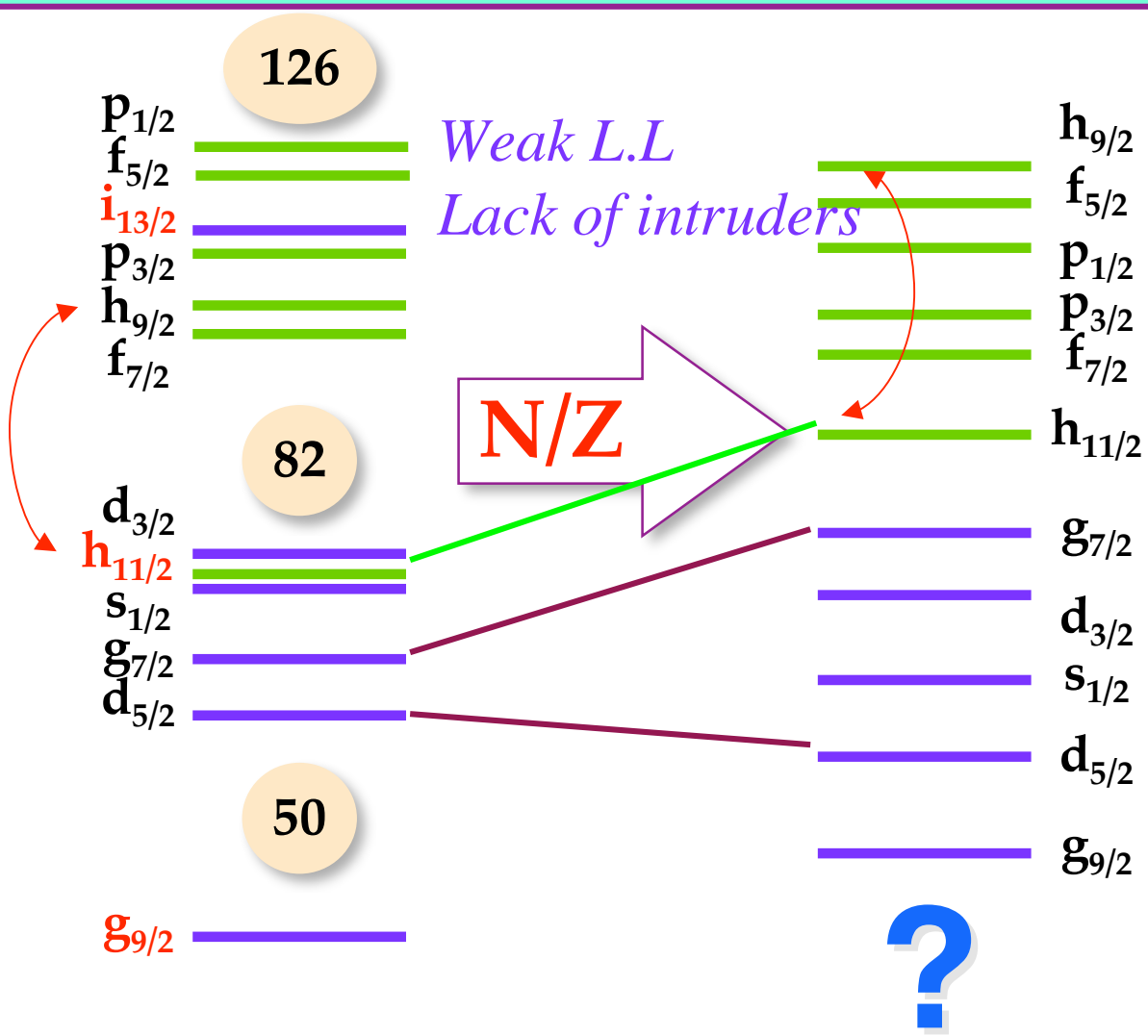
Probing Shell Structures Through Properties of the Low-Lying States

Cyrus Baktash
Oak Ridge National Laboratory

Joint JUSTIPEN-LACM Meeting, Oak Ridge, March 2007

Modification of shell structure near n drip line



Around the valley of nuclear stability
N/Z ≈ 1 - 1.6

Neutron-rich nuclei
N/Z ≈ 3

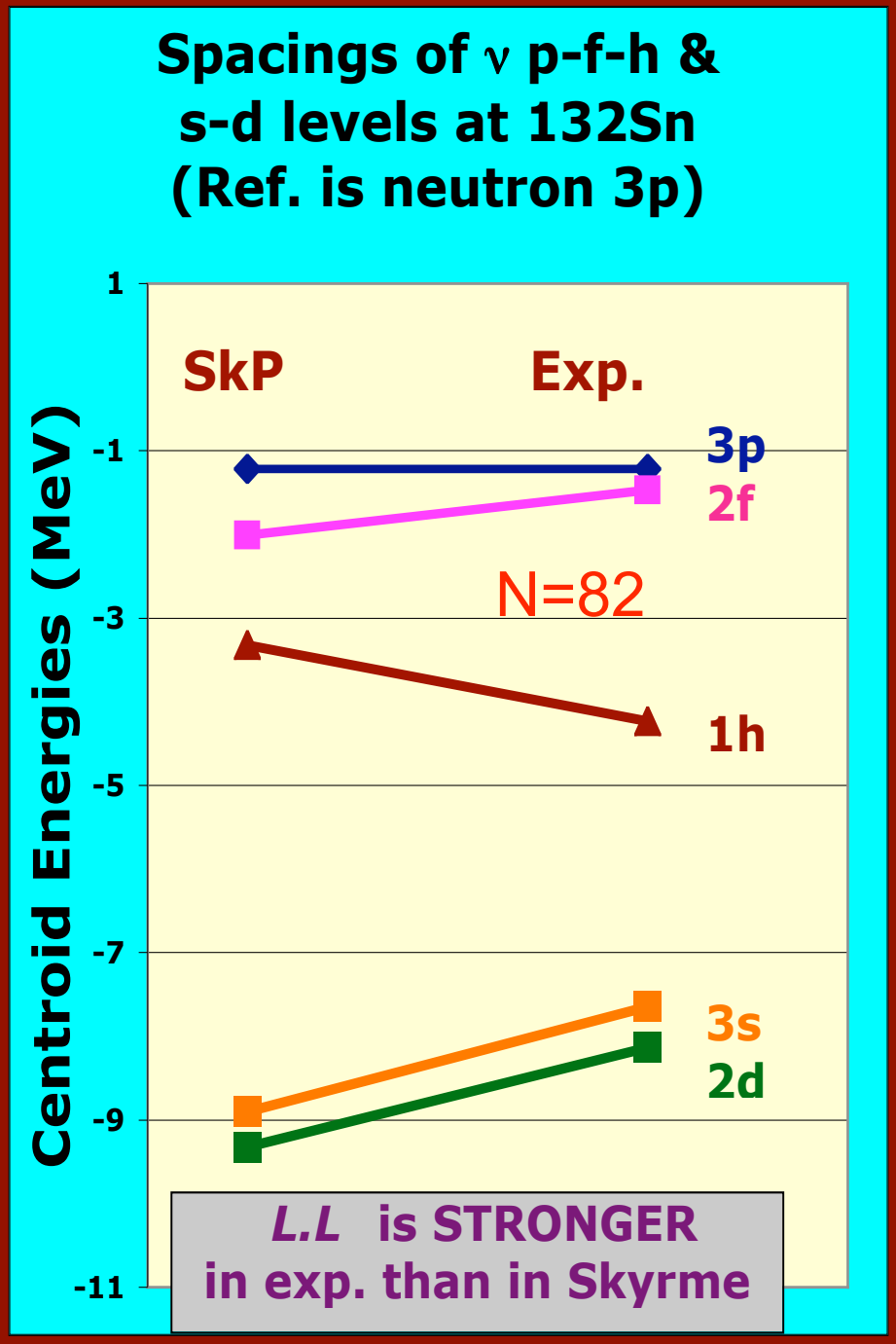
Questions:

- **What is the shell structure near neutron drip line?**
- **How to experimentally determine the new magic numbers?**
- **How to distinguish the conventional from drip-line physics?**

(single particle energies move around due to many factors, unrelated to drip line physics!)

If we observe discrepancies between experiments and Skyrme calculations near ^{132}Sn, it cannot be due to a weak L.L in theory.

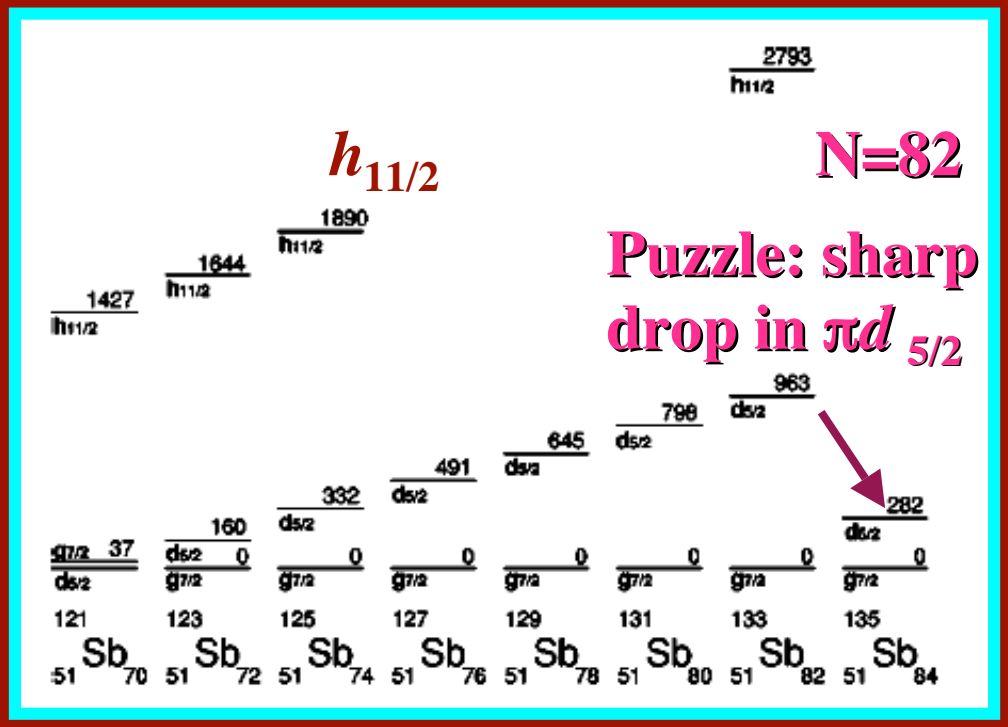
We should look for the answer elsewhere.



PHYSICAL REVIEW C, VOLUME 65, 034313

β-decay studies of $^{135-137}$Sn using selective resonance laser ionization techniques

J. Shergur,[1] B. A. Brown,[2] V. Fedoseyev,[3] U. Köster,[4] K.-L. Kratz,[5] D. Seweryniak,[1,6] W. B. Walters,[1] A. Wöhr,[1] D. Fedorov,[7] M. Hannawald,[5] M. Hjorth-Jensen,[8] V. Mishin,[3] B. Pfeiffer,[5] J. J. Ressler,[1] H. O. U. Fynbo,[4] P. Hoff,[9] H. Mach,[10] T. Nilsson,[4] K. Wilhelmsen-Rolander,[11] H. Simon,[4] A. Bickley,[1] and the ISOLDE Collaboration[4]



$d_{5/2}$ is too high in Shell models

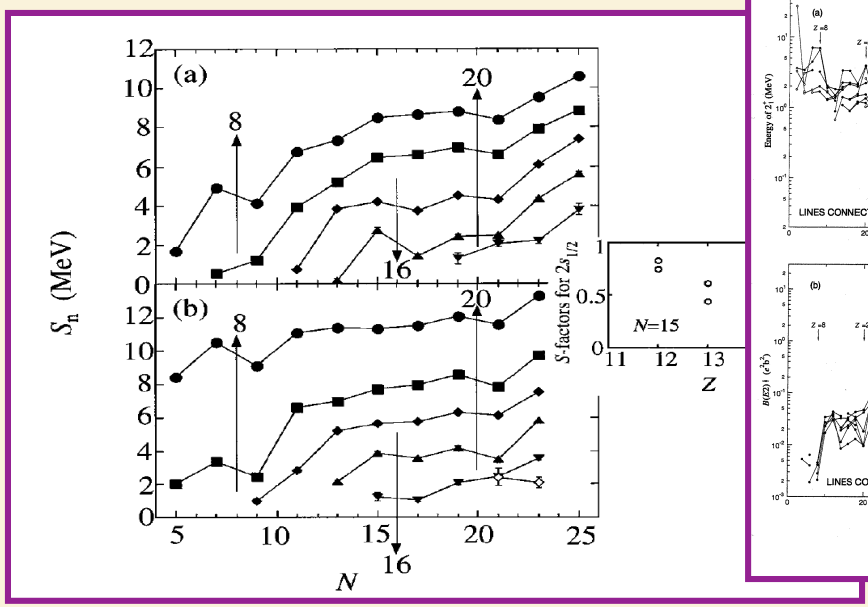
A. Brown artificially lowers the energy of $d_{5/2}$ by 300 keV to fit data;

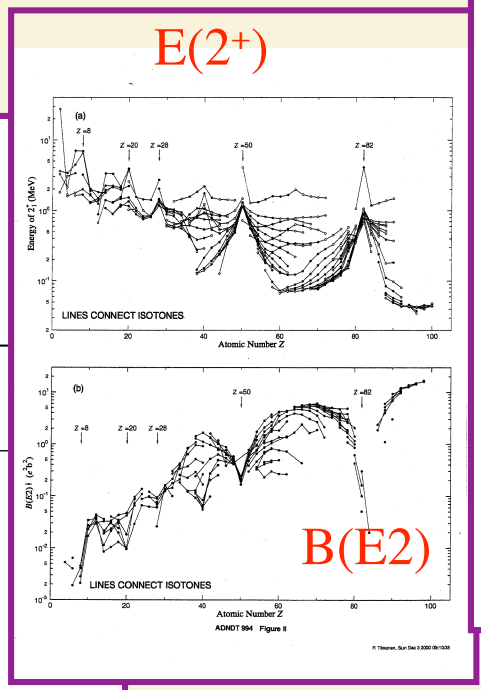
Justification: Neutron skin

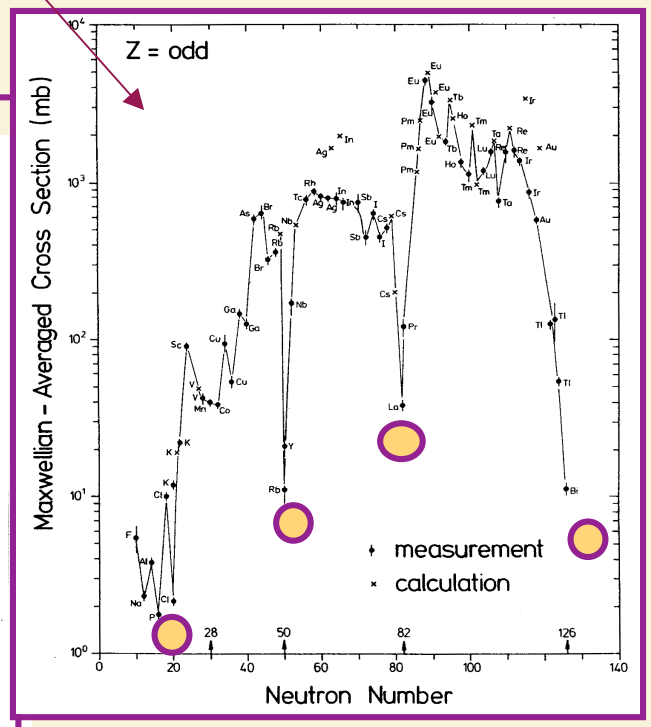
Signatures of large shell gaps & magic numbers

Combinations of:

- Kinks in *1n* and *2n* separation energies
- Large E(2$^+$) and small B(E2) -- signature of rigid spheres
- Small σ(n,γ) (peaks in element abundances)
- Kinks in single-particle energies
- Kinks in g-factors
- Kinks in radii





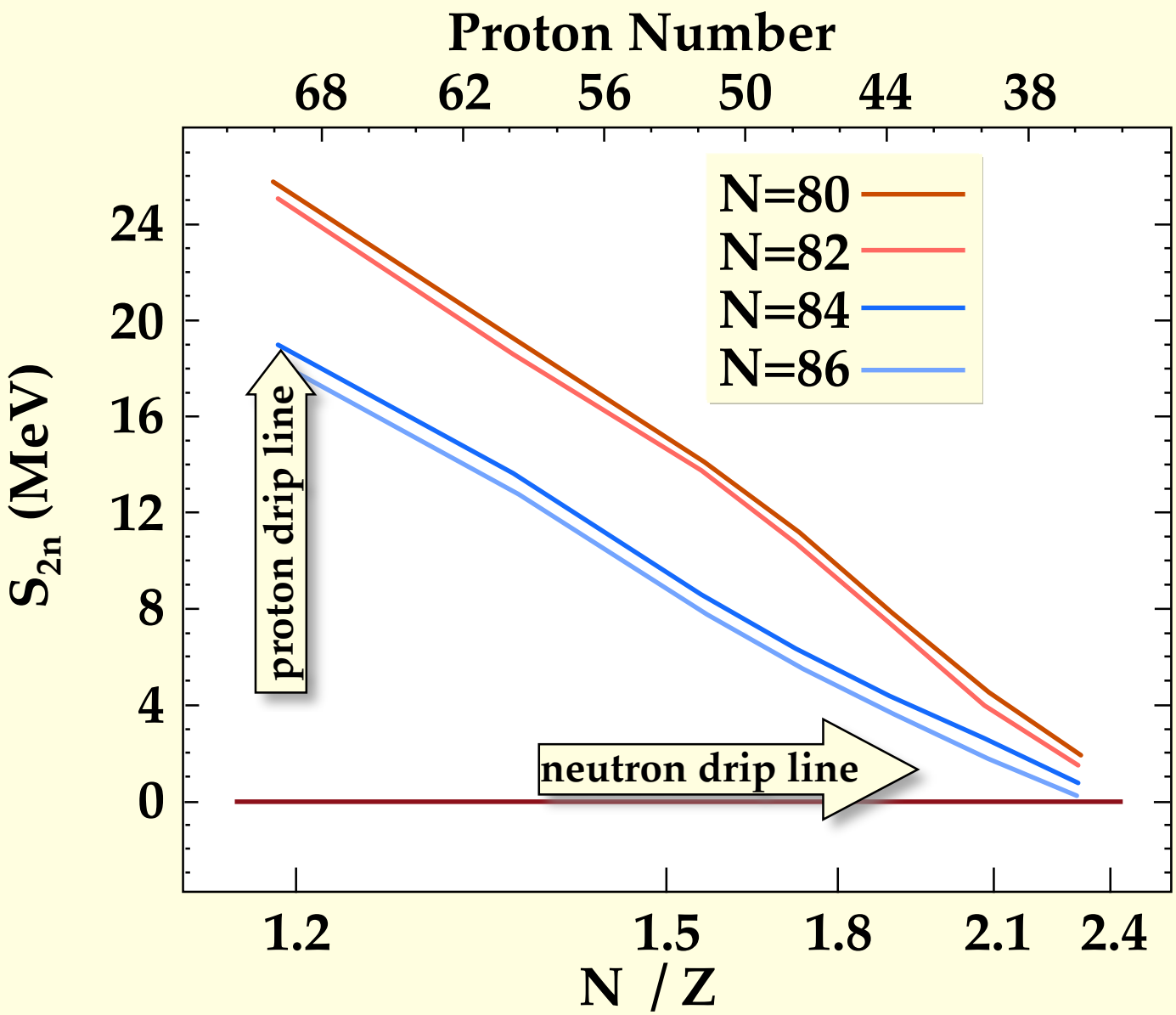


Ozawa *et al.*, Phys. Rev. Lett. 84 (2000) 5493

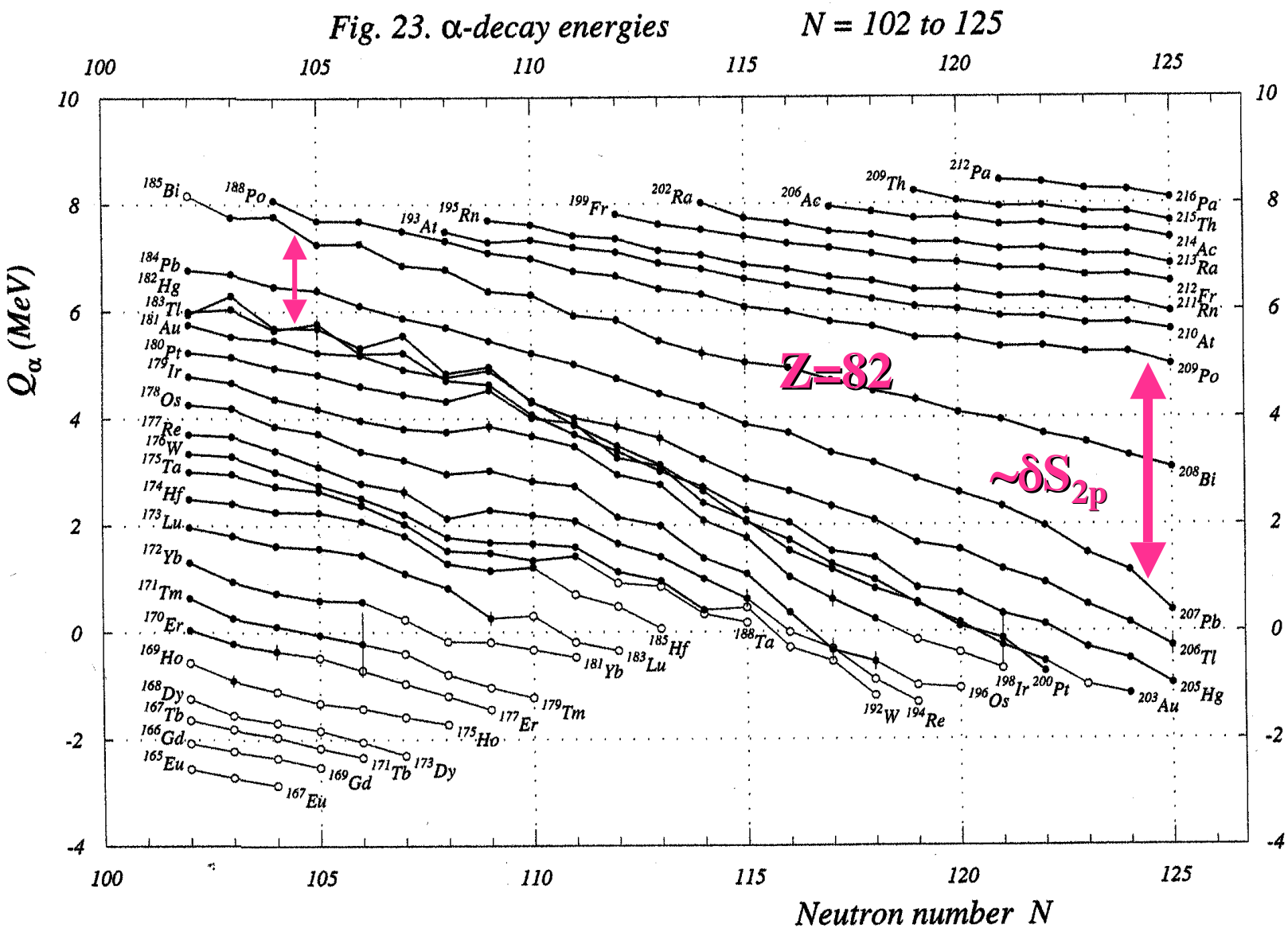
Measurements to probe shell structure far from stability

- *Gross properties:*
  - Masses (binding energies)
  - Half lives
  - Radii
  - Level densities
  - $\sigma(n,\gamma)$ -- related to r-process abundances, [use (*d*,*p*)]
- *Single-particle properties:*
  - Energy, spin, parity, spectroscopic factors, g-factors
  - Parallel momenta in knock out reactions (fast beams)
- *Collective properties:*
  - Low-lying energy spectra (*e.g.,* 2^+ states, 4^+)
  - B(E2) & electromagnetic moments
  - Higher spin states (band structures)

Evolution of shell structure: Weakening of shell gaps manifest in S_{2n} & S_{2p}

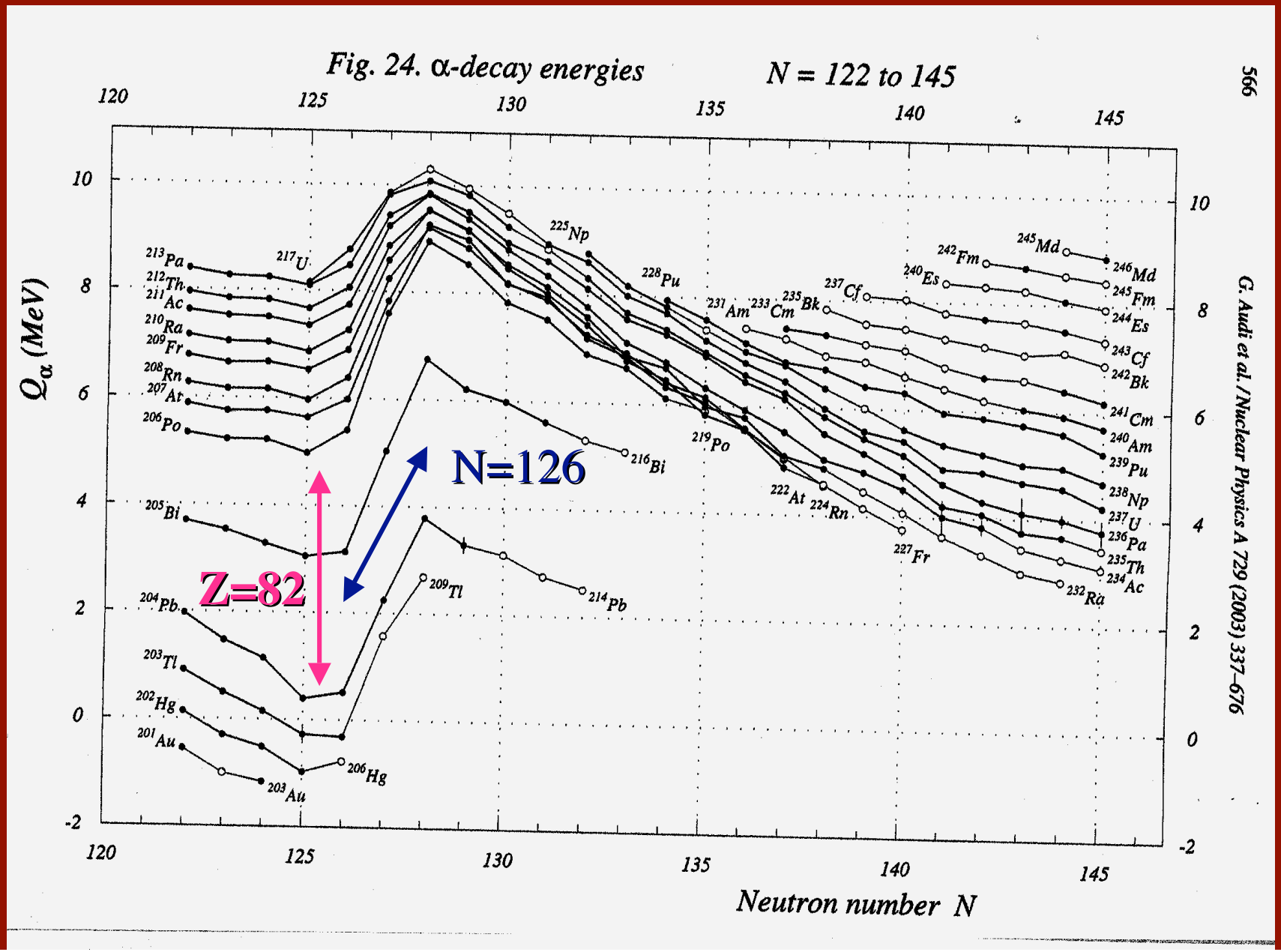


Widening of Z = 82 gap with increasing N
or, shrinkage of Z=82 with proton-rich

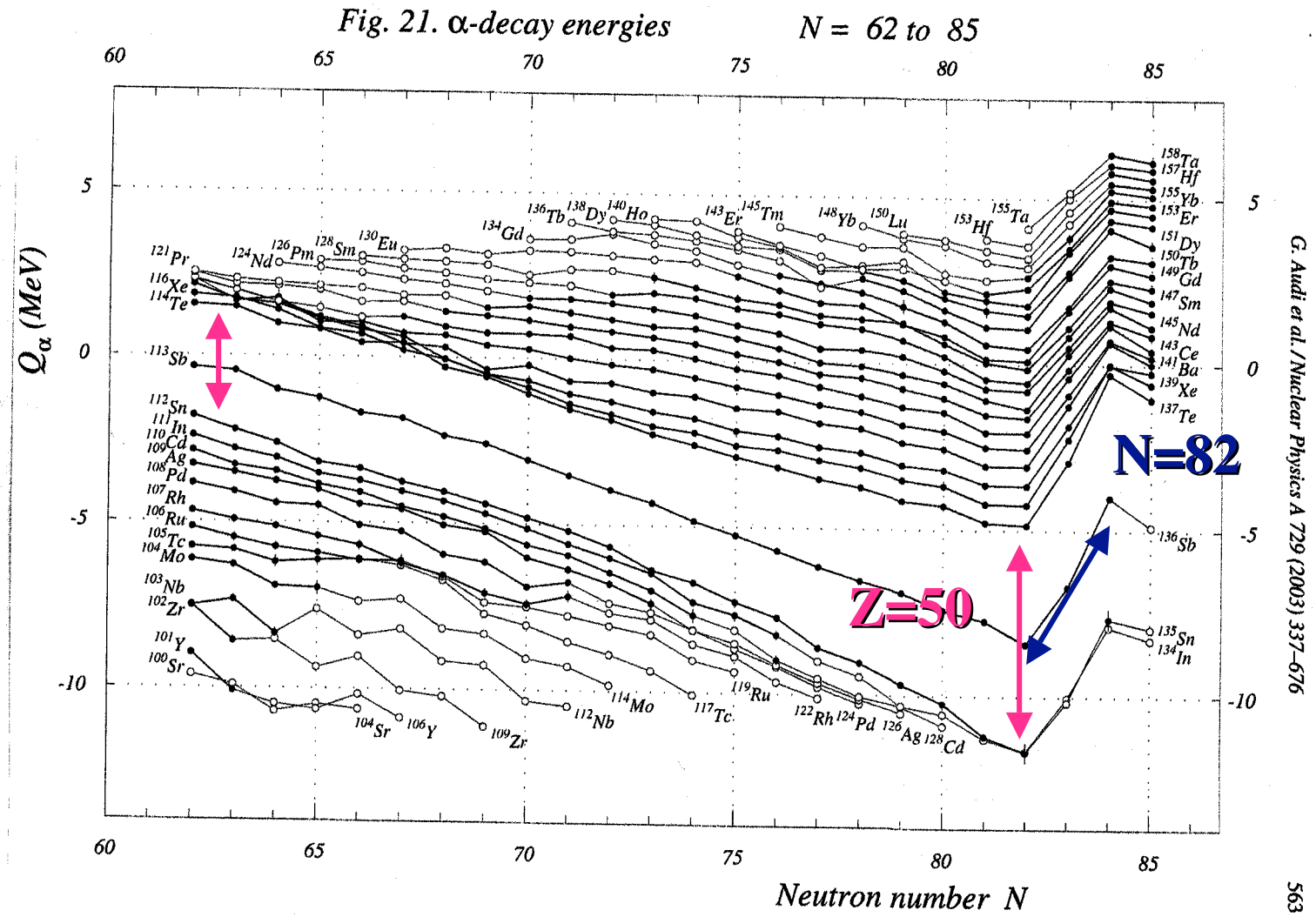


G. Audi et al. / Nuclear Physics A 729 (2003) 337–676

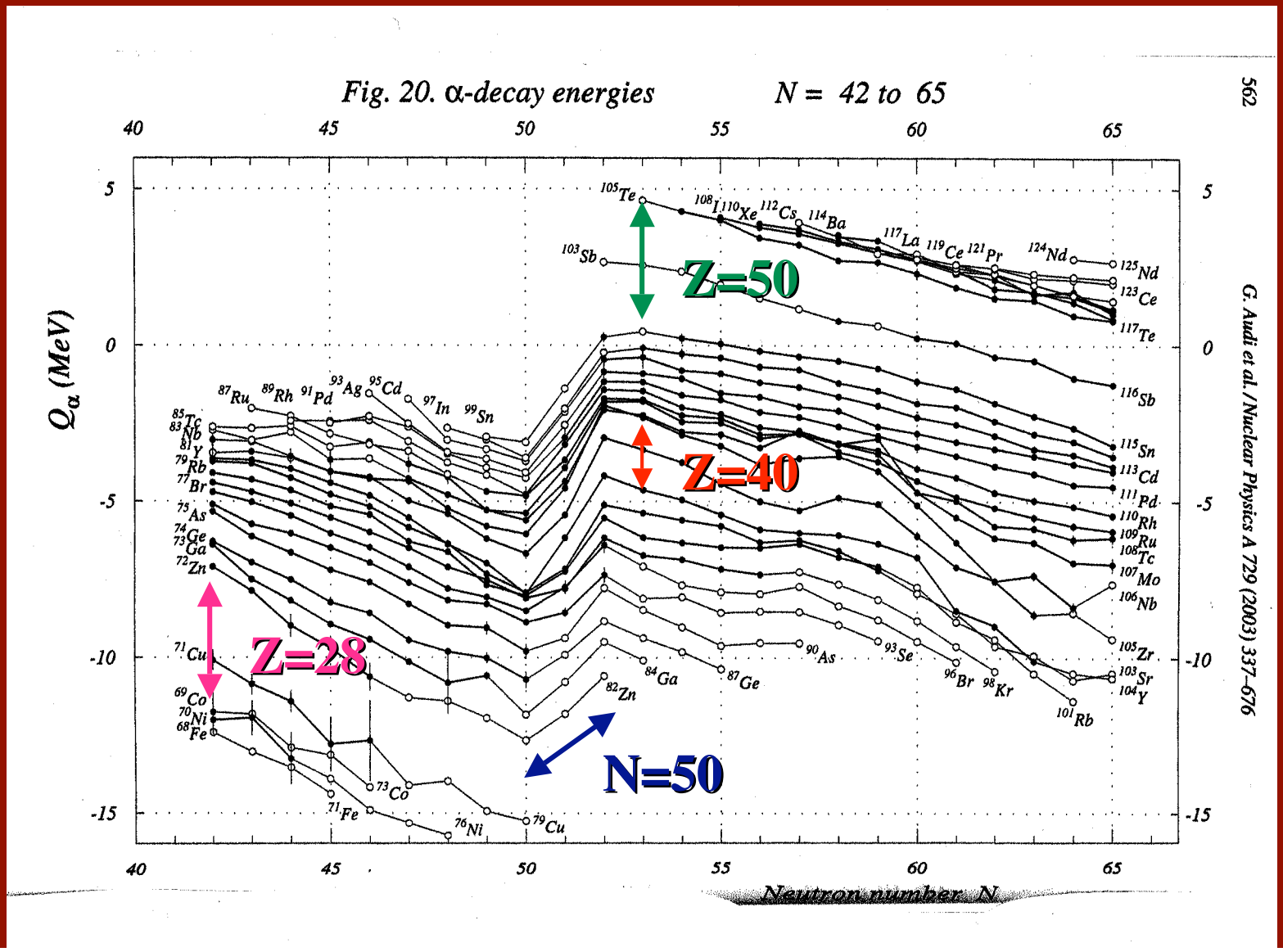
Z= 82 and N=126 are robust shell gaps



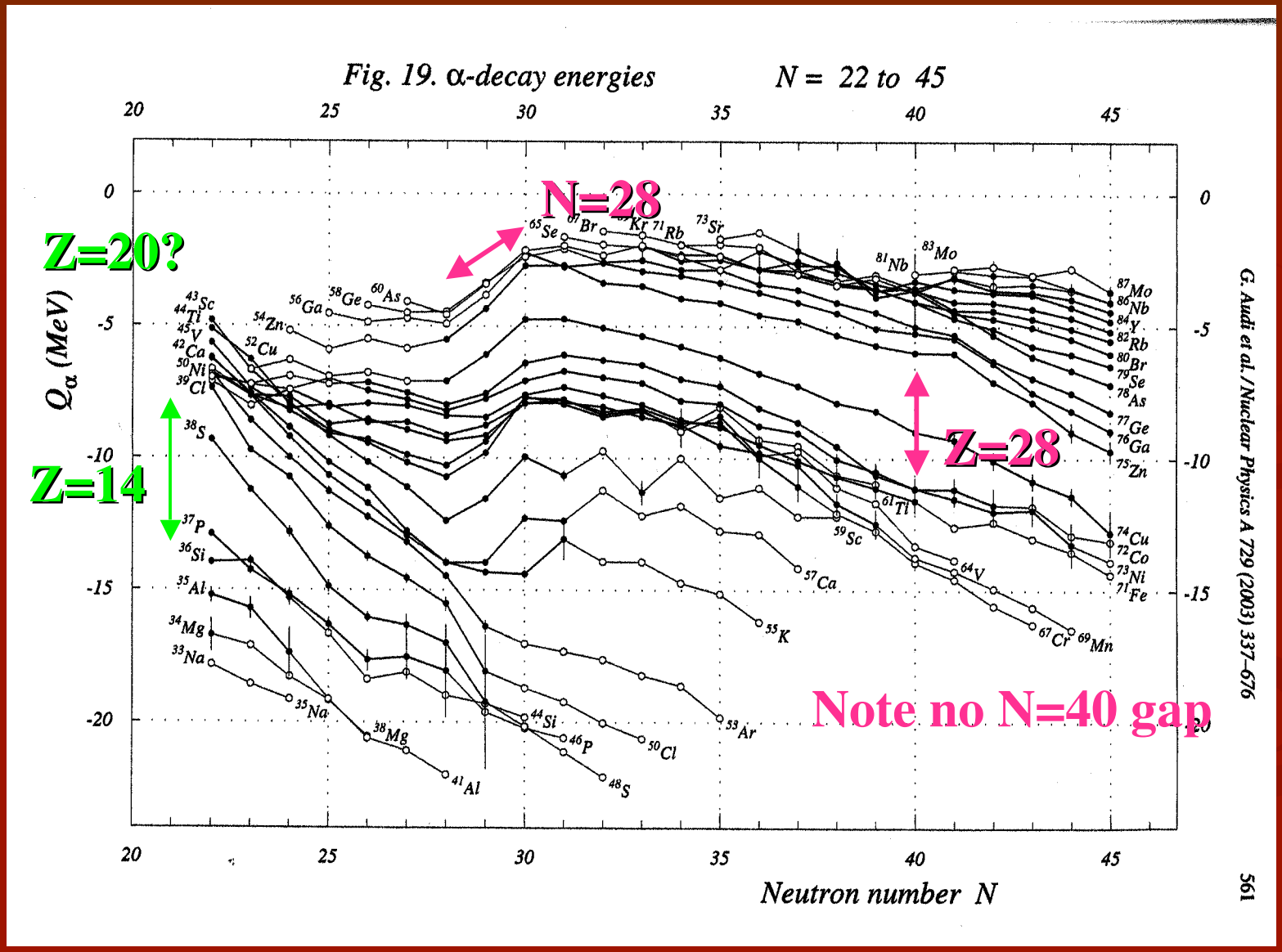
Z=50 is robust and increases with N



Z=28 and N=50 gaps are respectable.
A small Z=40 gap also appears

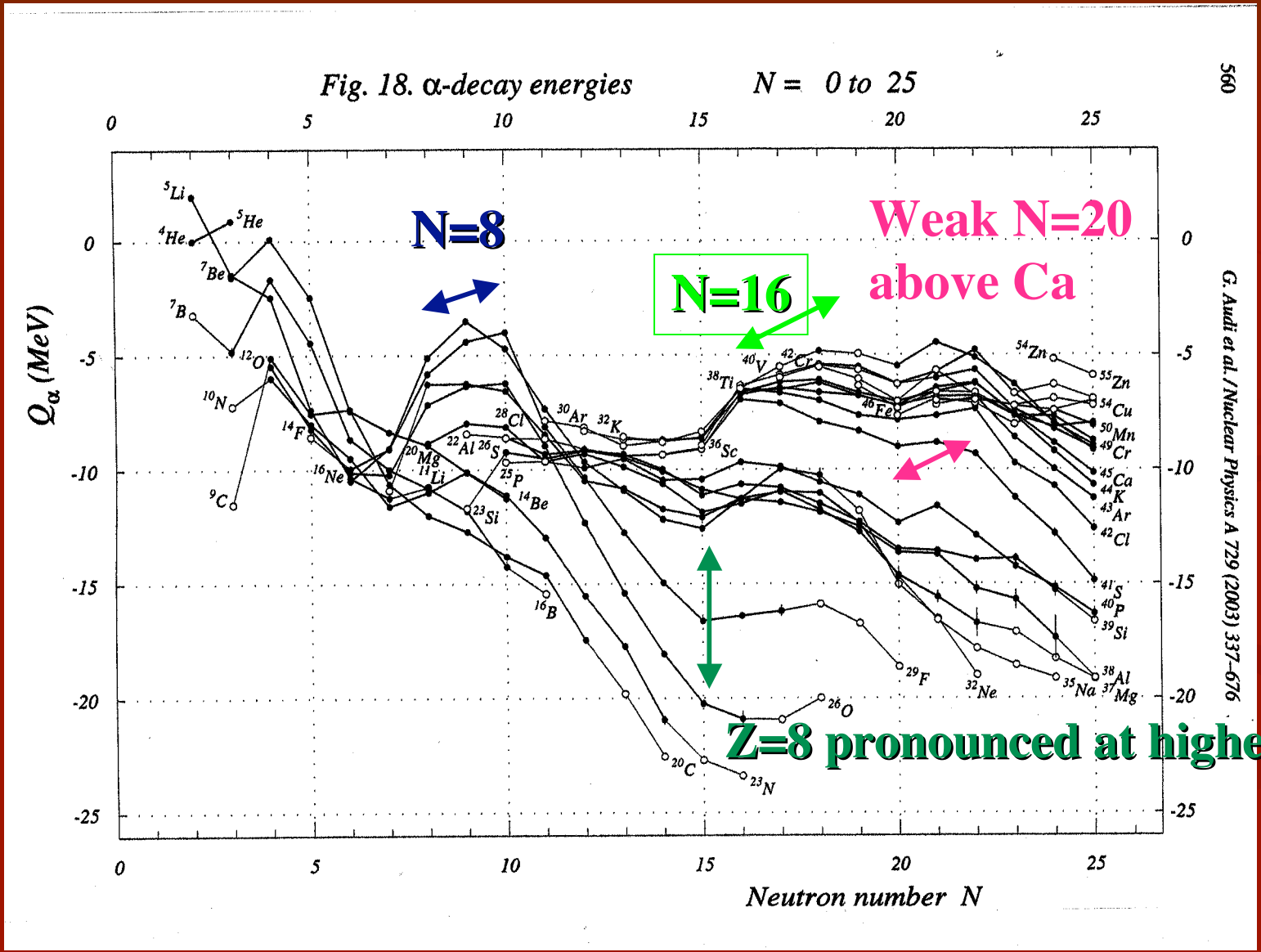


N=28 gap is less pronounced than Z=28



Light Nuclei:

Shell structure? What shell structure?



Some observations regarding spherical shell gaps

Light Nuclei (below A~40)

- N, Z = 8, 20 gaps are very weak; thus the concept of shell model calculations with a "doubly-magic core" is not very rigorous

- Monopole migration and other interactions produce fast and large changes in s.p. energies. These are the underlying causes of "Island of inversion", "melting of N=20 shell gap", "emergence of N=16 gap", etc.

- Should be careful not to relate ***all*** of these phenomena to drip-line physics

Heavy Nuclei

- Pronounced shell gaps start to appear around N, Z = 28
- Gaps at Z= 28 (f_7-p_3), 50 (g_9-d_5), and 82 (h_{11}-f_7) increase with N
- The N= 28, 50, 82, 126 gaps increase in more n-rich nuclei

Thus, the robustness of doubly-magic nuclei increases with N & Z:

$$^{208}\mathrm{Pb} > {}^{132}\mathrm{Sn} > {}^{100}\mathrm{Sn} > {}^{78}\mathrm{Ni} > {}^{56}\mathrm{Ni} > {}^{48}\mathrm{Ca} > {}^{40}\mathrm{Ca}$$

Hence, we need to travel farther from stability in heavier nuclei before we encounter exotic phenomena!

Can we use single-particle (s.p.) energies to infer changes in shell structure due to diffused potentials?

Procedural question: How to follow evolution of s.p. energies?

1. Follow n-orbitals (at constant Z) in semi-magic isotopes? e.g., odd Ni but they move with Fermi surface & are affected by n-n interactions

2. Follow n-orbitals (at constant N) in odd-N isotones? e.g., N=51, 83 they are affected by strong p-n interaction (so called monopole shift)

3. Follow p-orbitals (at constant Z) in odd-Z isotopes? e.g., Z=29, 51 but they are affected by strong p-n interaction (monopole shift) Furthermore, diffused neutron matter is supposed to affect mostly neutron orbitals!

One more problem:
Low-lying levels are usually impure (phonon admixtures, configuration mixing)

Properties of Low-Lying levels as probes of shell structure

- Energies of 2^+ and 4^+ may be obtained through decay studies or Coulex.

- B(E2), Q, and g-factors are best studied through Coulex.

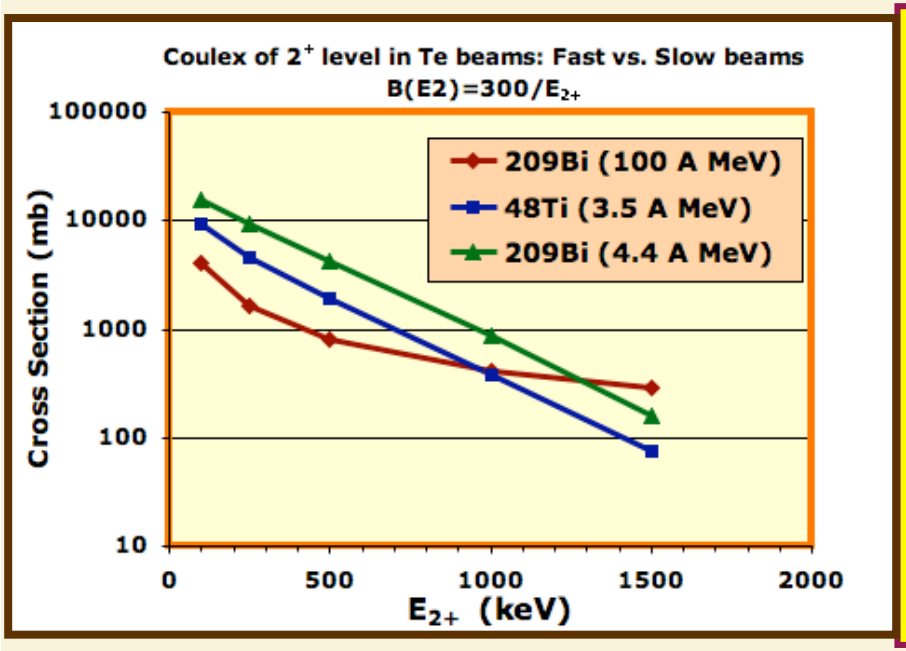
Coulomb excitation: Two complementary methods

Fast Beams at intermediate energies:

- Intermediate energies & *thick* targets (hundreds of mg/cm^2)
- One step process; excites levels connected to the ground state by an E2
- Are advantageous when E(2) is high; *e.g.* in light nuclei and near magic numbers

Slow beams near Coulomb barrier:

- Use *thin* targets (one to few mg/cm^2)
- Less problem with Doppler broadening
- Multi-step process:
  - 4^+ & high-spin states
  - Quadrupole moment
- Can use high-Z targets to increase σ

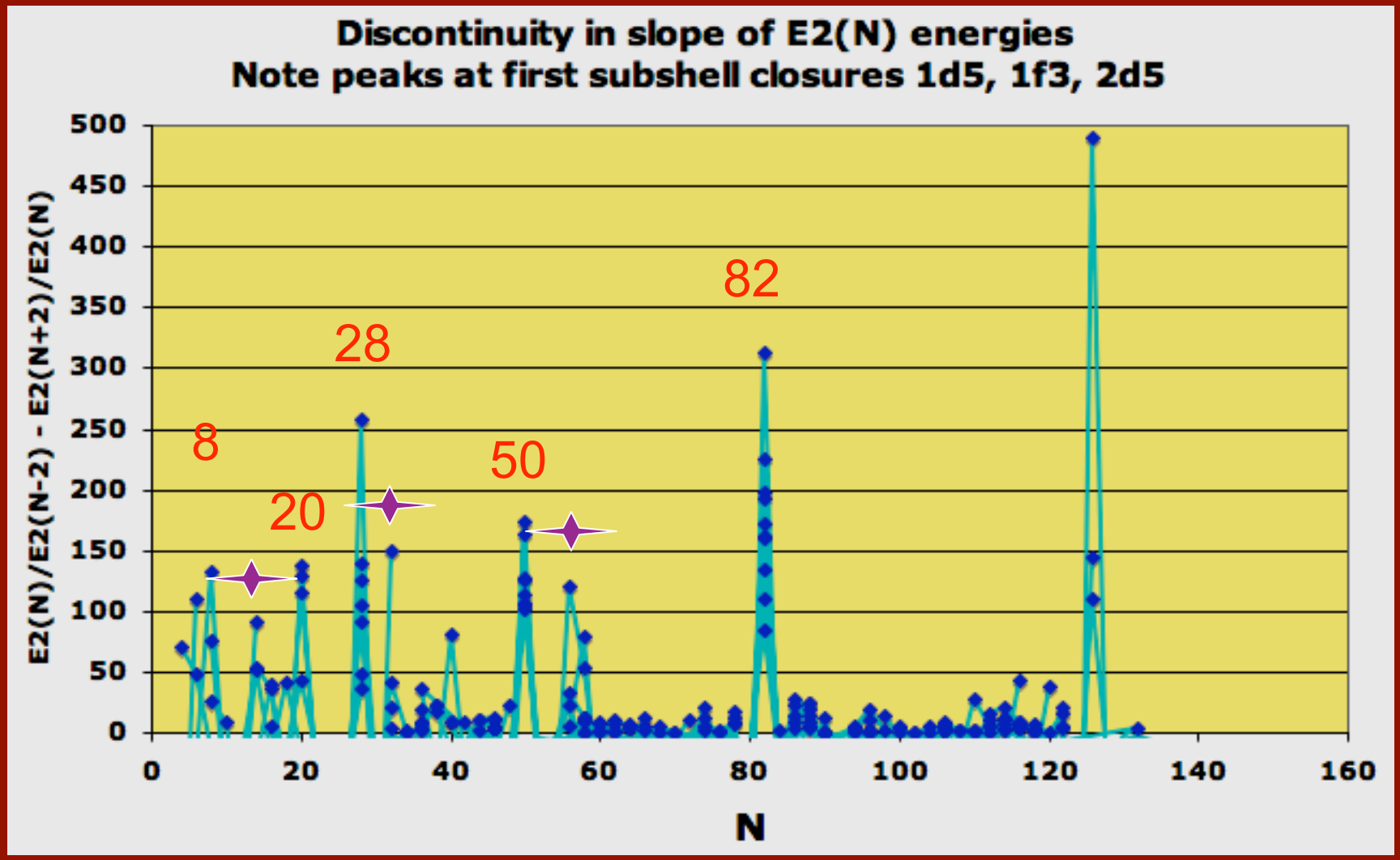


- *The main advantage of fast beams is higher target thickness; thus the required beam intensities are less by a factor of ~10-100, depending on E(2) or Z of target for ISOL beam.*

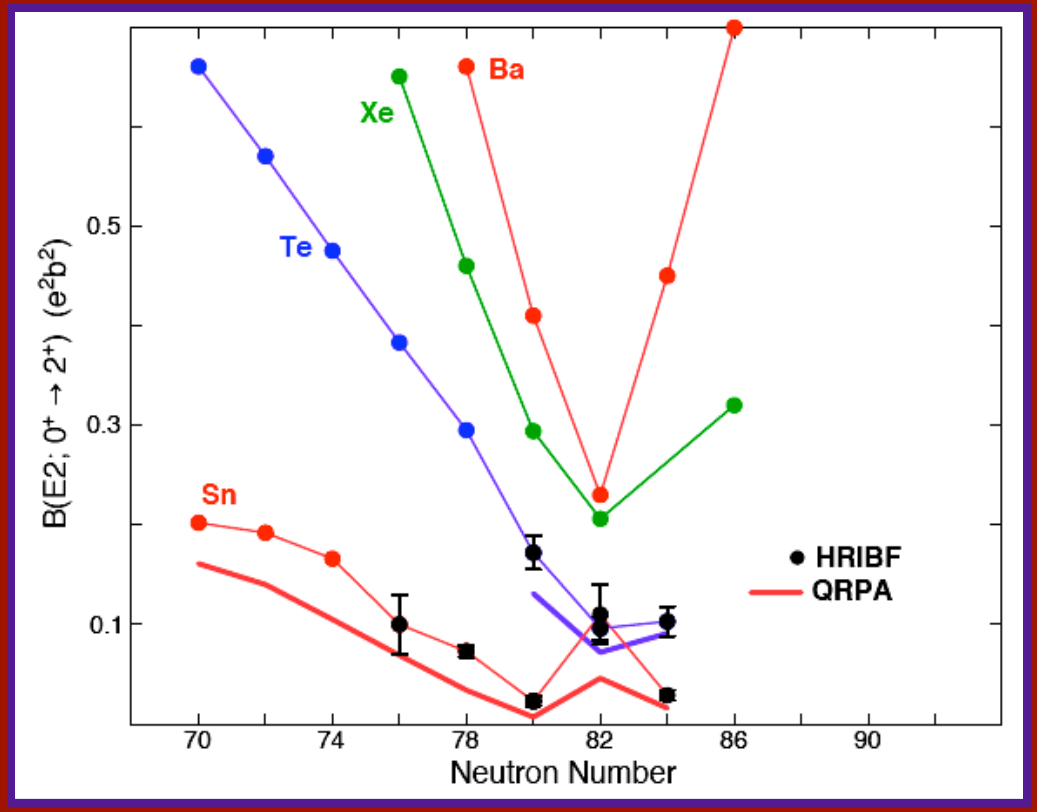
- *The main advantage of slow beams: Multi-step Coulex.*

Energies of the first 2^+

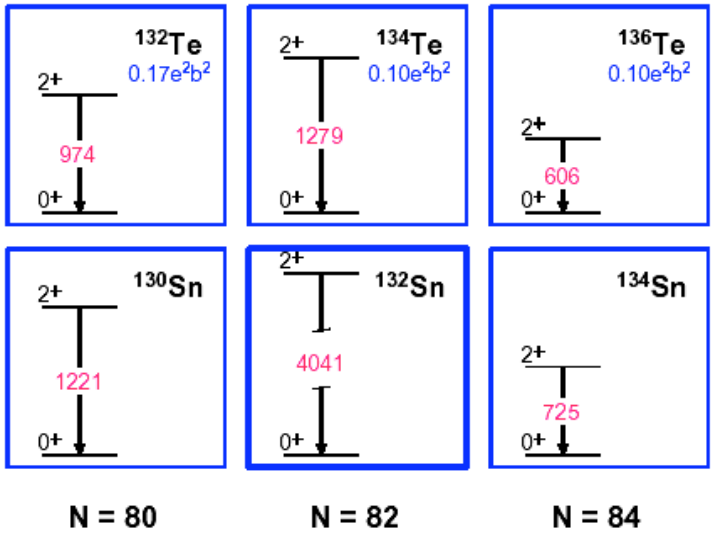
Shell gaps give rise to discontinuities in $E(2^+)$, which become more pronounced at larger N



B(E2) usually dip at magic numbers



Grodzins-Raman Scaling:
Product of B(E2; 0 -> 2) . E(2+)
~ [2.6 * Z²/ A^2/3]



- Surprising low B(E2) for ^{136}Te in the first exp't. This is contrary to Grodzins scaling
- A new measurement indicates 50% higher B(E2), in excellent agreement with Shell Model calculations (Naples & Tokyo)
- Small B(E2) in ^{136}Te attributed to dominance of neutron in the w.f.

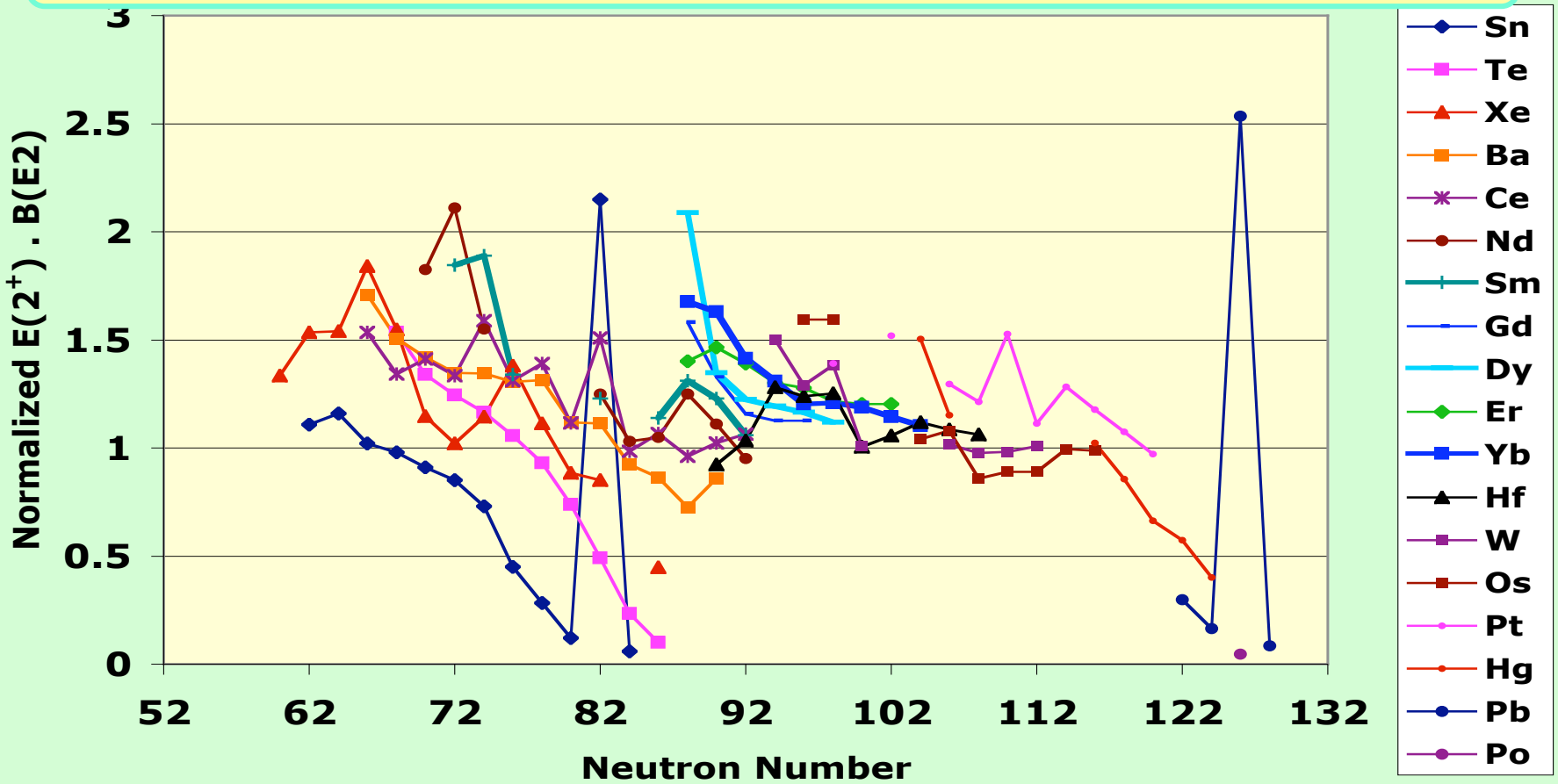
E(2) and B(E2) are correlated and, together, reflect the underlying shell structure.

For example, moment of inertia is ~ Q for spherical, and ~ Q^2 for deformed nuclei.

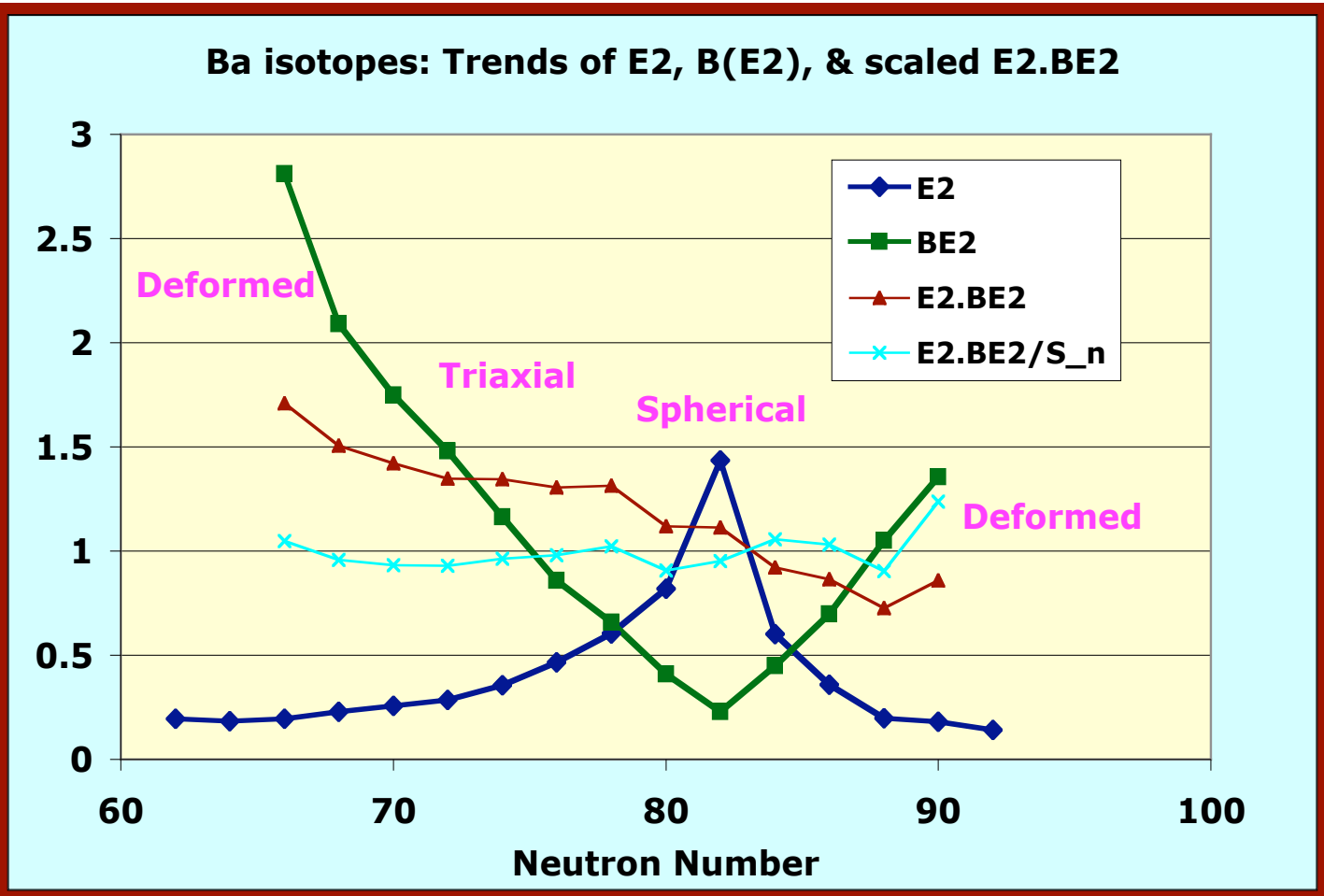
However, the absolute value of E(2) is inversely proportional to J^2 M.o.I and, hence, is strongly affected by variations in pairing.

A preliminary study indicates that these correlations may reveal the deformed shell gaps.

Quenching of Quadrupole Strength of 2^+ with Increasing *N*



- Grodzins' scaled $E(2^+)$. B(E2) products for isotopic chains are not constant, but steadily decrease with increasing *N*
- The trend persists across magic numbers & is not strongly correlated with shapes (see Ba isotopes)
- *Hierarchy and steeper decrease in $E(2^+)$. B(E2) signal approach to magic π*

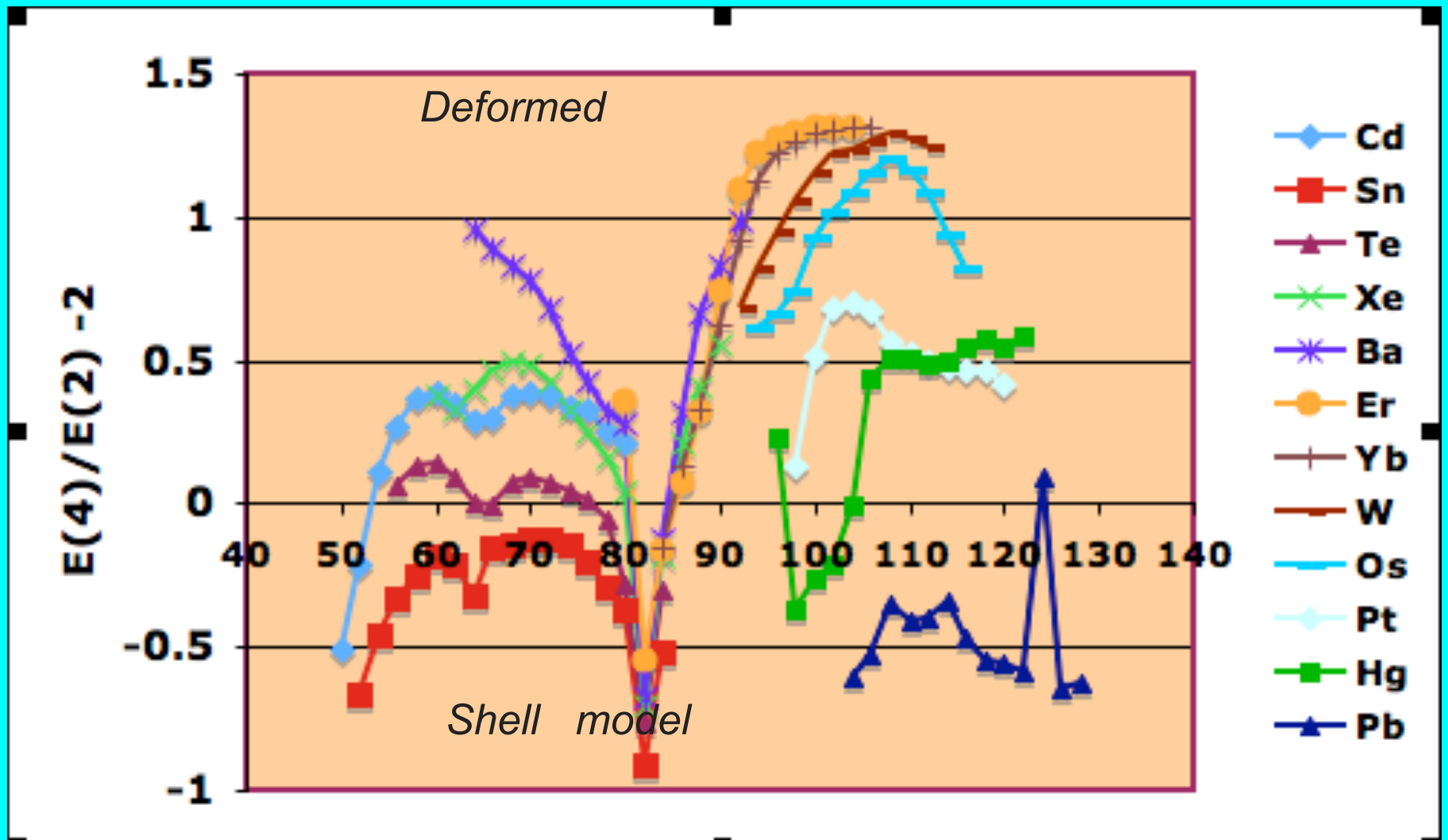


- Decrease in $E(2^+)$ x B(E2) is not usually correlated with shapes
- This indicates that first 2^+ exhausts a smaller fraction of En. Wt. Sum Rule in n-rich nuclei -- Weaker n-pairing increases n-contribution to the w.f. of 2^+
- Weaker n-pairing also increases J^2 M.o.I and lowers 2^+
- Division by S_n seems to compensates for this, thus providing a better tool to predict B(E2) from known $E(2^+)$ values

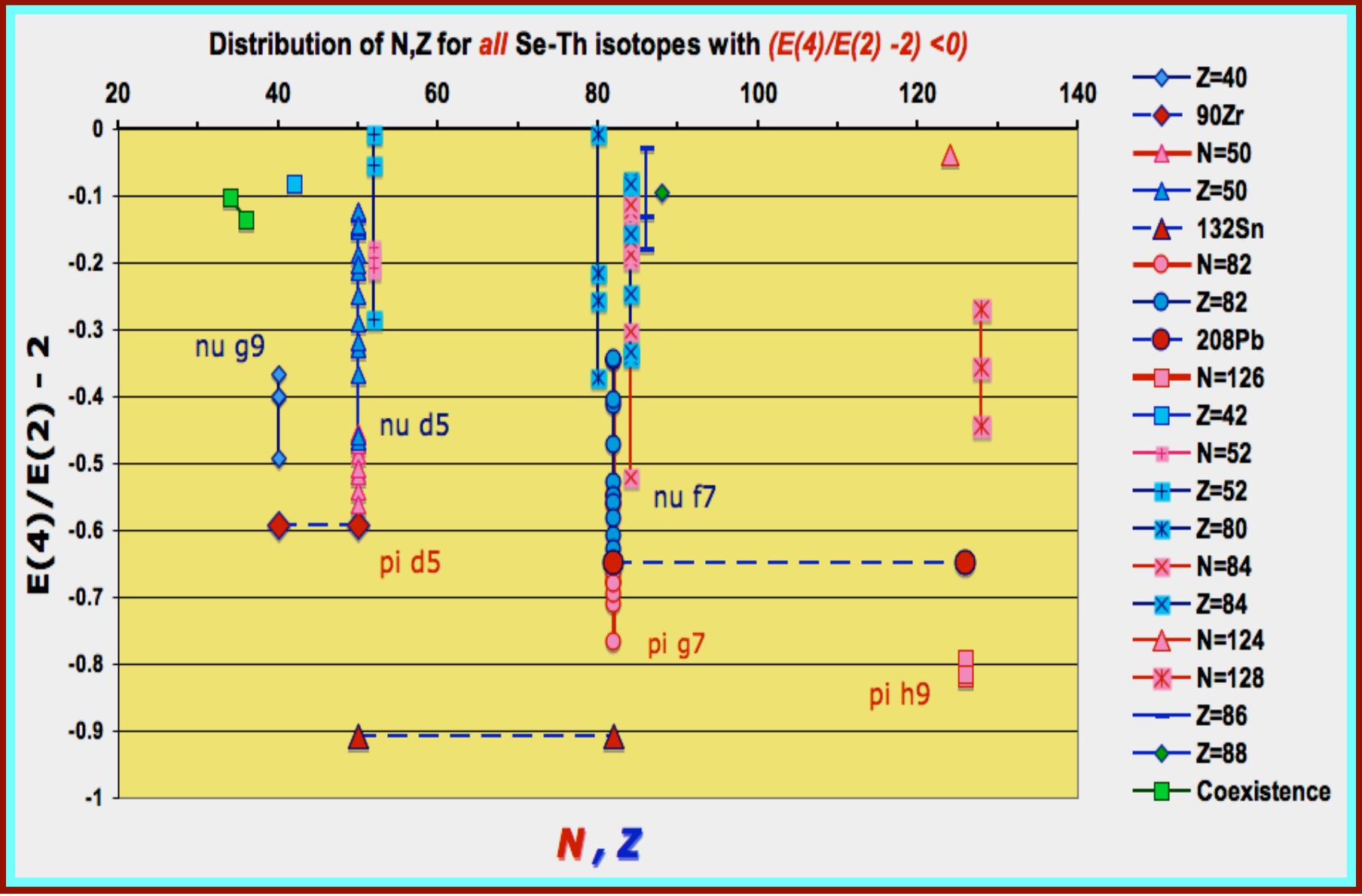
Energy ratio R4=E(4)/E(2) reflects shell gaps

- At and near magic numbers: R4-2 < 0 (spherical shell model)

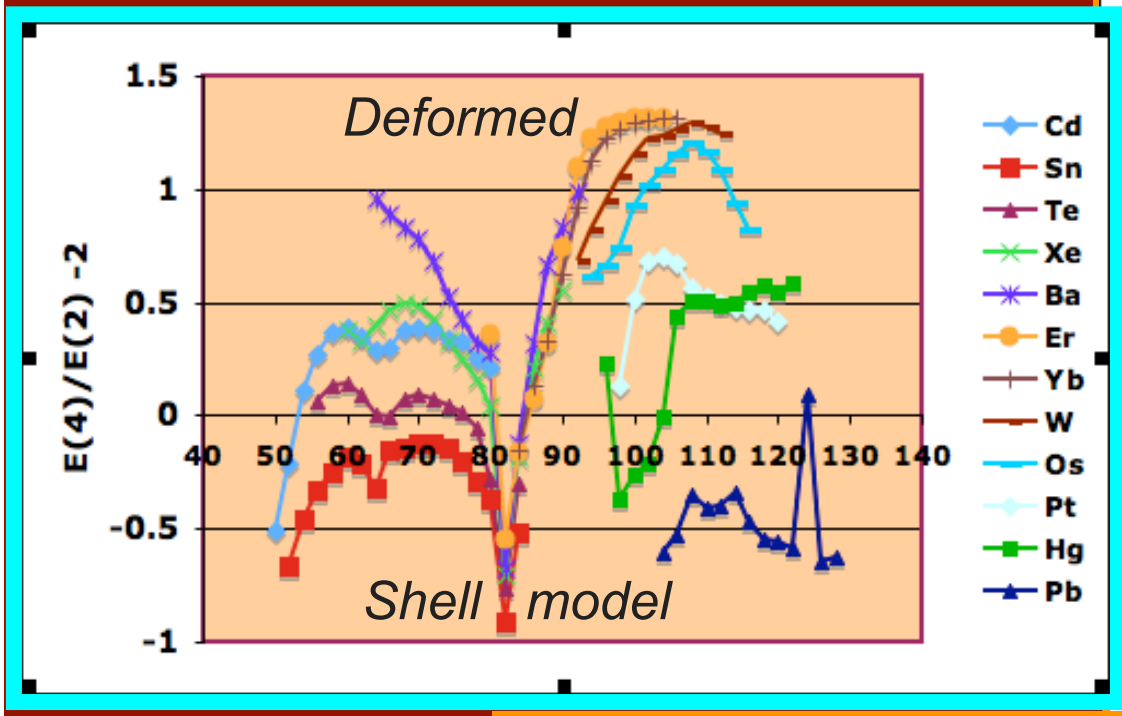
- Near mid-shell: R4-2 climb to 1.3 (onset of deformation)

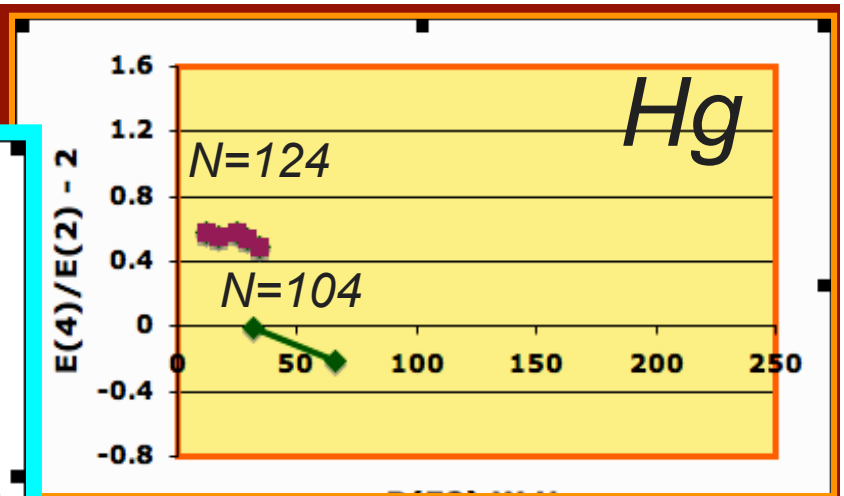


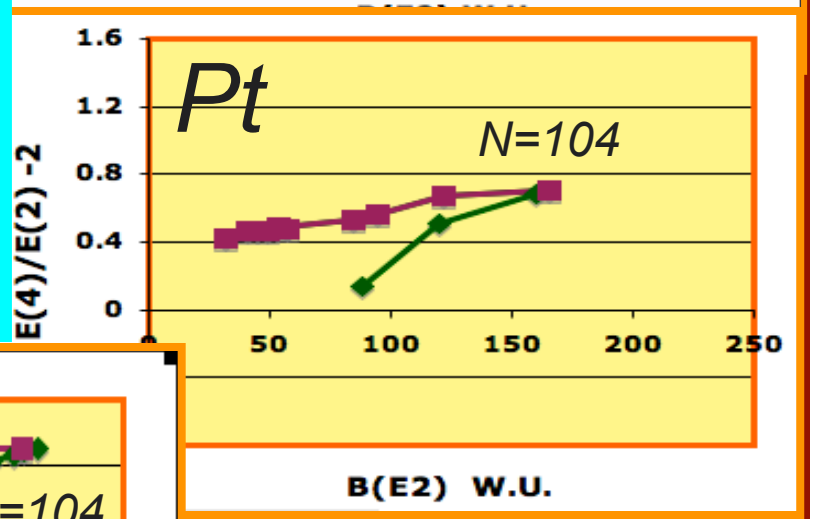
All negative (R4-2) are located at semi-magic nuclei or very close to them

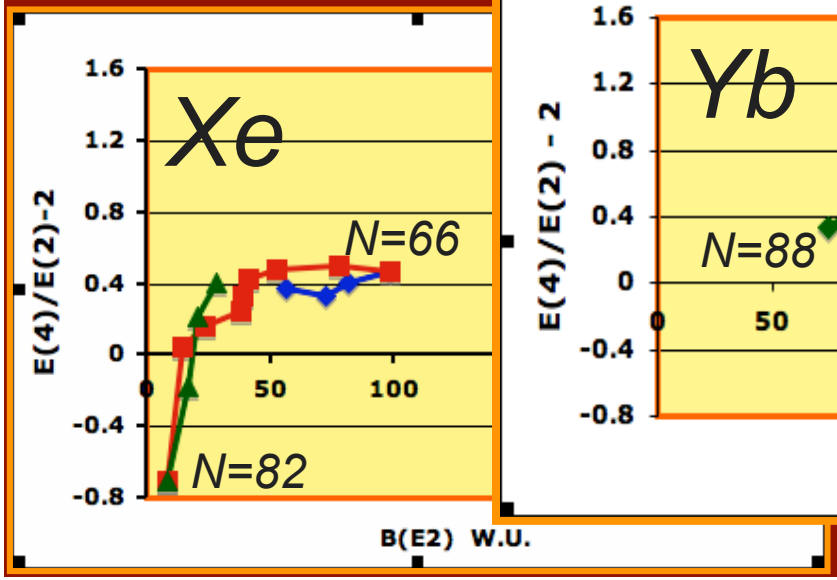


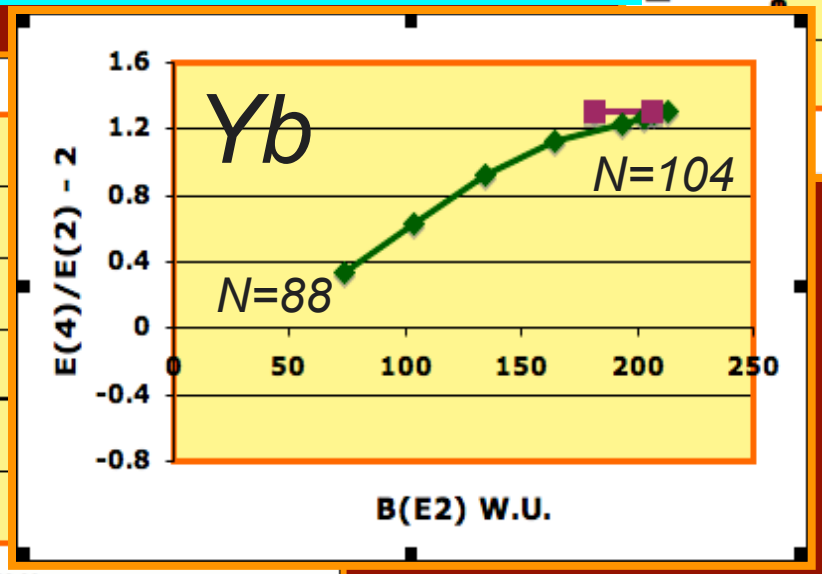
E(4) - E(2) - B(E2) Correlations







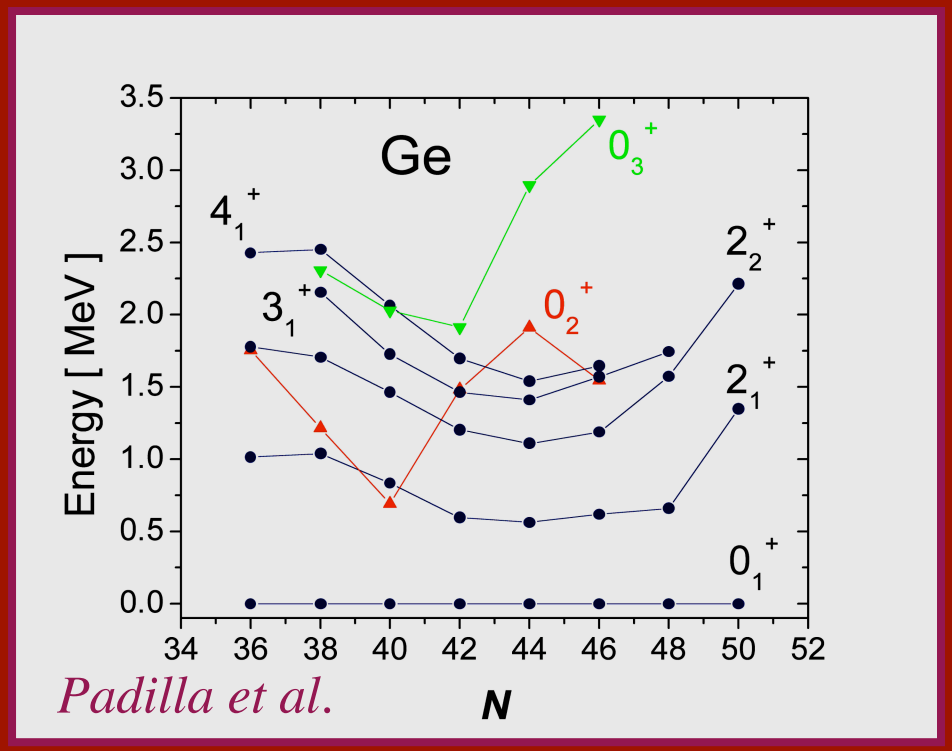


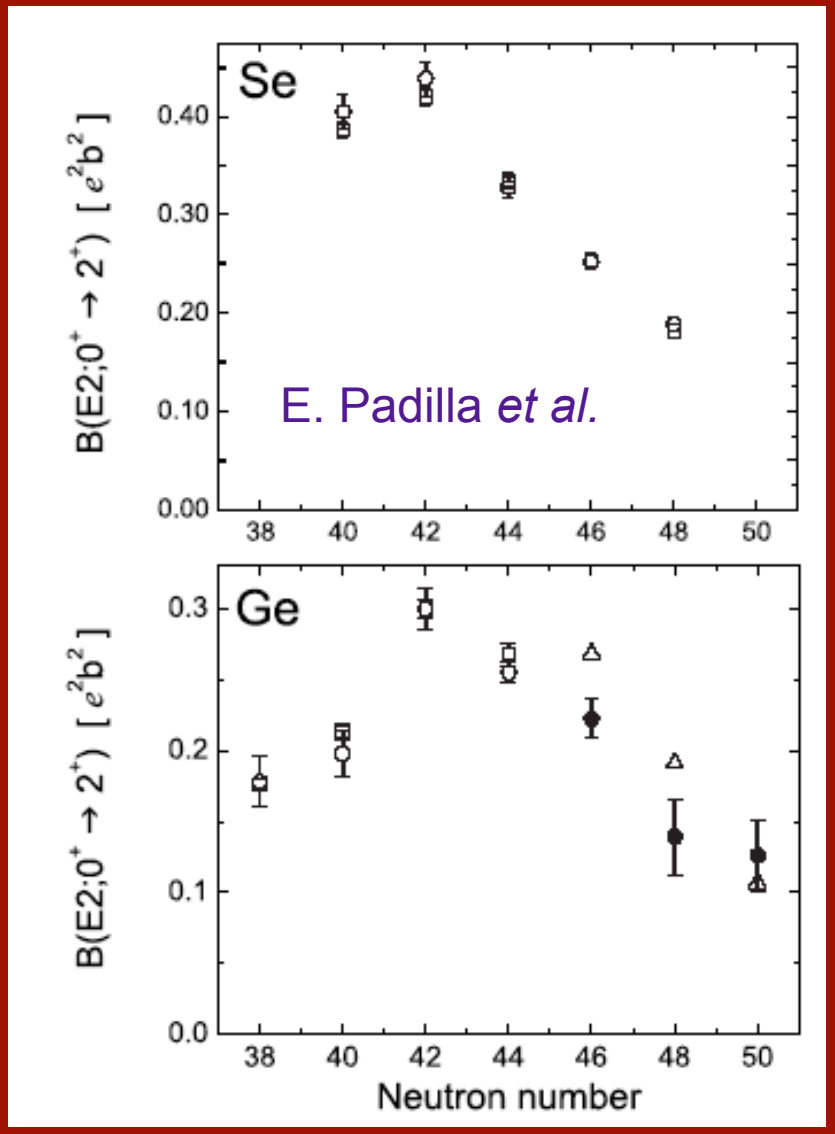


E(4)/ E(2) Vs. B(E2) plots reveal shell & sub-shell structures for BOTH N & Z

Shapes & Collectivity:

Sensitive tests of models in transitional nuclei





Triaxiality is reflected in simple quantities:

- Relative positions of 4_1 and 2_2
- Branching ratios of $(2_2 \rightarrow 2_1)/(2_2 \rightarrow 0)$
- Quadrupole moments

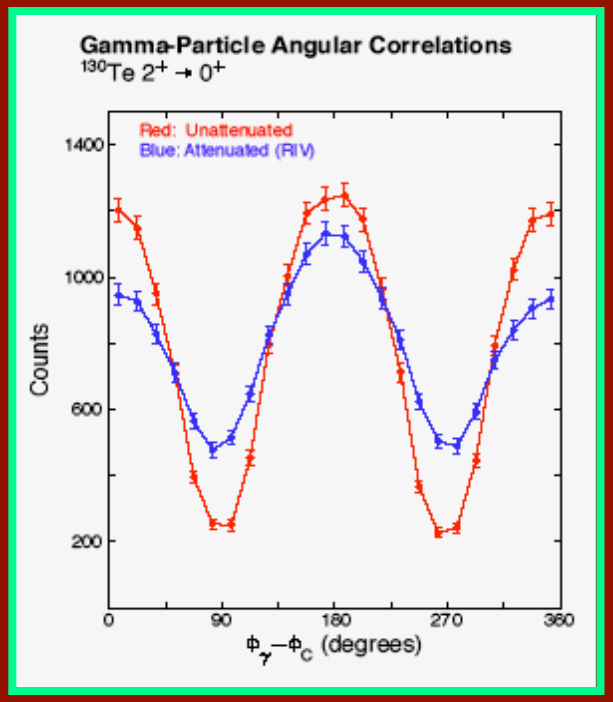
Triaxiality usually occurs at the "North-East" quadrant of the magic box

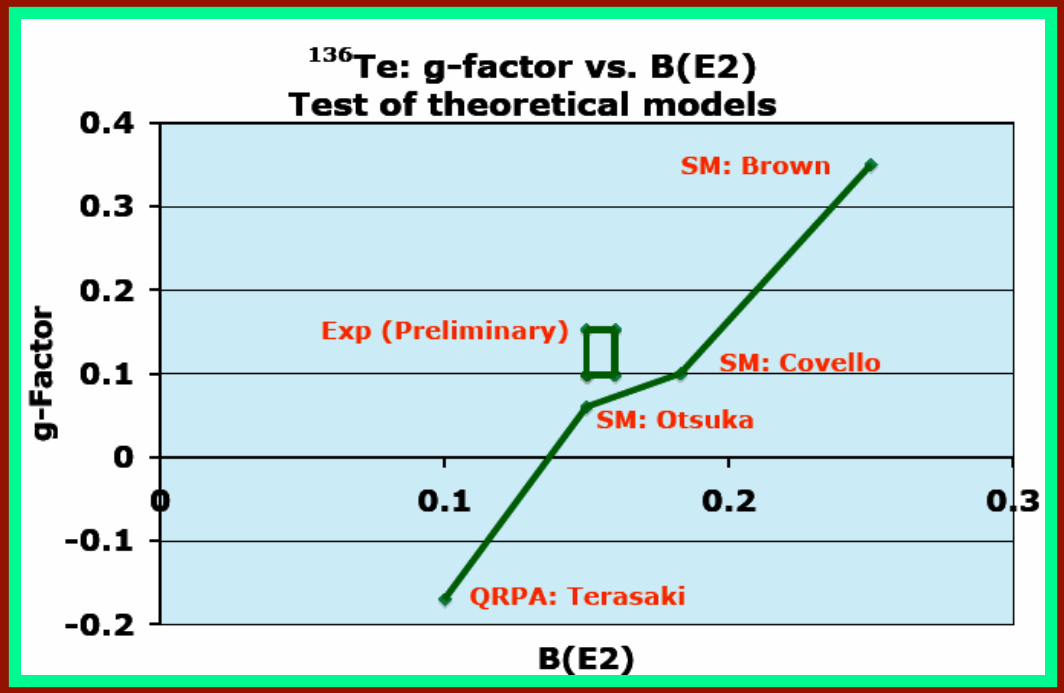
g-factors

- *An excellent probe of s.p. states & magic numbers*
  (e.g., they show a distinct discontinuity at magic numbers)

- *Two techniques: TF, RIV measurements using Coulomb excitation*
  (Stable Te & ^{132,136}Te have been studied with RIV)

- *A sensitive test of models -- especially when combined with B(E2)*





Apply to odd-A, & 2^+, 4^+ to probe p-n components of w.f near magic #

Summary

-We should utilize a wide variety of observable to study the evolution of shell structure and changes in magic numbers

- It is highly desirable to have model-independent signatures

- Ground-state masses (Q_α) provide the first hints

- Further evidence can come from the energies and B(E2) values of the low-lying 2^+ and 4^+ states

- In particular R4-B(E2) correlations provide clear signal about positions of N & Z relative to the closest gaps

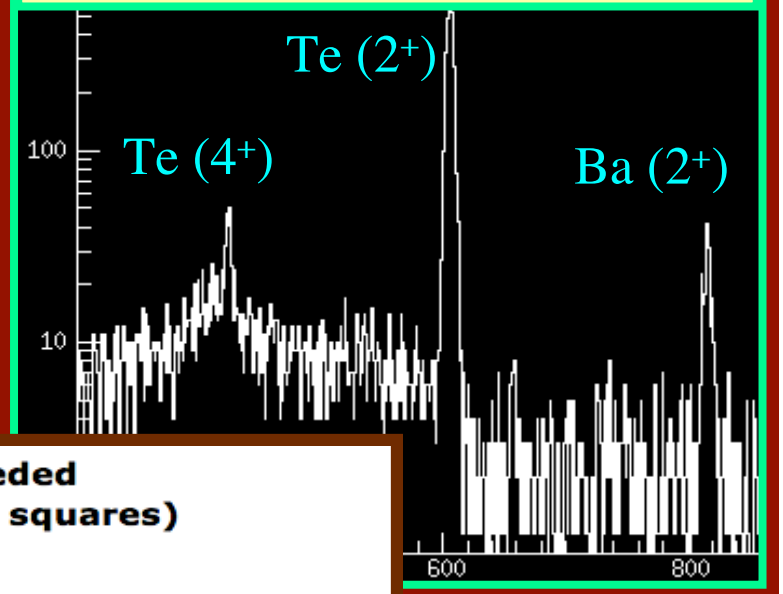
Reach of Coulex Studies with RIBs

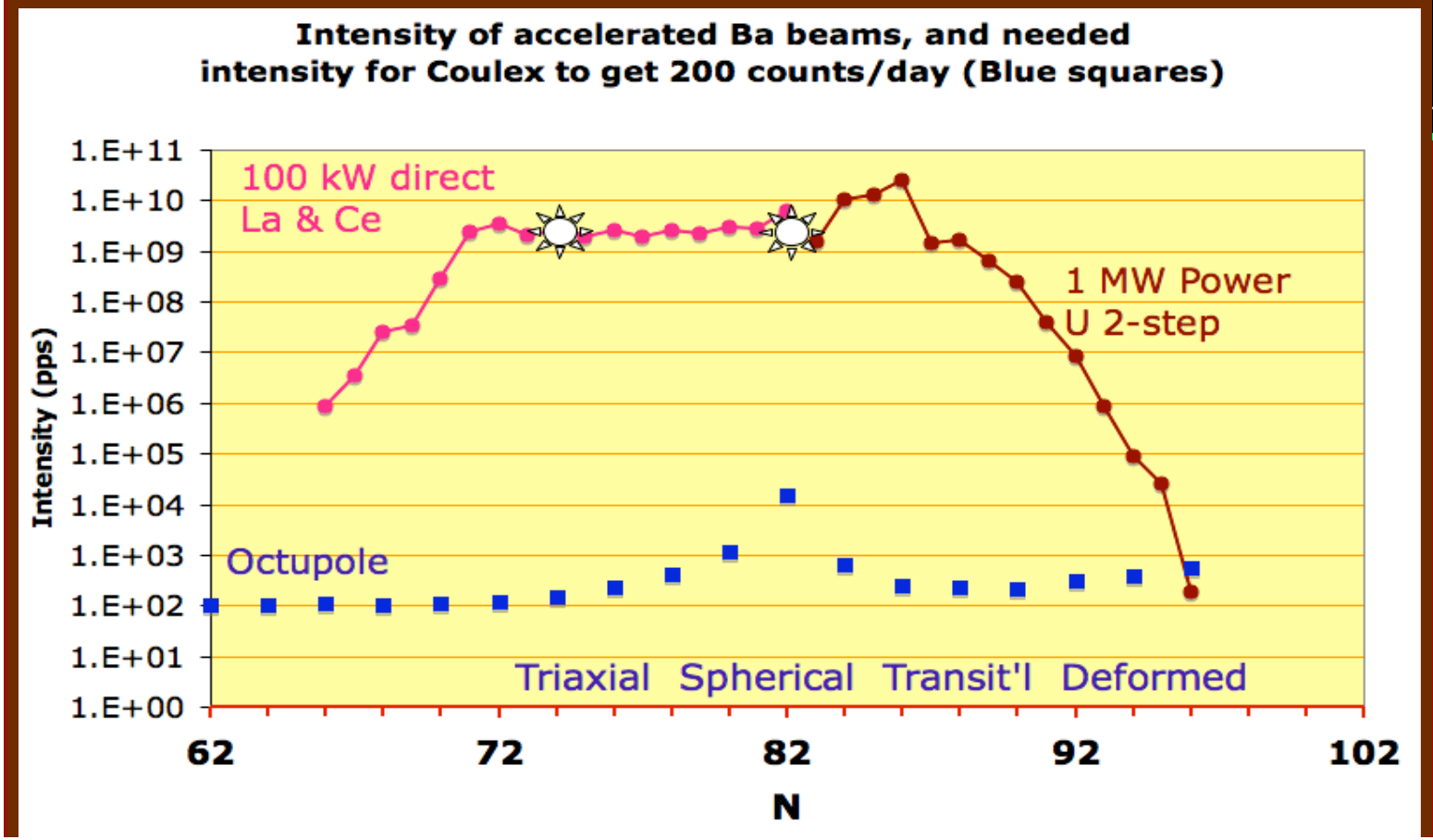
Illustrative cases using a Ti target

Right: ^{136}Te & ^{136}Ba @ HRIBF

Below: Ba beams @ a Hi-Power facility

Coulex of ^{136}Te @ HRIBF





B(E2) known for N= 66 - 90