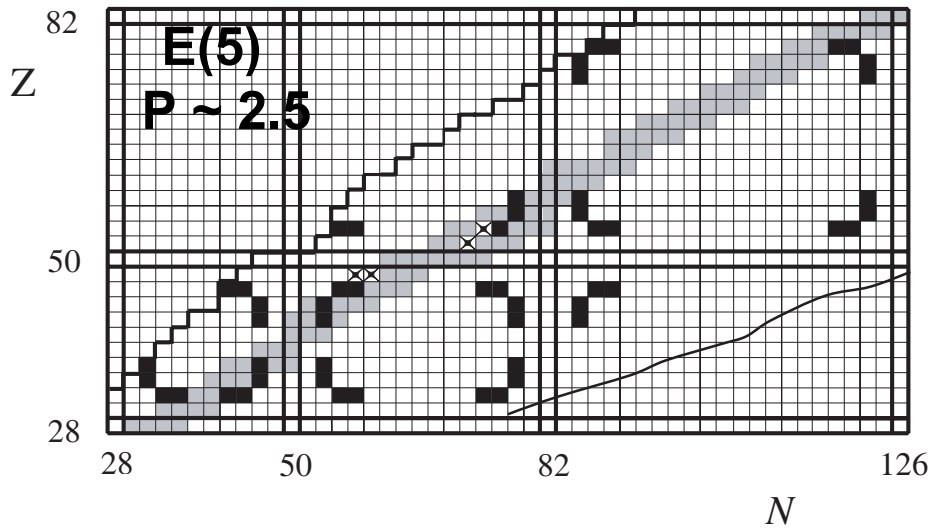
Where can we expect phase transitional behavior? – pairing vs. p-n, an Ising-like competition



$$P = \frac{N_p N_n}{(N_p + N_n)}$$

p-n interactions per pairing interaction





Measurement p-n Interaction Strengths

δV_{pn}

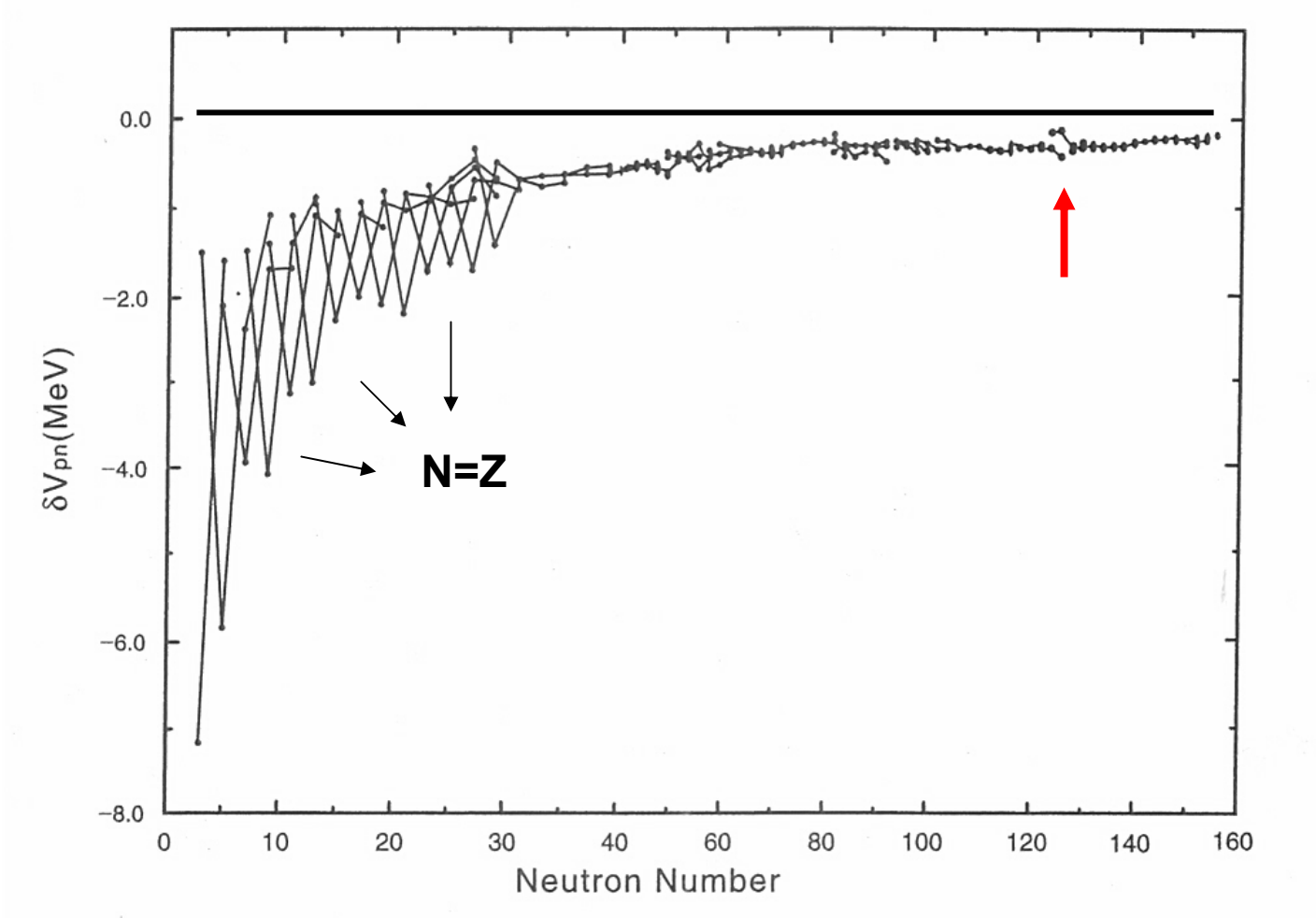
Average p-n interaction between last proton and last neutron

Double Difference of Binding Energies

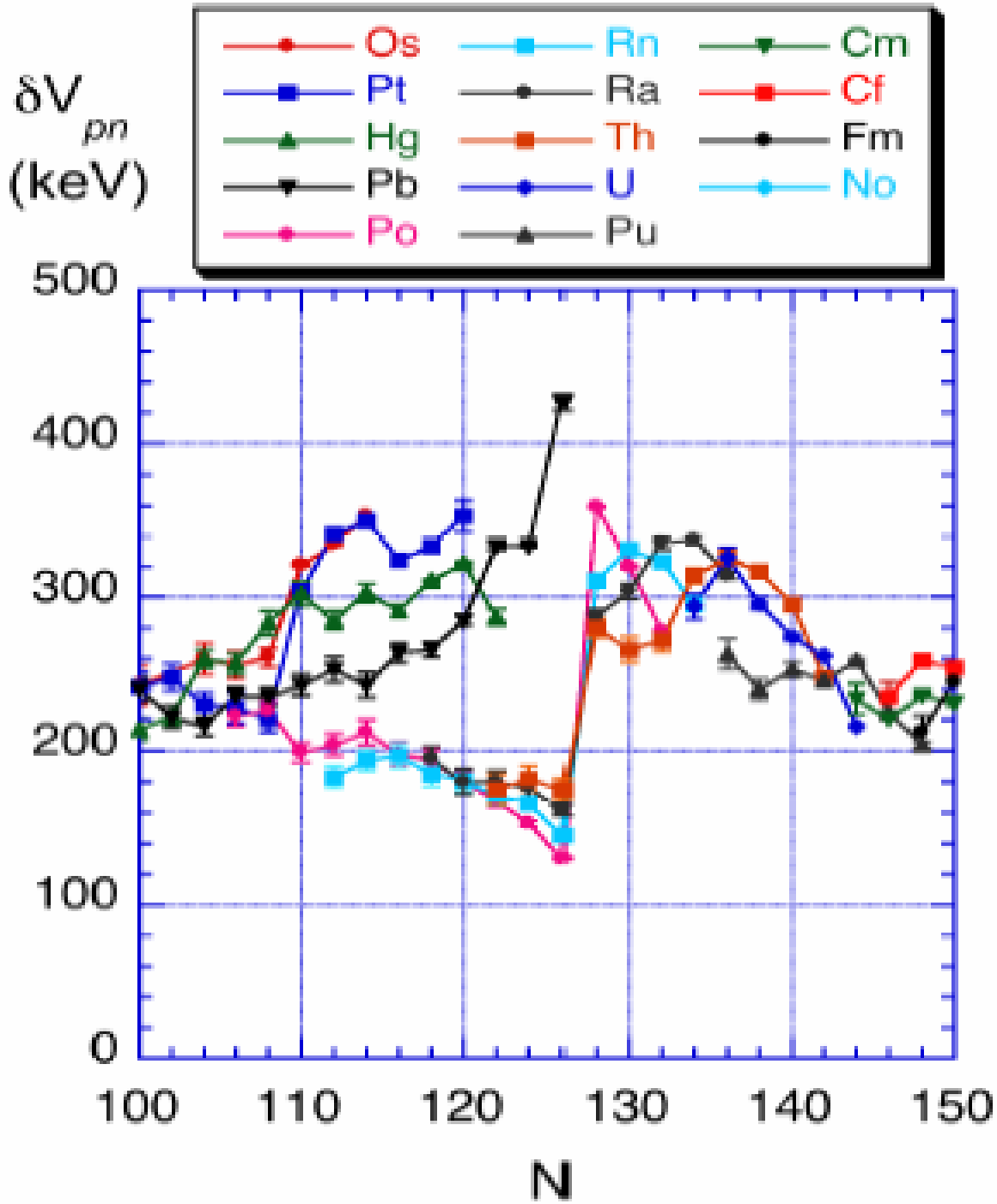
$$\delta V_{pn}(Z,N) = \tfrac{1}{4}\left[\{B(Z,N) - B(Z,N-2)\} - \{B(Z-2,N) - B(Z-2,N-2)\}\right]$$

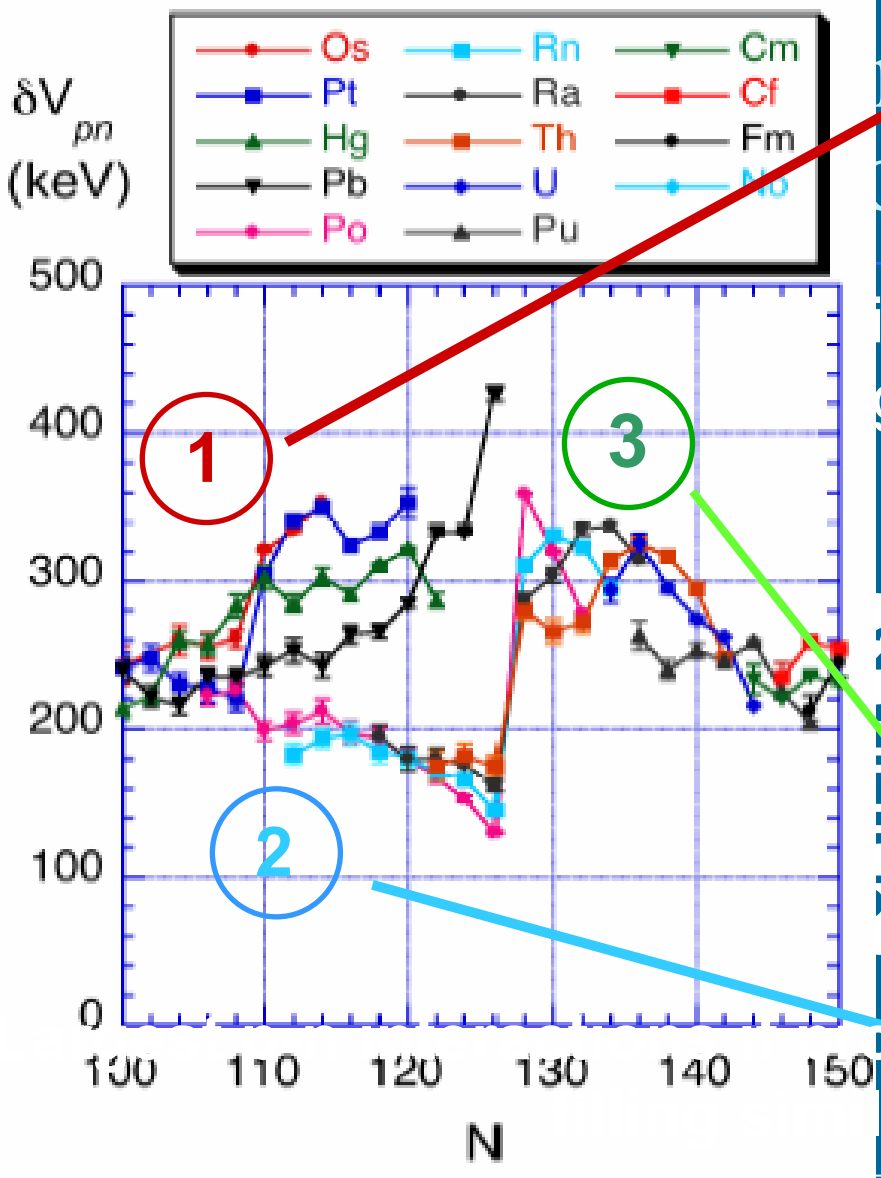
Ref: J.-y. Zhang and J. D. Garrett

Empirical interactions of the last proton with the last neutron



^{208}Pb region



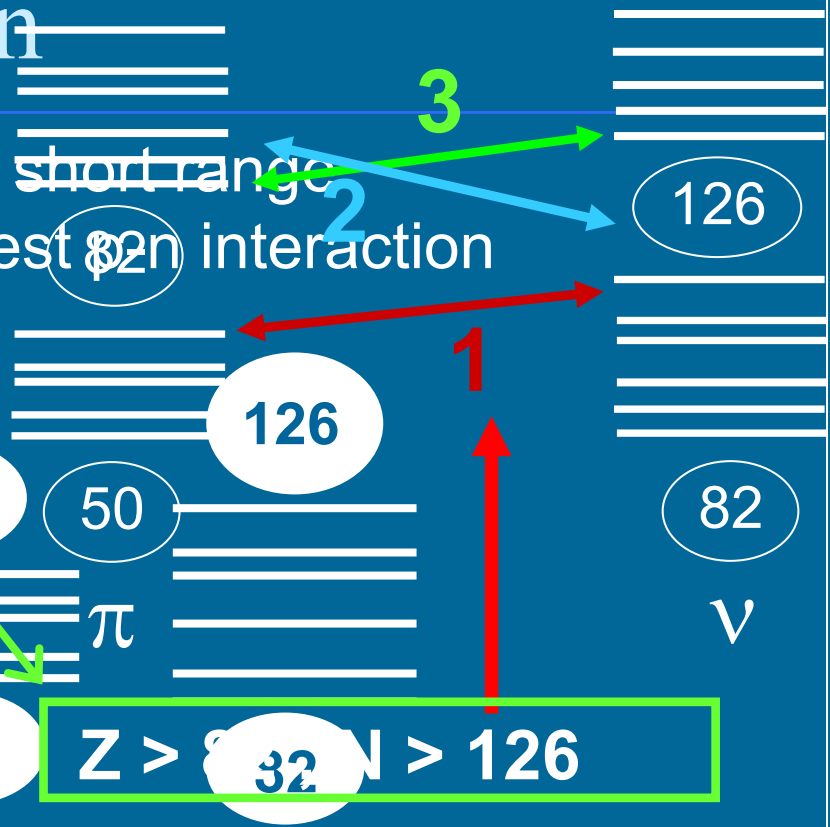


nd neutron orbit

on

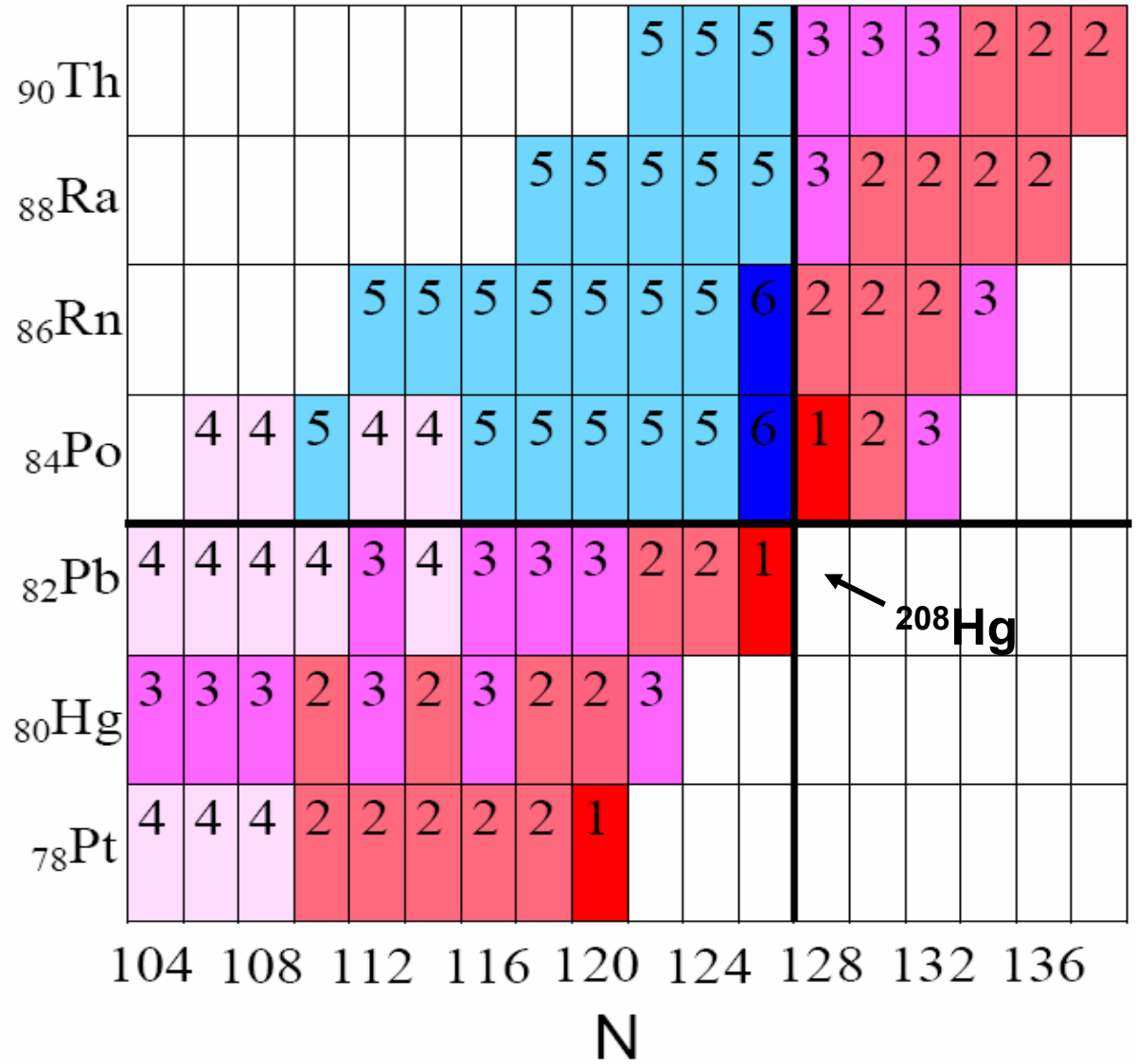
is ~~short range~~

gest pn interaction



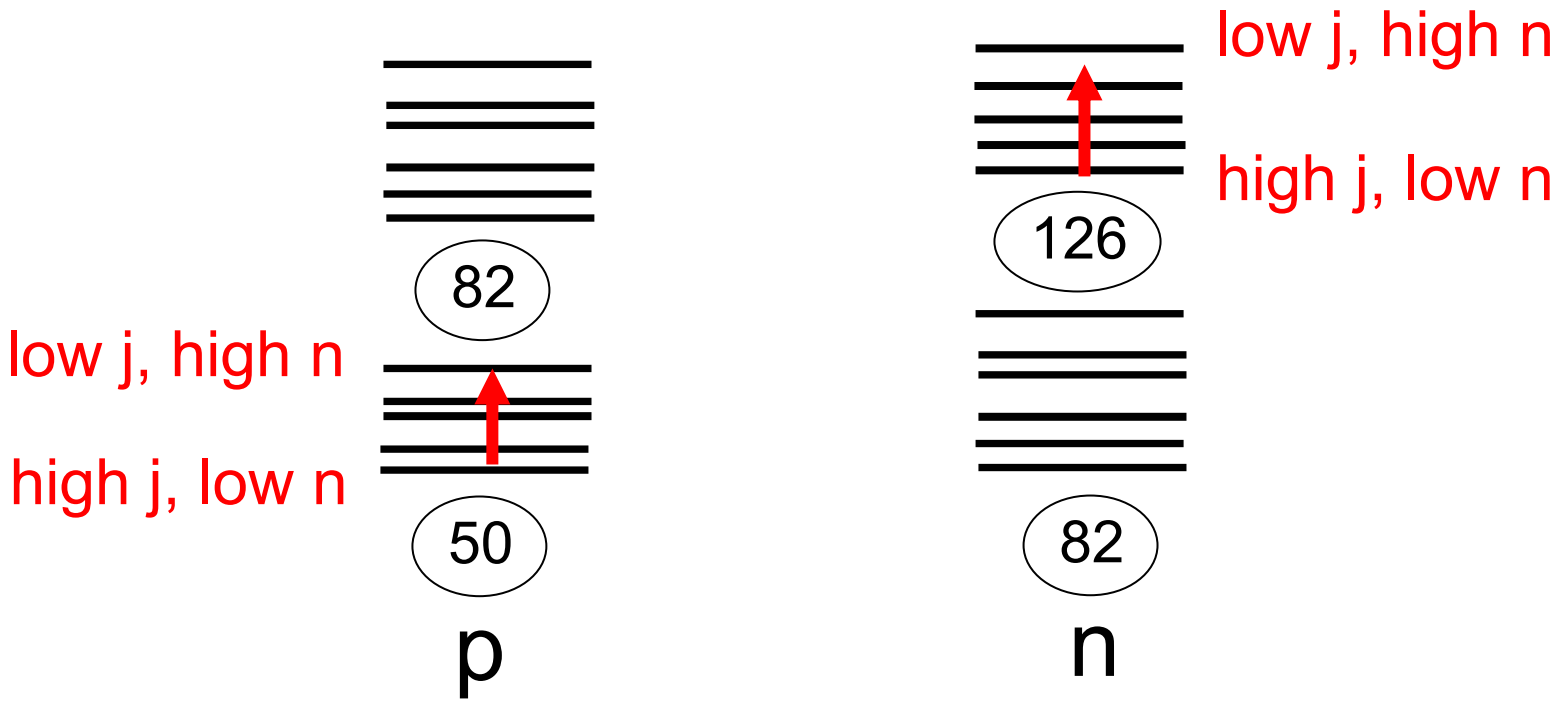
oton and neutron shells are

ar orbits



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

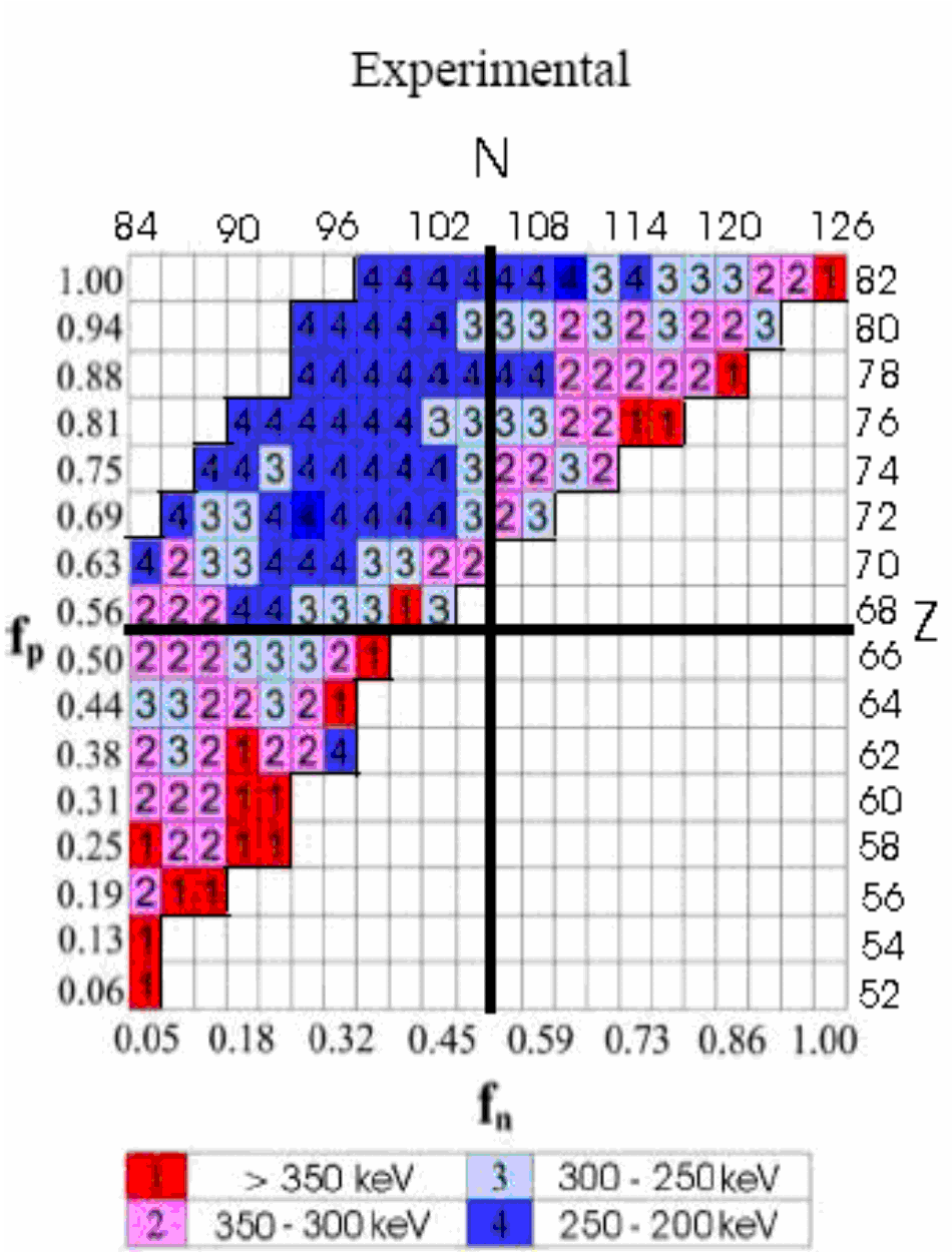


Hence, if the protons and neutrons are filling their shells similarly

– similar **fractional filling, $f_p \sim f_n$** –

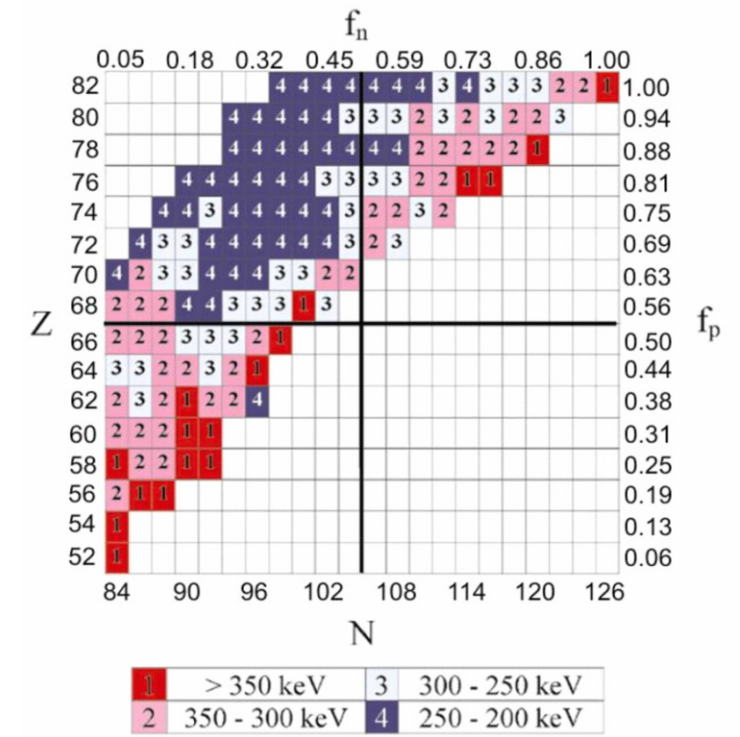
p-n interaction should be largest, that is, along the “diagonal” in an N-Z fractional filling plot

Valence p-n Interactions



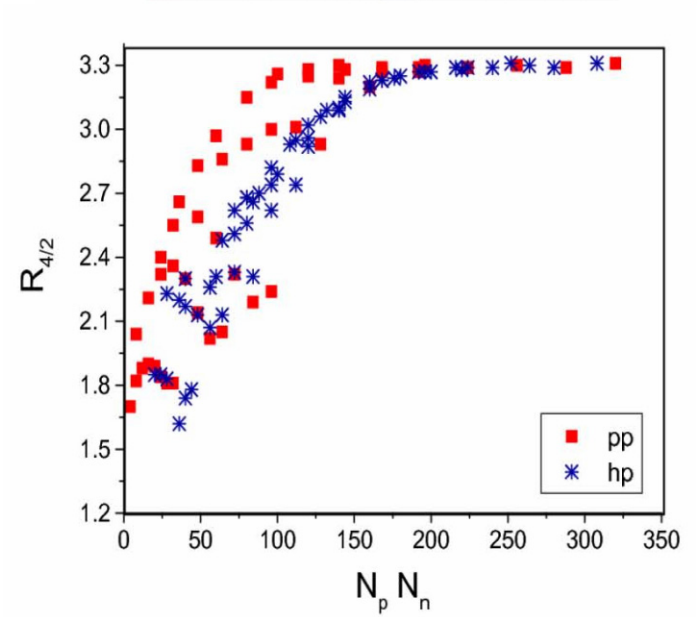
p-n interactions

Strongest along diagonal where highest p-n overlaps occur



Note difference in p-p or h-h (red-ish) compared to p-h regions (blue-ish)

Empirical $R_{4/2}$



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

Breaking Paradigms

Changes in Shell Structure as a function of N / Z

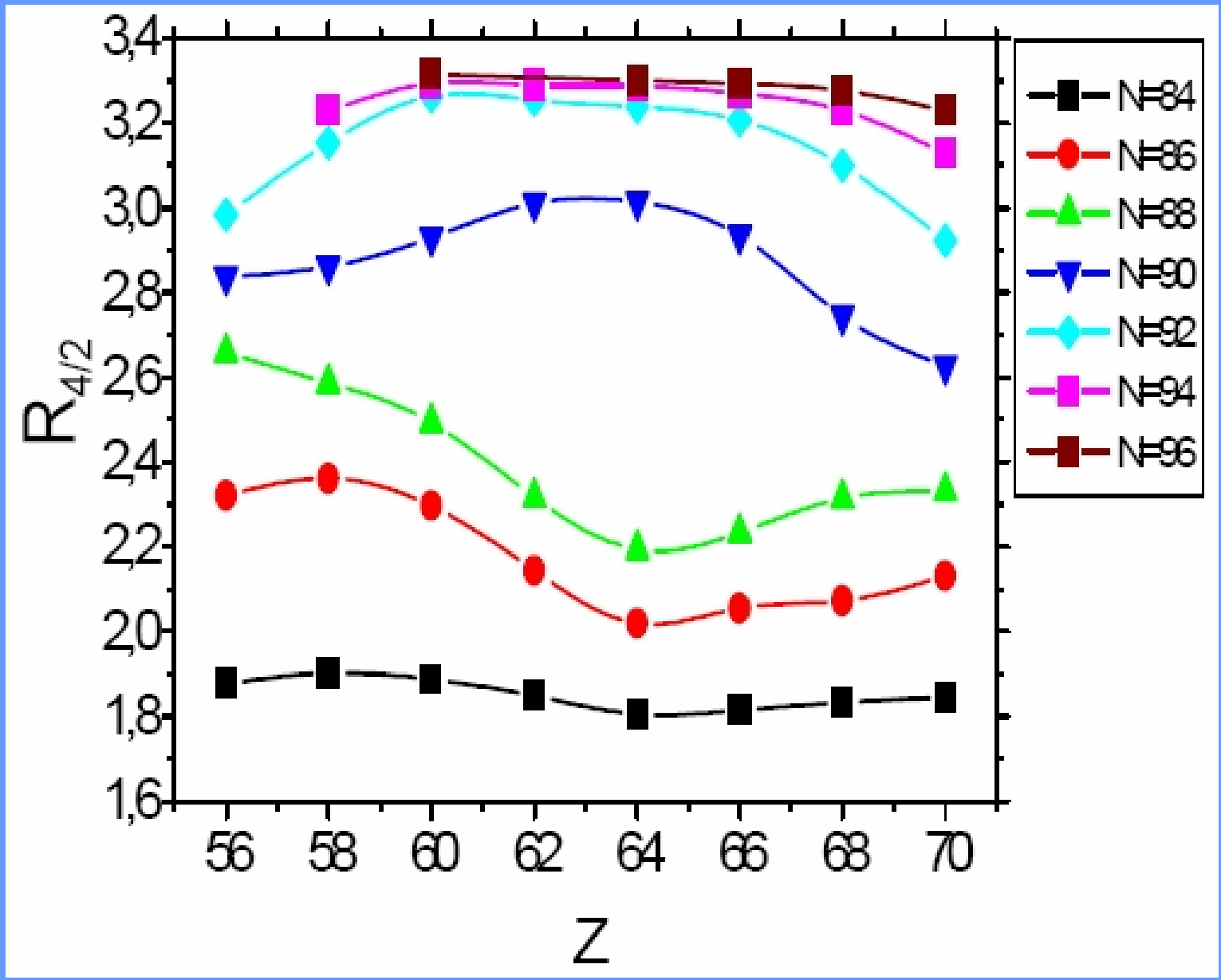
Two mechanisms

Monopole proton- neutron interactions (tensor?)

(everywhere)

Changes in shape of nuclear potential

(near drip lines – weakly bound nuclei)



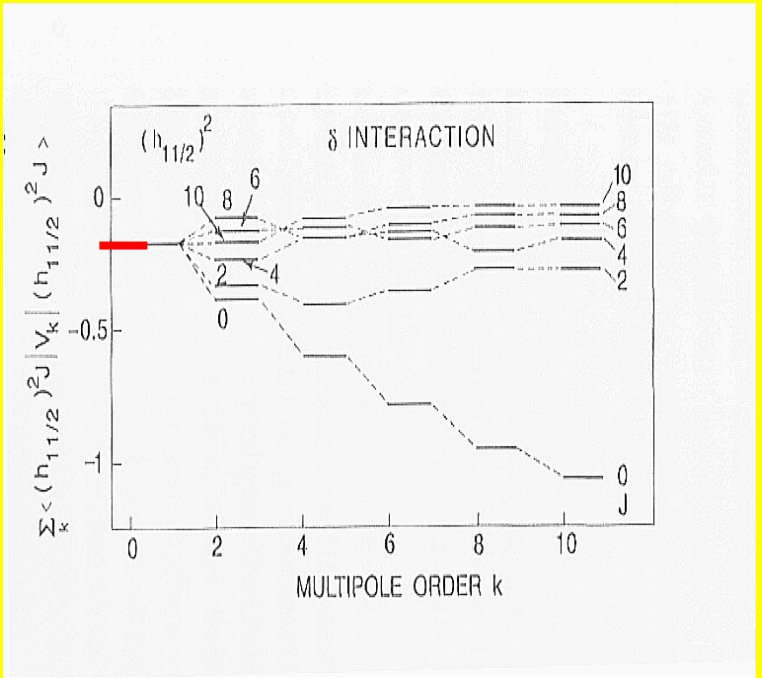
Direct empirical evidence of changing shell structure

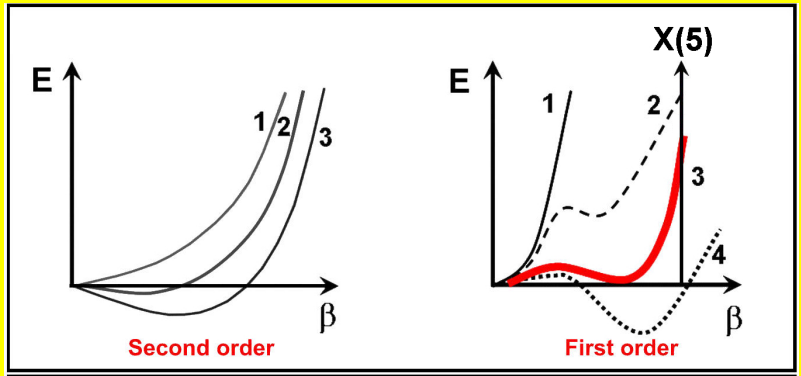
Microscopic mechanism for phase trans. behavior

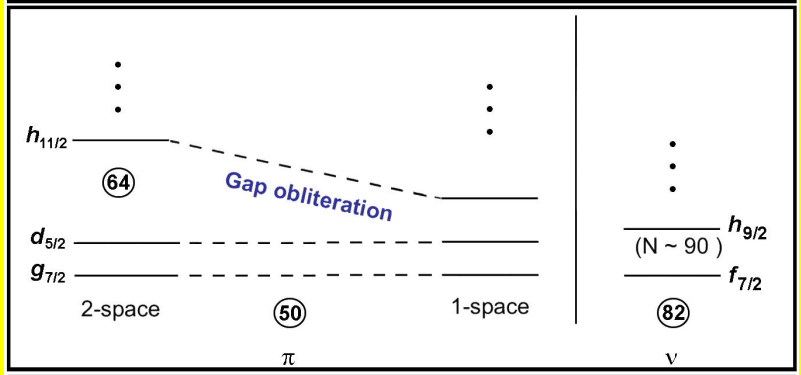
$$H\,(N\text{-}N) \sim H_{IPM.} + H_{resid.}$$

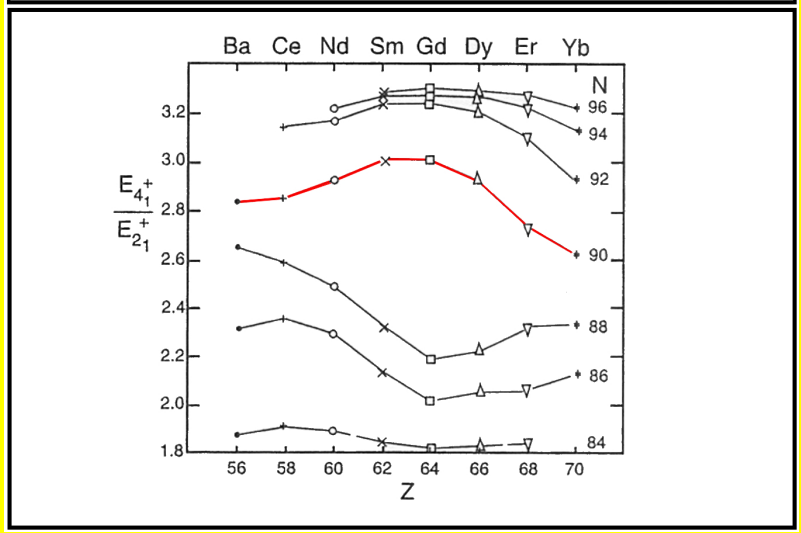
Multipole decomposition of 2-body Residual interactions

$$v\,(\bar{r}_{12}) = \sum_k v_k\, P_k\,(\cos\Theta)$$









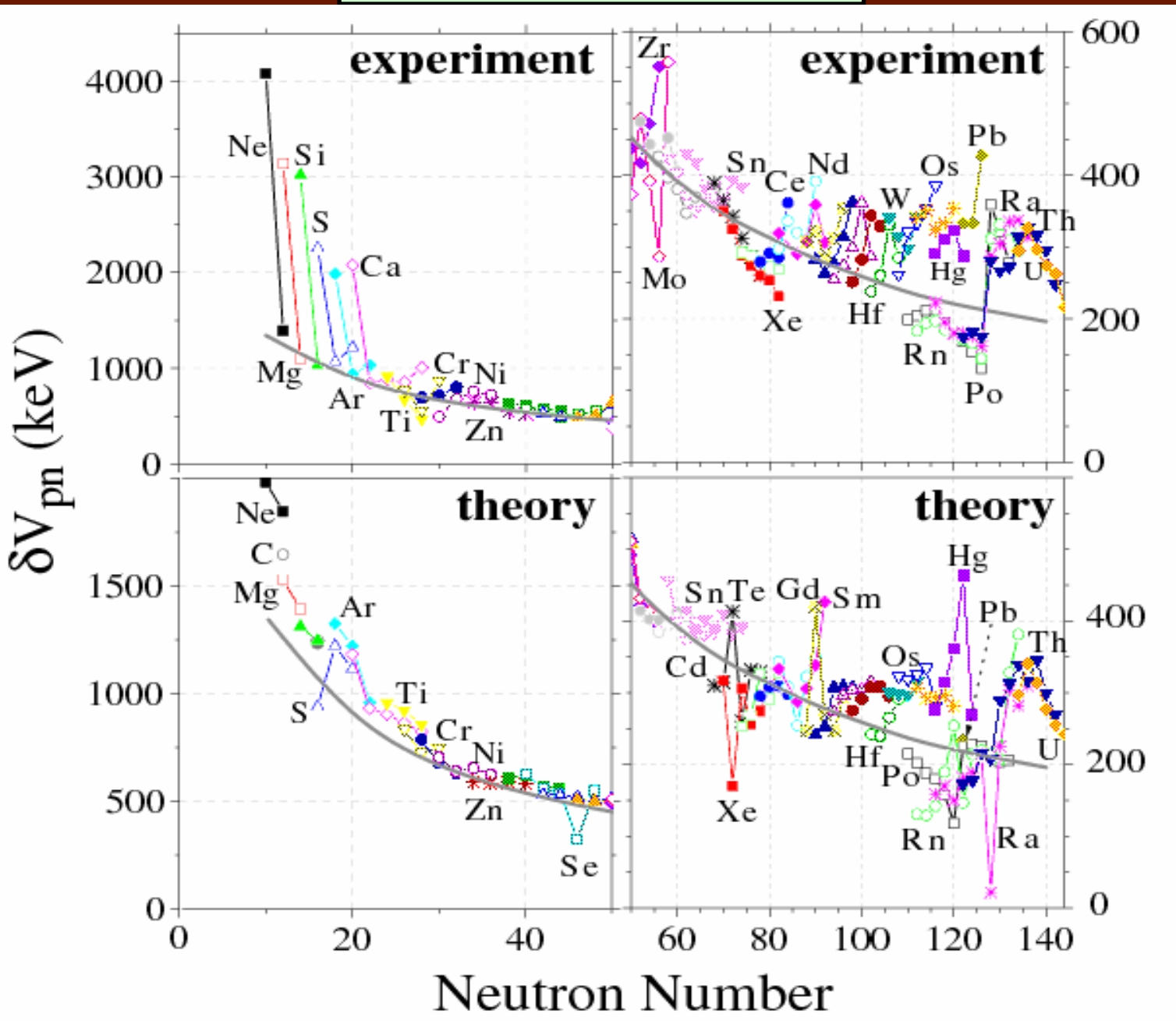
Part of the story – other orbits, tensor Forces ??

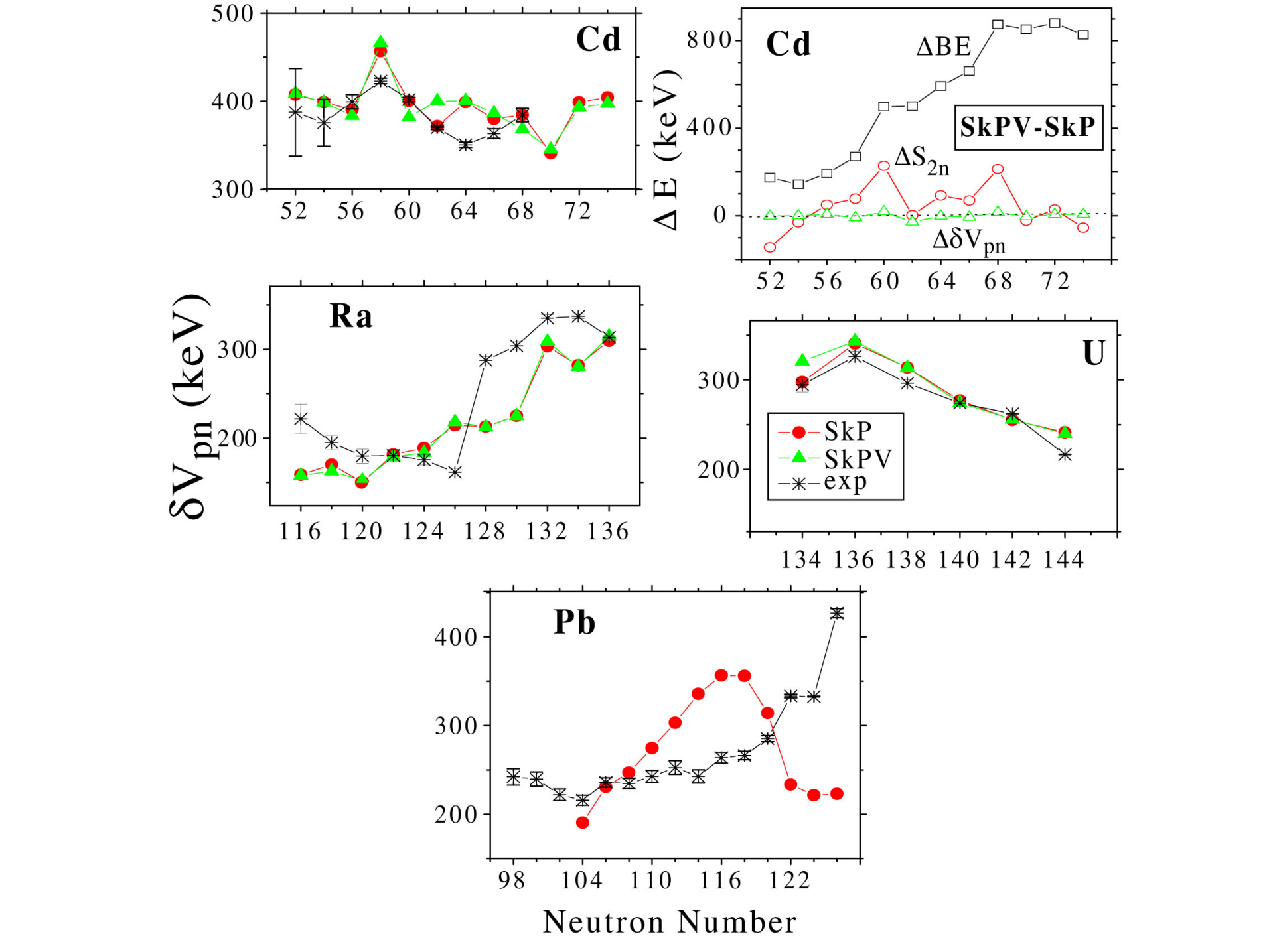
Realistic Calculations

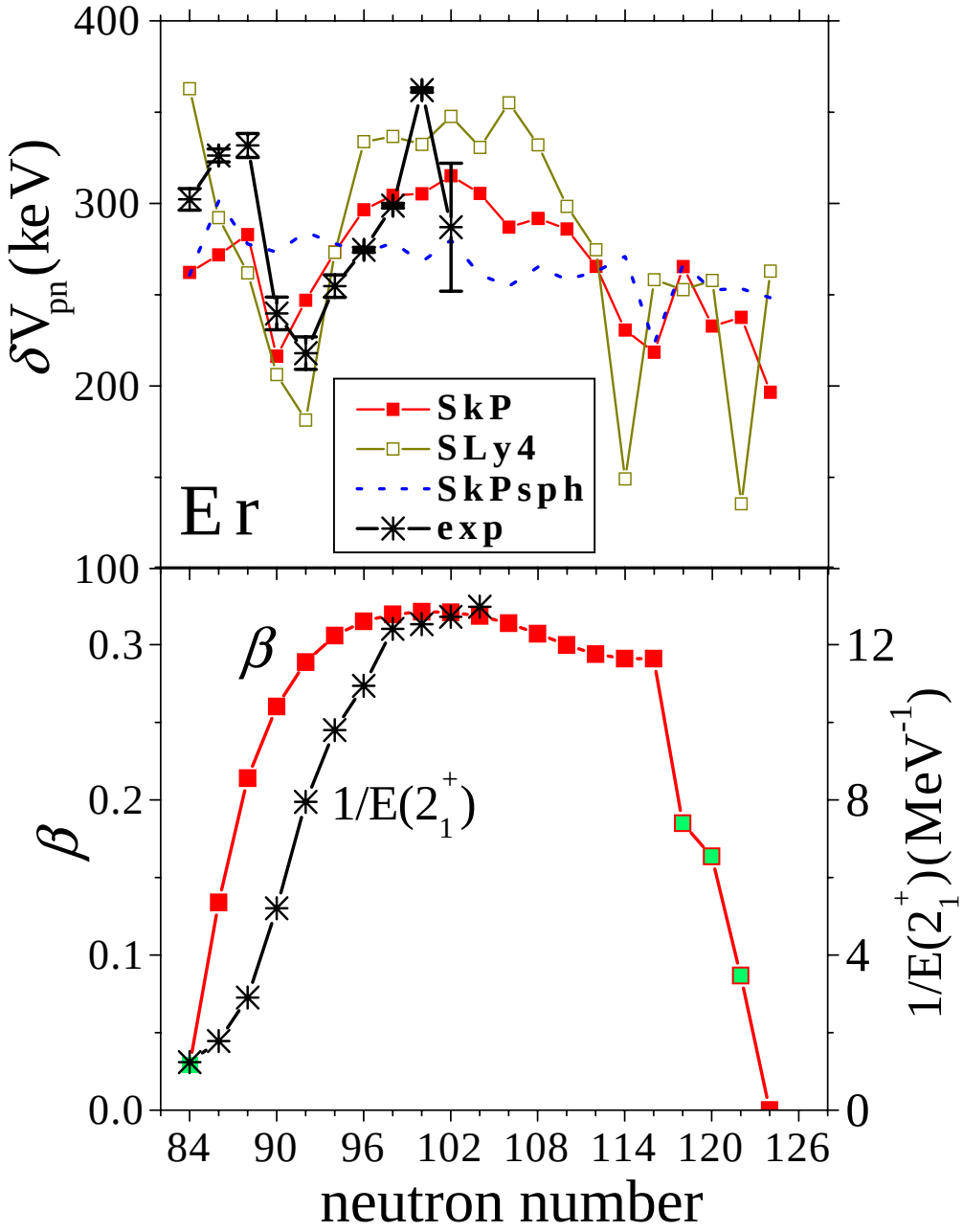
Microscopic Density Functional Calculations with Skyrme forces and different treatments of pairing

W. Nazarewicz, M. Stoitsov, W. Satula

Stable Nuclei



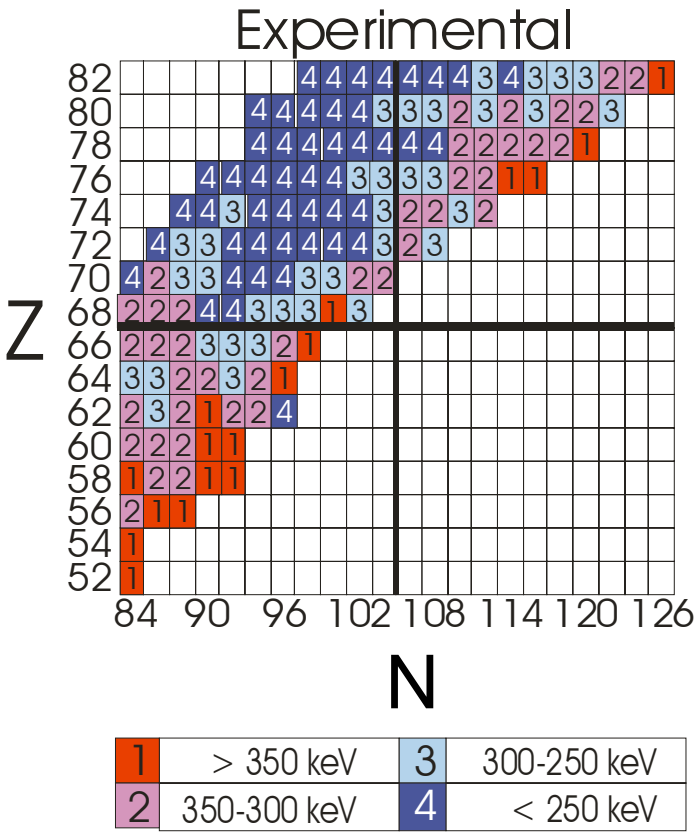

Cd
500
400
300
52
56
60
64
68
72
Cd
ΔBE
SkPV-SkP
ΔS2n
ΔδVpn
800
400
0
Δ E (keV)
52
56
60
64
68
72
Ra
δVpn (keV)
300
200
116
120
124
128
132
136
U
SkP
SkPV
exp
300
200
134
136
138
140
142
144
Pb
400
300
200
98
104
110
116
122
Neutron Number

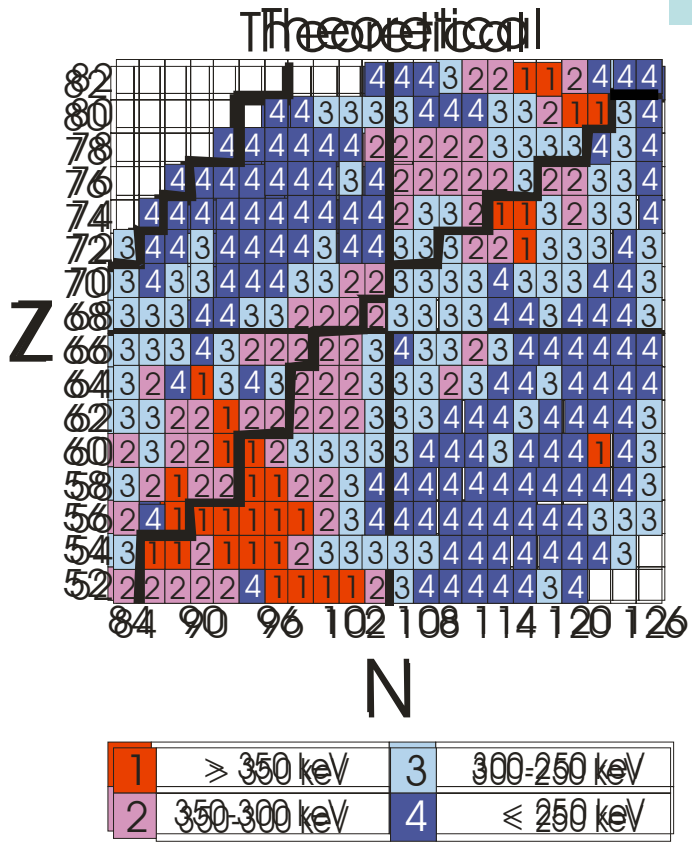

400
300
200
100
δV_{pn} (keV)
Er
SkP
SLy4
SkPsph
exp
0.3
0.2
0.1
0.0
β
$1/E(2_1^+)$
12
8
4
0
$1/E(2_1^+)(MeV^{-1})$
84
90
96
102
108
114
120
126
neutron number

Valence p-n Interactions

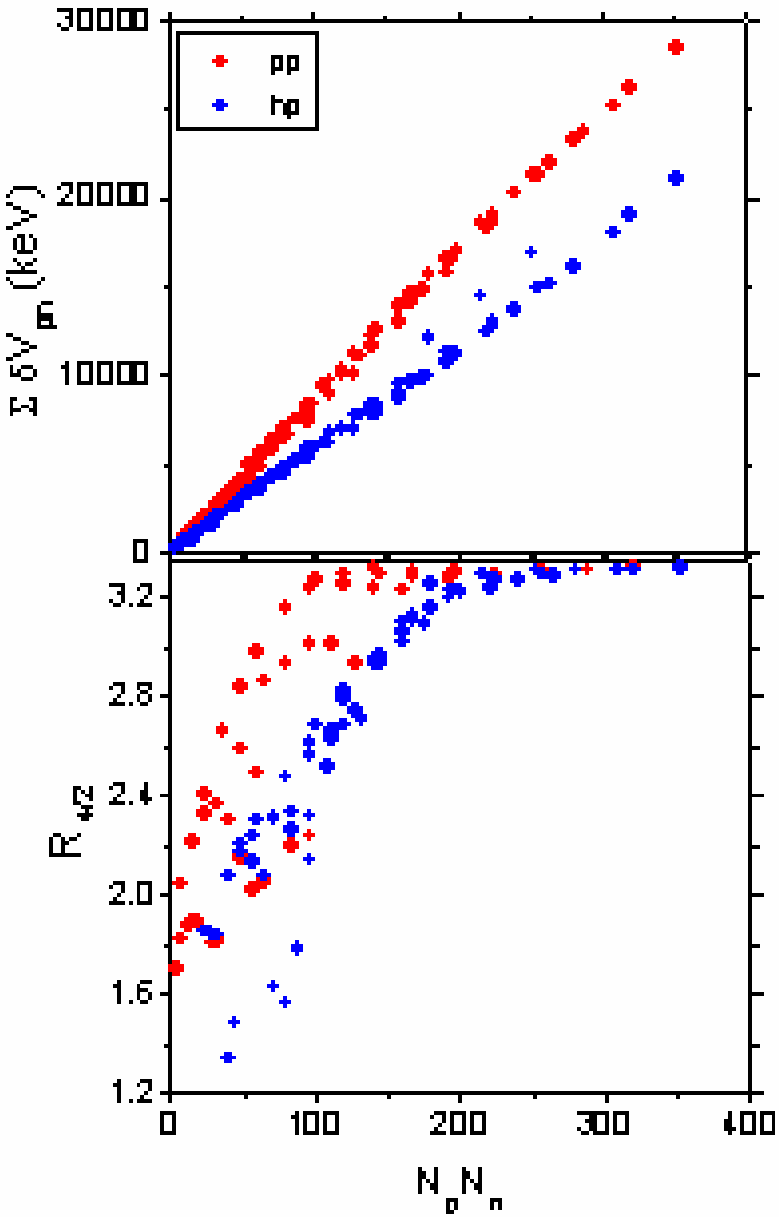
Regional comparison with microscopic calculations

DFT

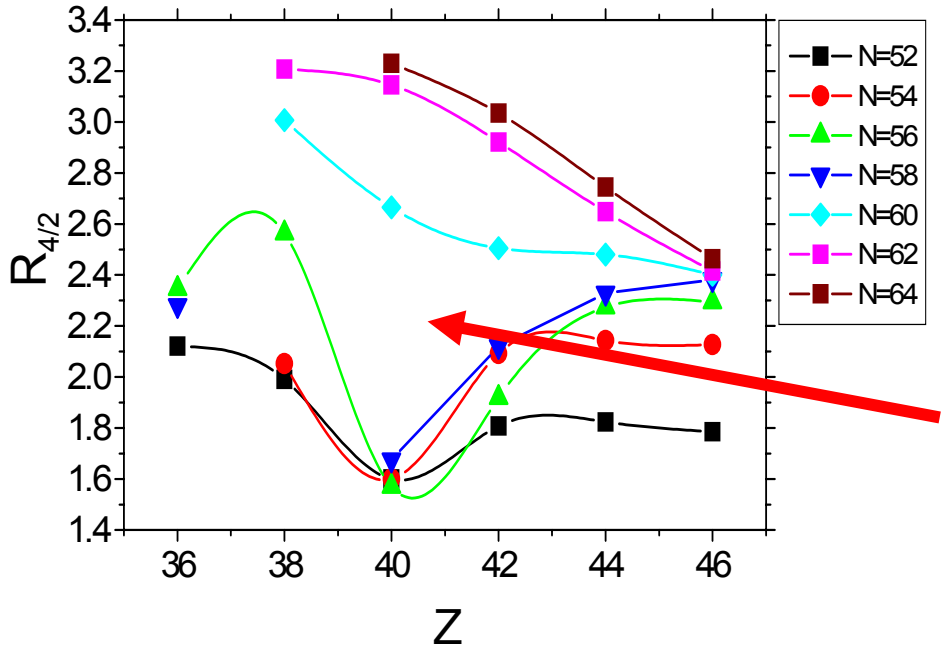




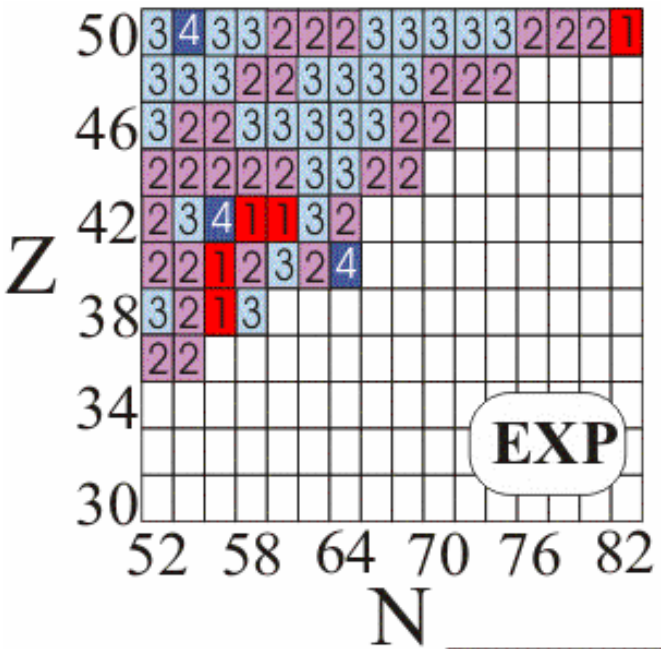
Integrated p-n interaction strengths and growth rates of collectivity

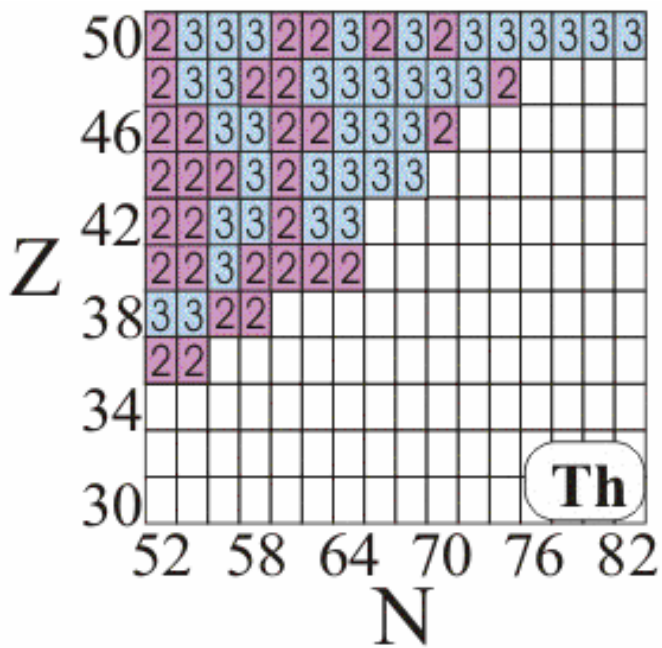


A ~ 100 region



Complex shape-changing region with shell gap change at N = 60 as in A ~ 150 region at N = 90





1	> 500 keV	3	400 - 350 keV
2	500 - 400 keV	4	< 350 keV

Collaborators

R. Burcu Cakirli

Daeg Brenner

Yesim Oktem

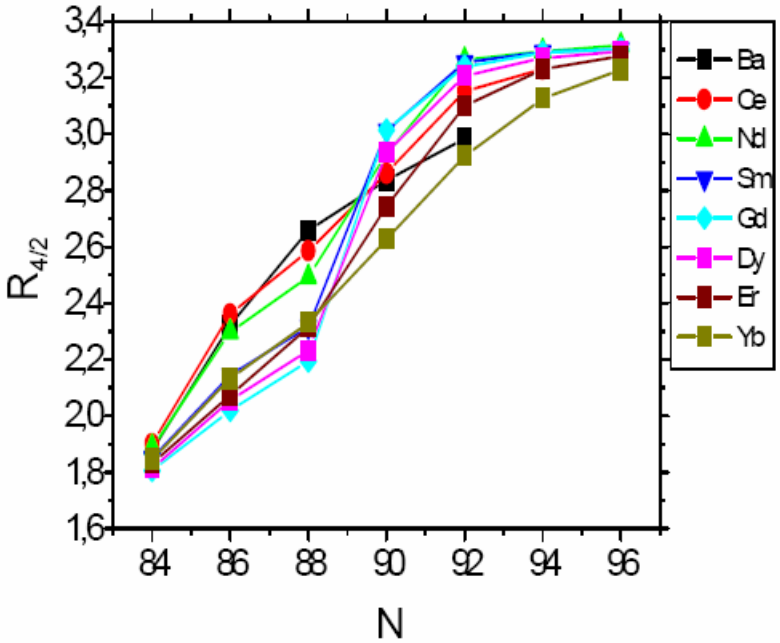
Robert Casperson

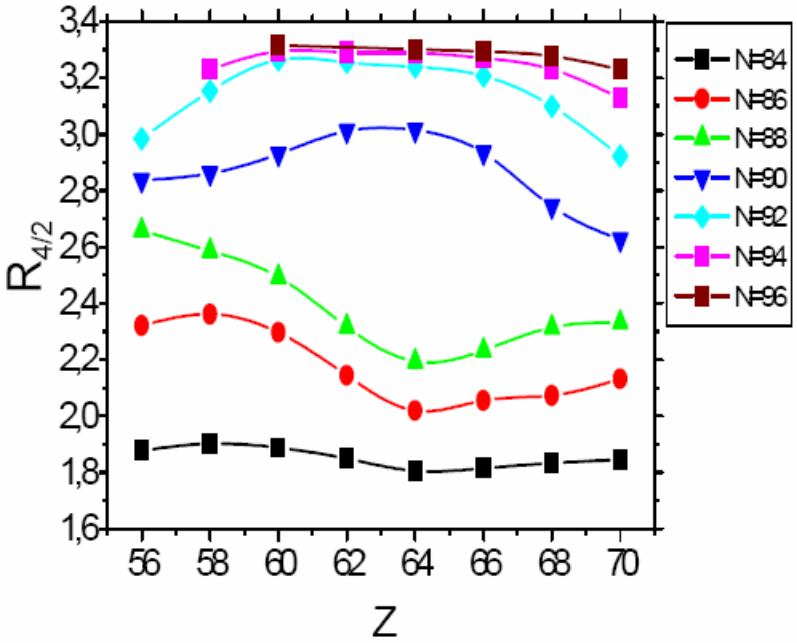
Witek Nazarewicz

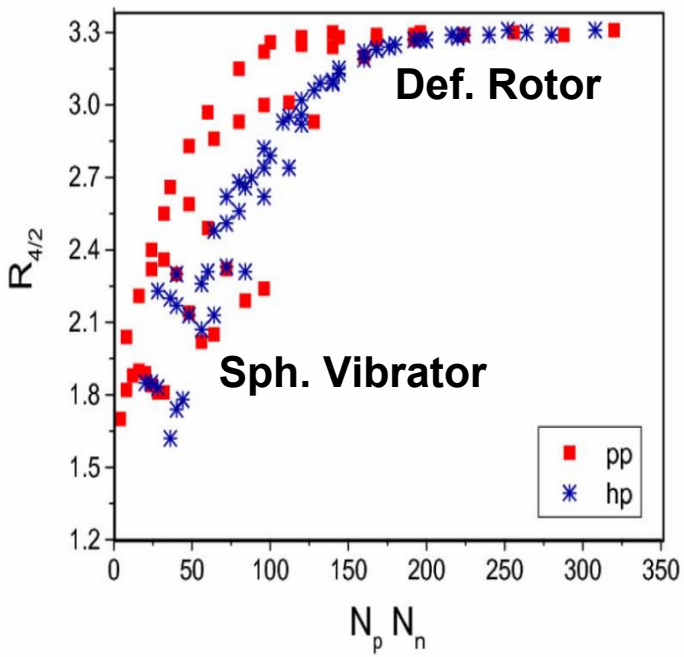
Mario Stoitsov

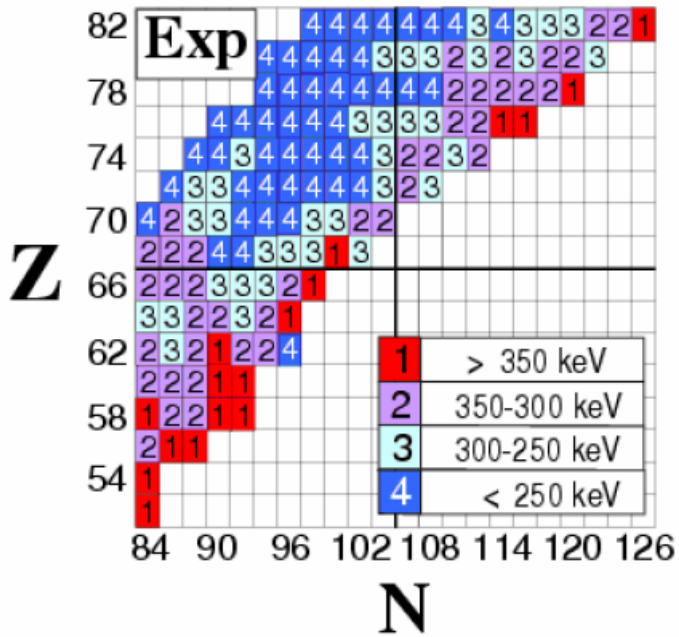
Wojciech Satula

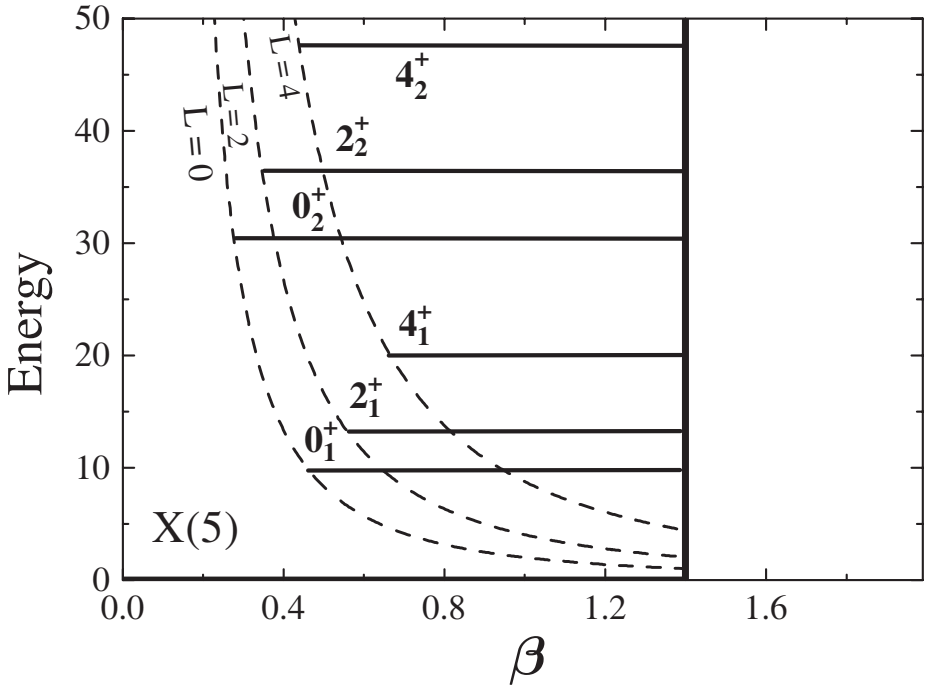
backups

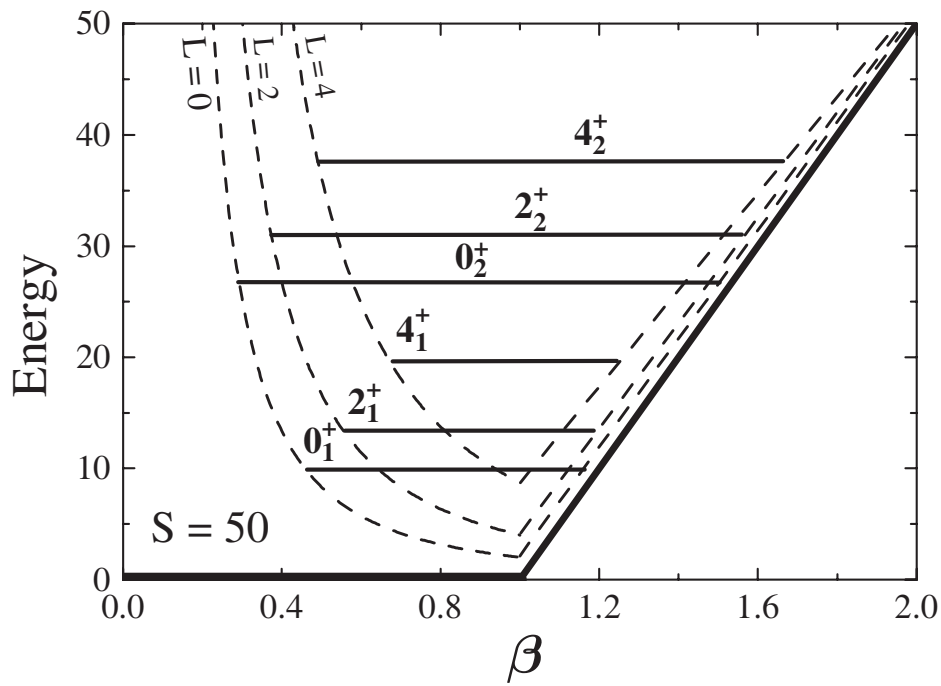

$R_{4/2}$
N
Ba
Ce
Nd
Sm
Gd
Dy
Er
Yb

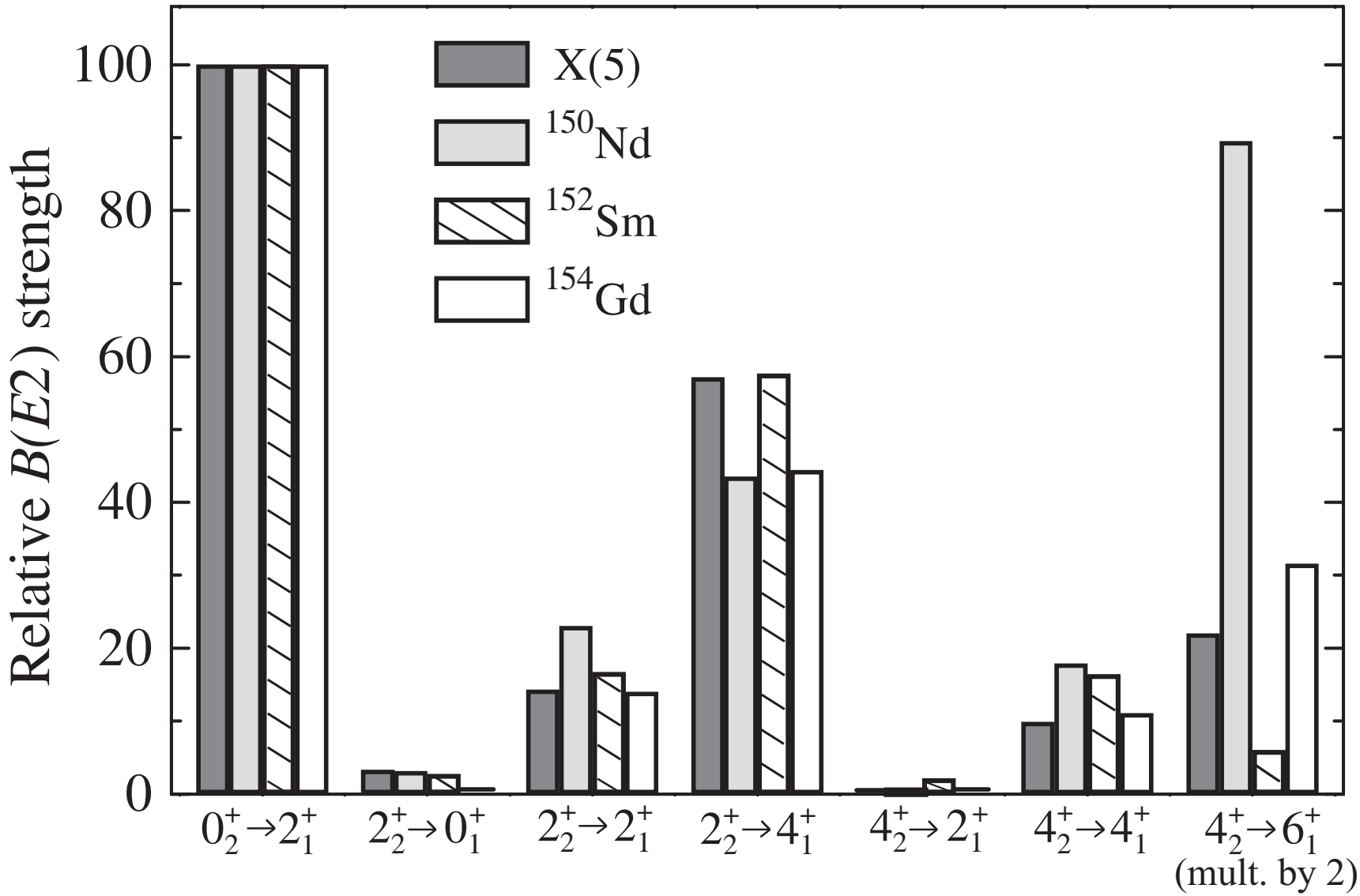

$R_{4/2}$
Z
N=84
N=86
N=88
N=90
N=92
N=94
N=96


$R_{4/2}$
N_p N_n
Def. Rotor
Sph. Vibrator
pp
hp


Exp
Z
N
1 > 350 keV
2 350-300 keV
3 300-250 keV
4 < 250 keV


Energy
β
X(5)
L = 0
L = 2
L = 4
0_1^+
2_1^+
4_1^+
0_2^+
2_2^+
4_2^+

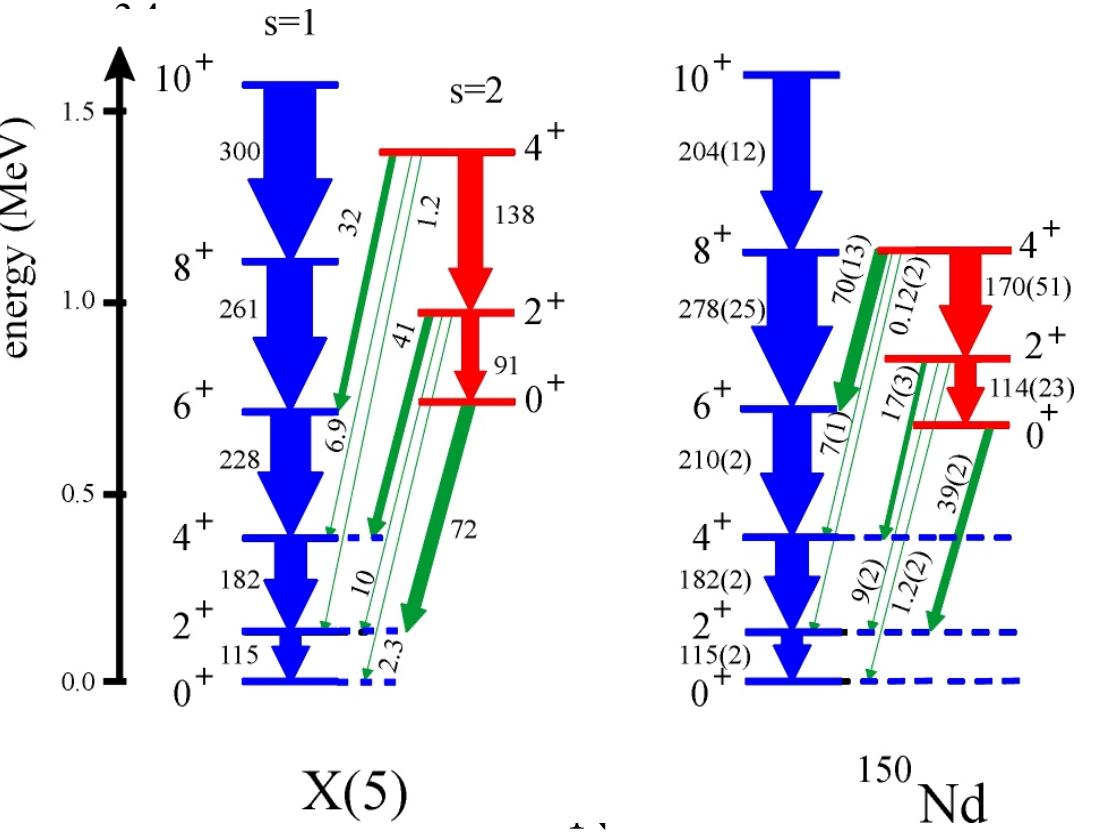

Energy
β
S = 50
L = 0
L = 2
L = 4
0_1^+
2_1^+
4_1^+
0_2^+
2_2^+
4_2^+

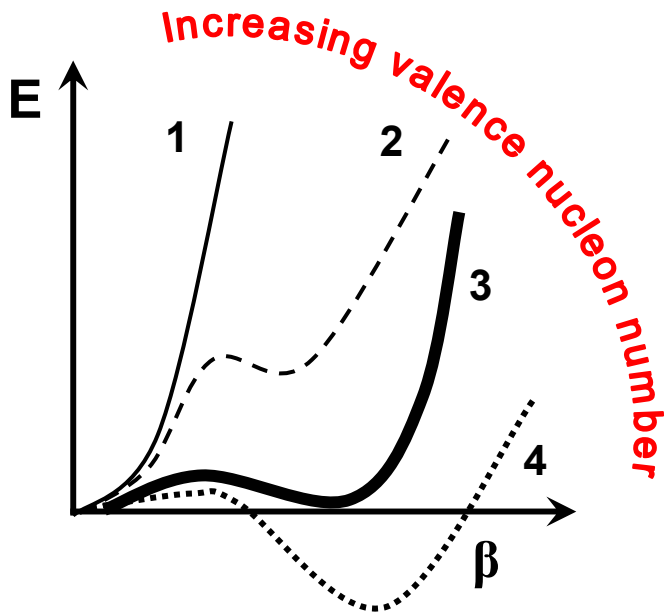

Relative B(E2) strength
100
80
60
40
20
0
X(5)
150Nd
152Sm
154Gd
0+2→2+1
2+2→0+1
2+2→2+1
2+2→4+1
4+2→2+1
4+2→4+1
4+2→6+1
(mult. by 2)

The evolution of collective motion in complex nuclei: ***Heavier nuclei exhibit novel collective properties. In many cases, these regularities arise from underlying symmetries. Goals include identifying the relevant collective coordinates, understanding their connections to these symmetries, and how [they] arise from microscopic theory. One example is the sharp structural change in nuclear ground states that occurs in certain mass regions.***

Quantum phase transitions in equilibrium shapes of nuclei with *N*, *Z*

Critical Point Symmetries – A new paradigm





Themes in Nuclear Structure

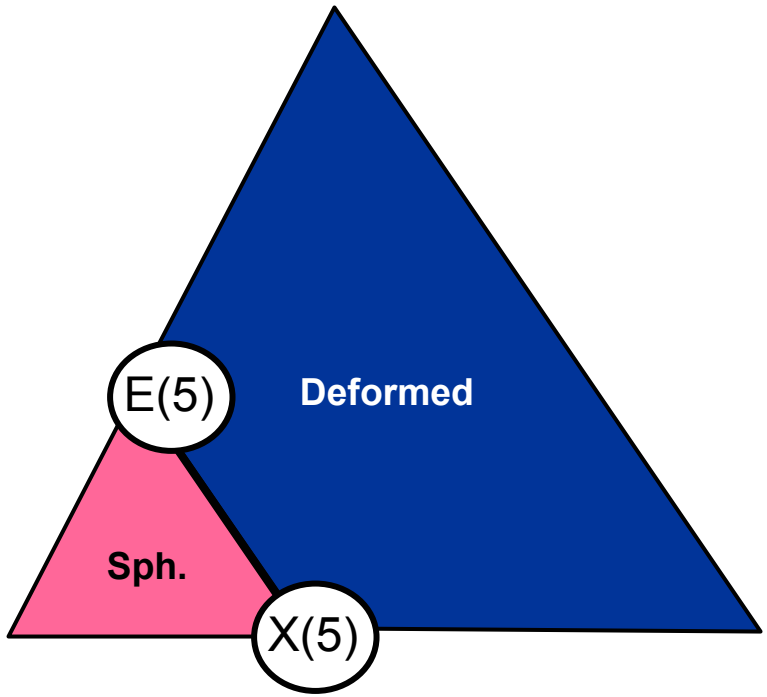
- **Changing Shell Structure – The nucleonic foundation of nuclear behavior – changing paradigms after half a century**
- **The evolution of structure – Symmetries, phase transitions, and critical points -- simplicity in complex nuclei**
- **Nucleonic interactions – especially pairing and p-n**
- **The limits of nuclear existence**
- **The heaviest nuclei – Quantal binding**
- **The links to Astrophysics, and exploiting opportunities to test fundamental symmetries**

Classifying Equilibrium Collective Structure – The Casten Triangle

Benchmarks/paradigms

Dynamical Symmetries (the IBA)

Phase/shape Transitions(Critical Point Symmetries)



Most nuclei do not exhibit the idealized symmetries but rather lie in transitional regions.
Trajectories of structural evolution