The shell structure and stability of super-heavy nuclei

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Reflections on the atomic nucleus
Liverpool, 28–30 July 2015

Ongoing research

Construction of improved parameterizations of the nuclear EDF

- better **local** control of single-particle structure possible,

  Shi, Dobaczewski, Greenlees, PRC 89 (2014) 034309

  but better **global** control of single-particle structure difficult

  Lesinski, M. B., Bennaceur, Duguet, Meyer, PRC 76 (2007) 014312

  M. B., Bennaceur, Duguet, Heenen, Lesinski, Meyer, PRC 80 (2009) 064302

  Kortelainen, Dobaczewski, Mizuyama, Toivanen, PRC 77 (2008) 064307

  Kortelainen, McDonnell, Nazarewicz, Olsen, Reinhard, Sarich, Schunck, Wild, Davesne, Erler, Pastore, PRC 89 (2014) 054314

- better control of surface properties

  Kortelainen, McDonnell, Nazarewicz, Reinhard, Sarich, Schunck, Stoitsov, Wild, PRC 85 (2012) 024304

  R. Jodon, thesis, Lyon (2014)

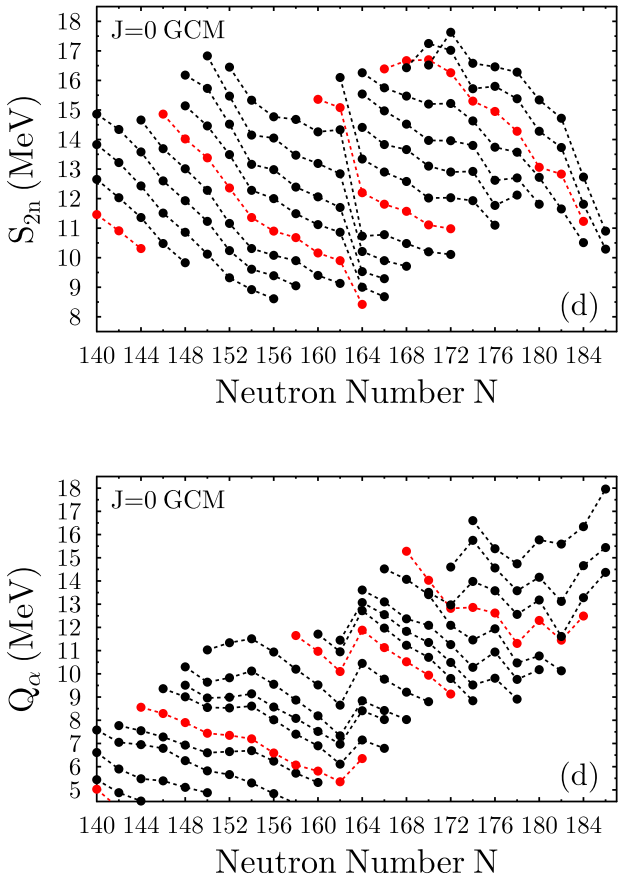
  Jodon, Bennaceur, Meyer, M. B., in preparation.

Better modeling

- towards symmetry-unrestricted calculations
- explicit treatment of correlation effects

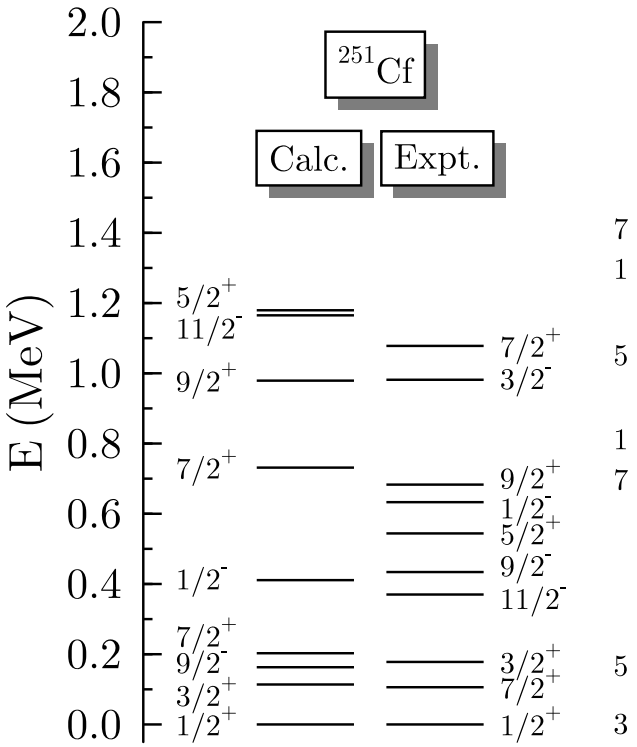
Indications of shell structure

Mass differences



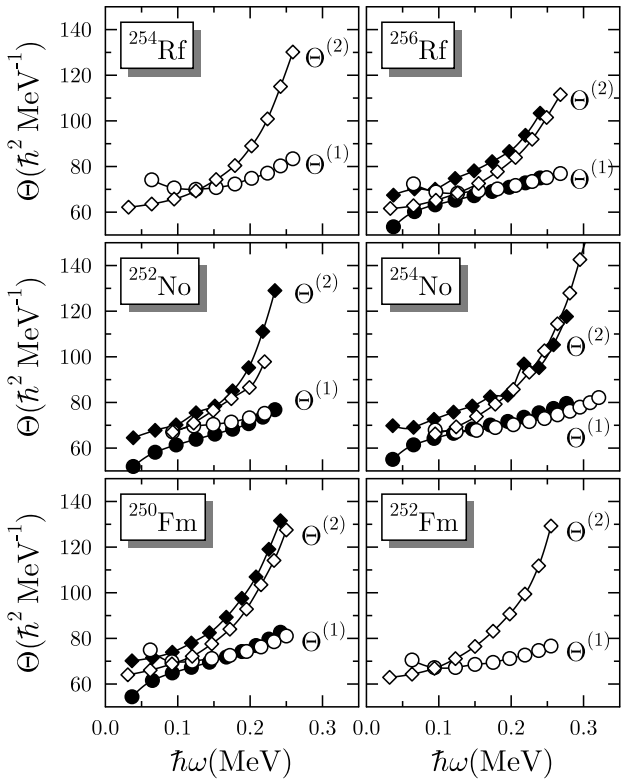
M. B. and Heenen, to be published

Spectra of bandheads in odd-mass nuclei



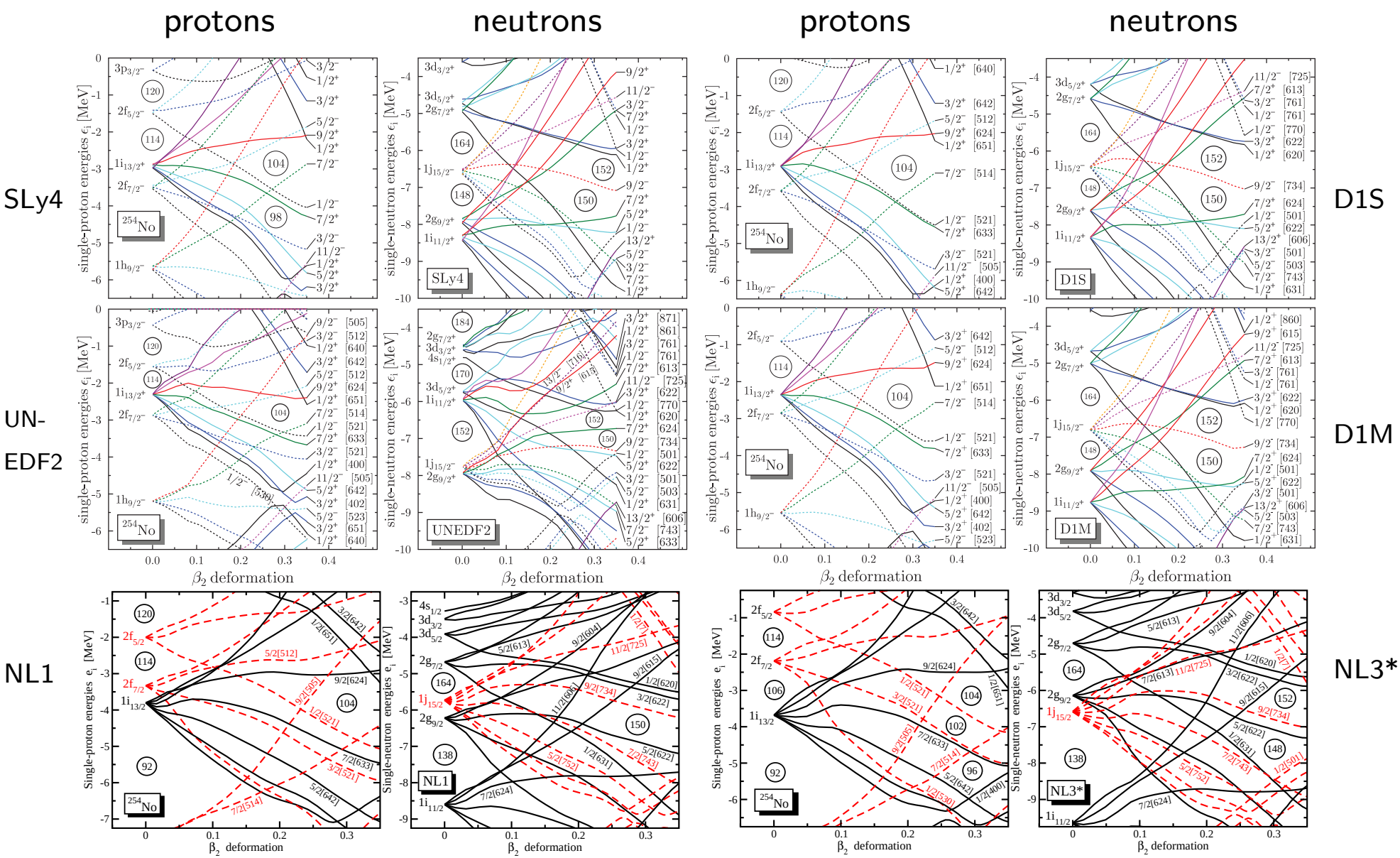
M. B., Bonche, Duguet, Heenen, NPA723 (2003) 354

Moment of inertia



M. B. and Heenen, J. Phys. Conf. Ser. 420 (2013) 012002

Nilsson diagrams of ^{254}No obtained with Skyrme, Gogny, RMF

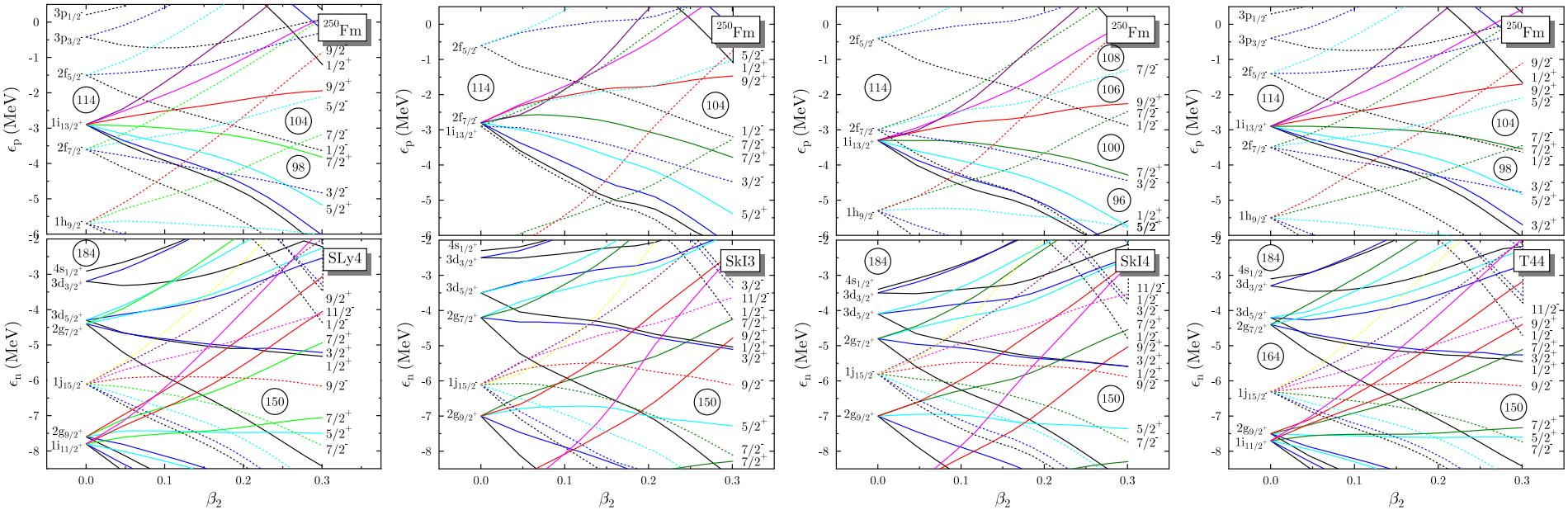


J. Dobaczewski, A. V. Afanasjev,M. B., L. M. Robledo, and Yue Shi, arXiv:1504.03245

Parameterization sensitivity: the example of ^{250}Fm

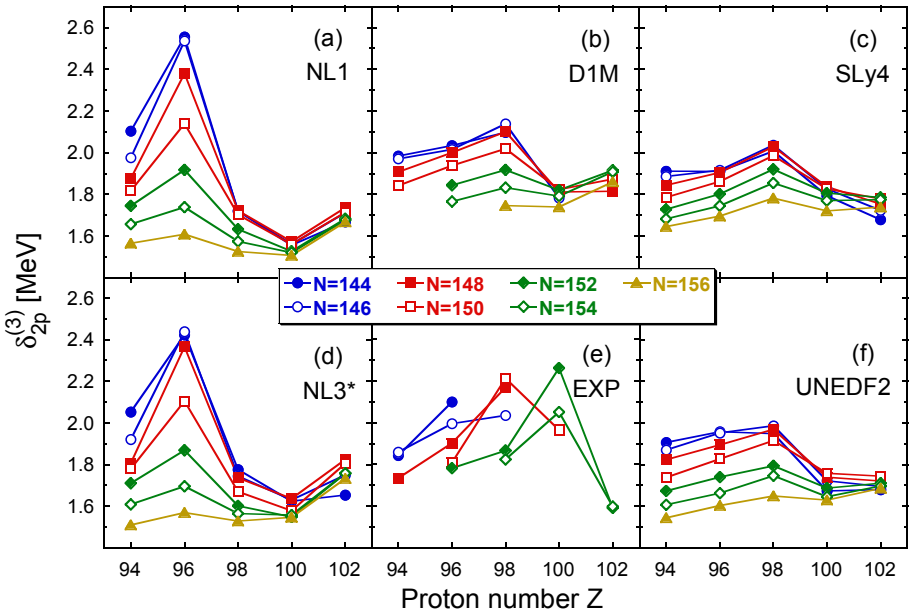
M. B. and P.-H. Heenen, J. Phys. Conf. Ser. 420 (2013) 012002

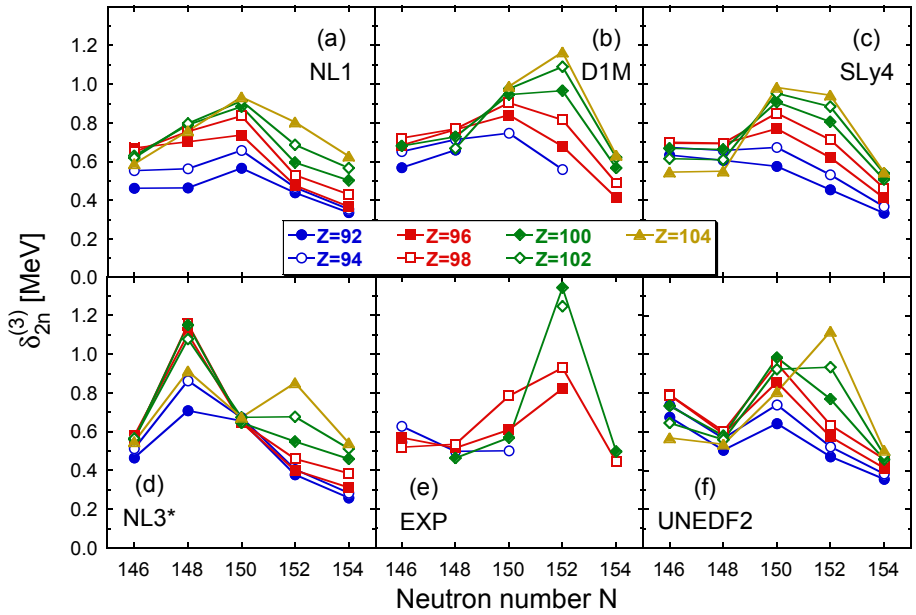
SLy4	SkI3	SkI4	T44
standard spin-orbit	modified spin-orbit	modified spin-orbit	tensor force added



- Nilsson diagram of protons (top) and neutrons (bottom) going from spherical shape (left) to the prolate deformed ground state (right)
- different colours indicate different mean values of j_z
- compare bunching of levels, not the details.

Two-nucleon "shell gaps" $\delta^{(3)}$(Z,N)



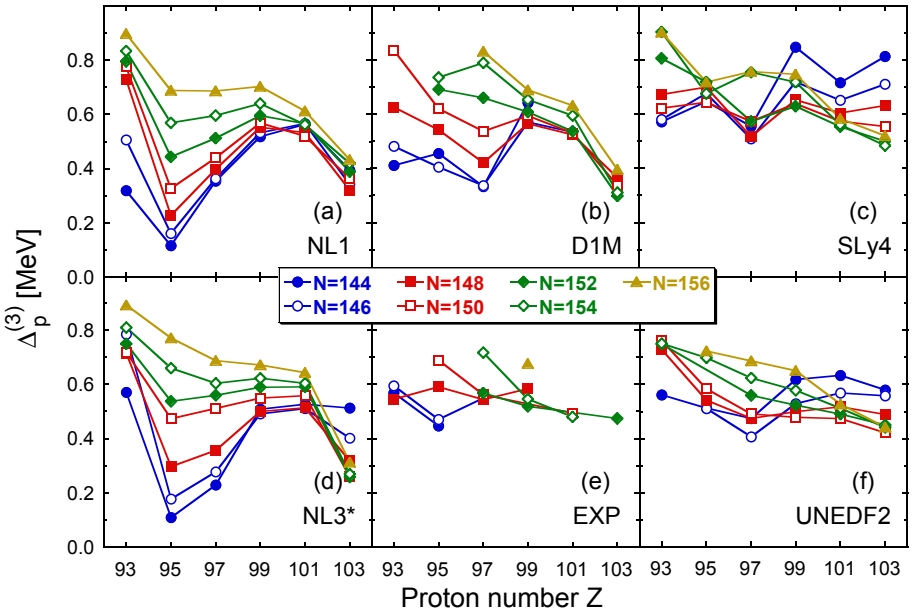


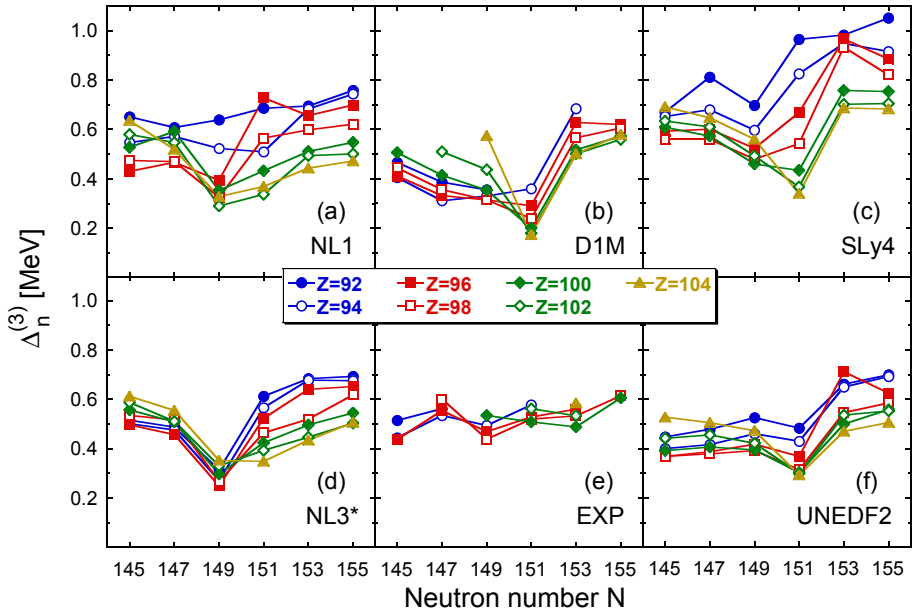
$$\delta_p^{(3)}(Z,N) = 2B(Z,N) - B(Z+2,N) - B(Z-2,N) = S_{2p}(Z,N) - S_{2p}(Z+2,N)$$

$$\delta_n^{(3)}(Z,N) = 2B(Z,N) - B(Z,N+2) - B(Z,N-2) = S_{2n}(Z,N) - S_{2n}(Z,N+2)$$

J. Dobaczewski, A. V. Afanasjev,M. B., L. M. Robledo, and Yue Shi, arXiv:1504.03245

Three-point pairing gaps $\Delta^{(3)}$



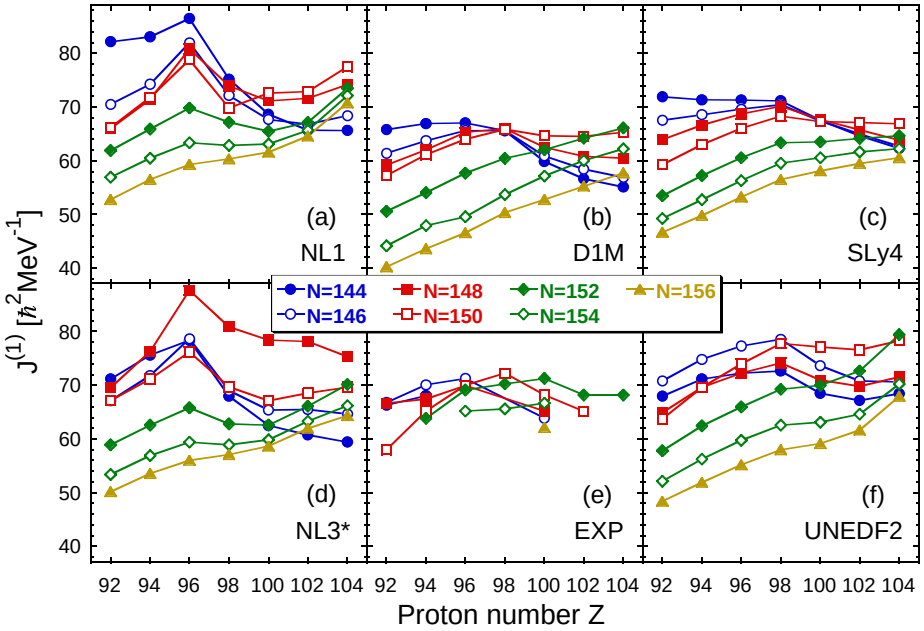


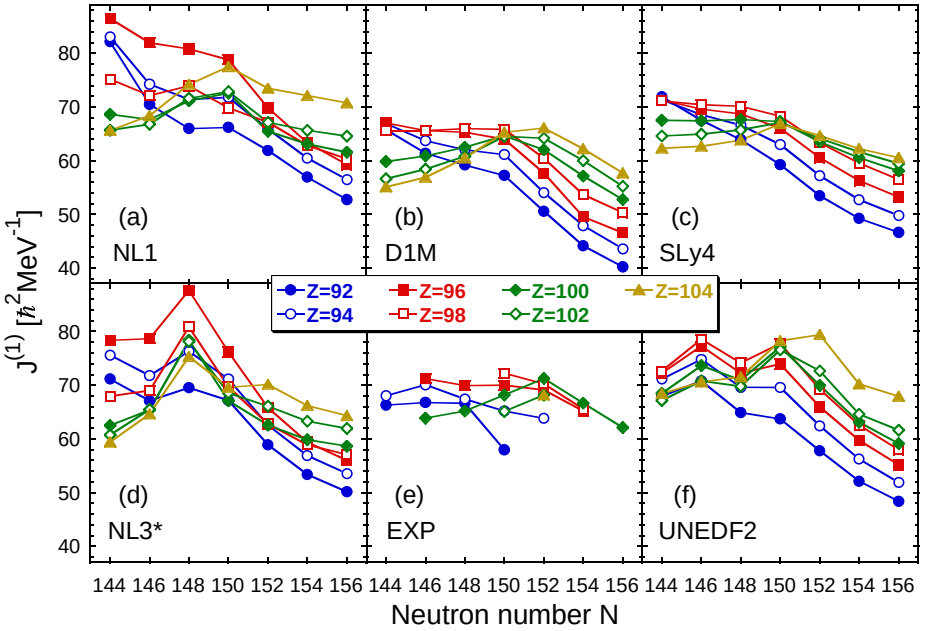
$$\Delta_p^{(3)}(Z,N) = \frac{1}{2}\left[B(Z+1,N)+B(Z-1,N)-2B(Z,N)\right] \quad \text{for odd } Z$$

$$\Delta_n^{(3)}(Z,N) = \frac{1}{2}\left[B(Z,N+1)+B(Z,N-1)-2B(Z,N)\right] \quad \text{for odd } N$$

J. Dobaczewski, A. V. Afanasjev,M. B., L. M. Robledo, and Yue Shi, arXiv:1504.03245

Kinematical moment of inertia



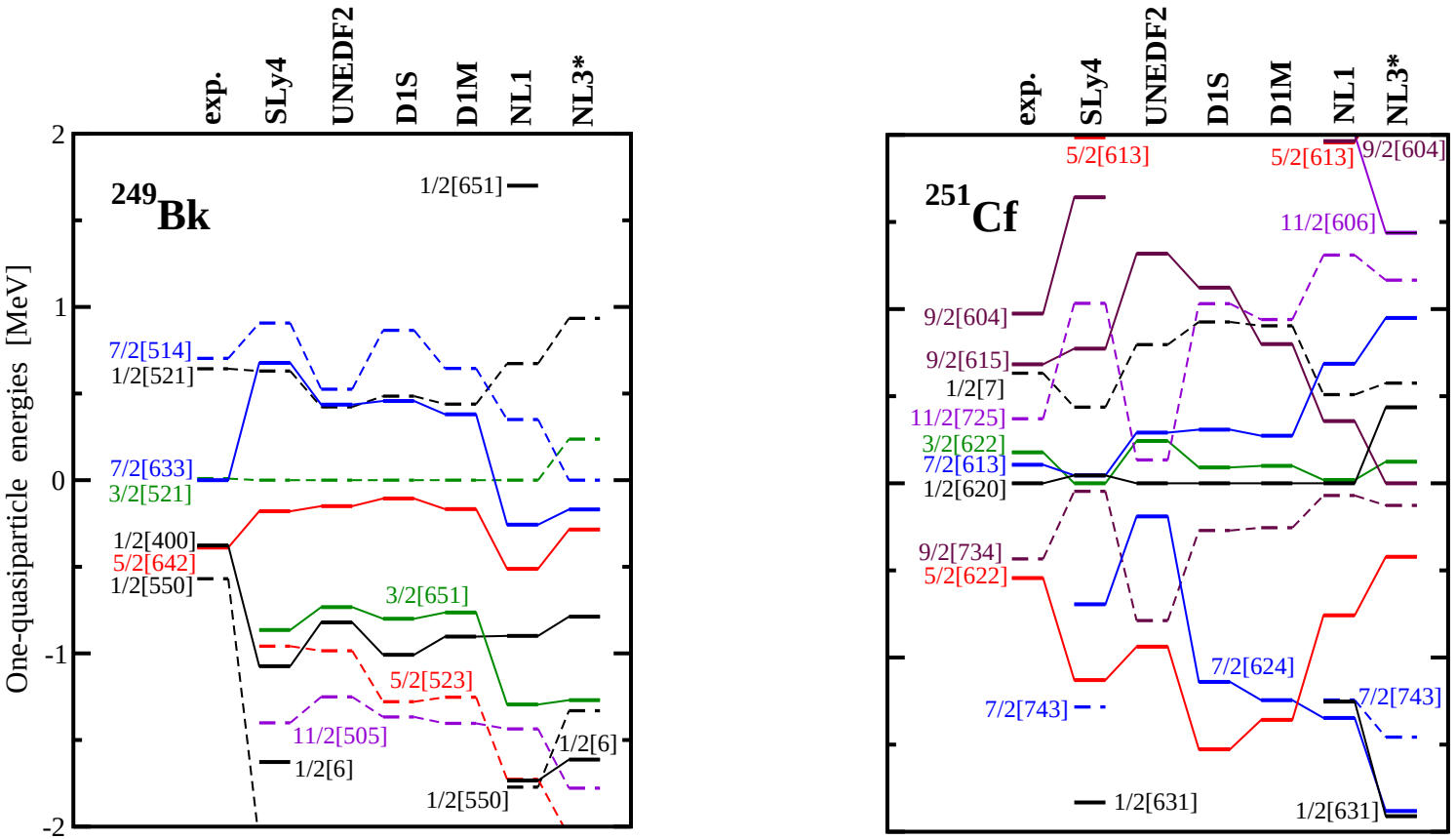


$$J^{(1)} \equiv \frac{\langle \hat{J}_\perp \rangle}{\omega_\perp},$$

evaluated at $\hbar\omega_\perp = 20\,\mathrm{keV}$.

J. Dobaczewski, A. V. Afanasjev,M. B., L. M. Robledo, and Yue Shi, arXiv:1504.03245

One-quasiparticle states (bandheads) in ^{249}Bk and ^{251}Cf

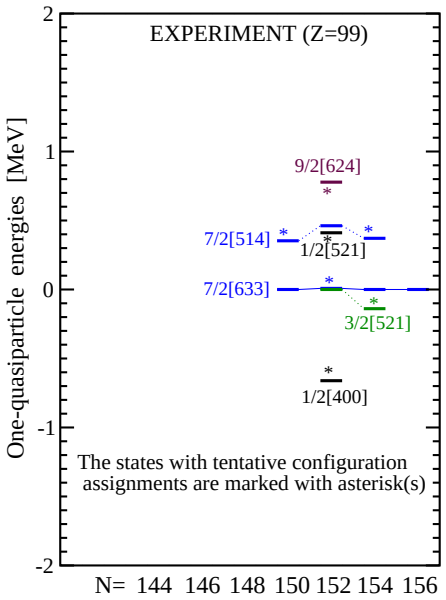


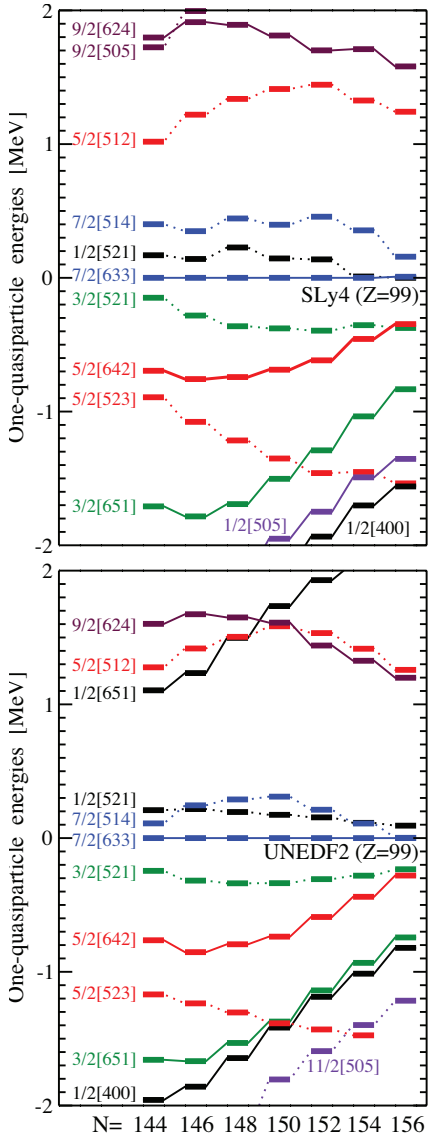
- intruder levels (ν 11/2[725] and π 7/2[633]) misplaced in the spectrum (which can be partially cured with local readjustment of the spin-orbit interaction, [Shi, Dobaczewski, Greenlees PRC 89 (2014) 034309]), but that's not the only problem.

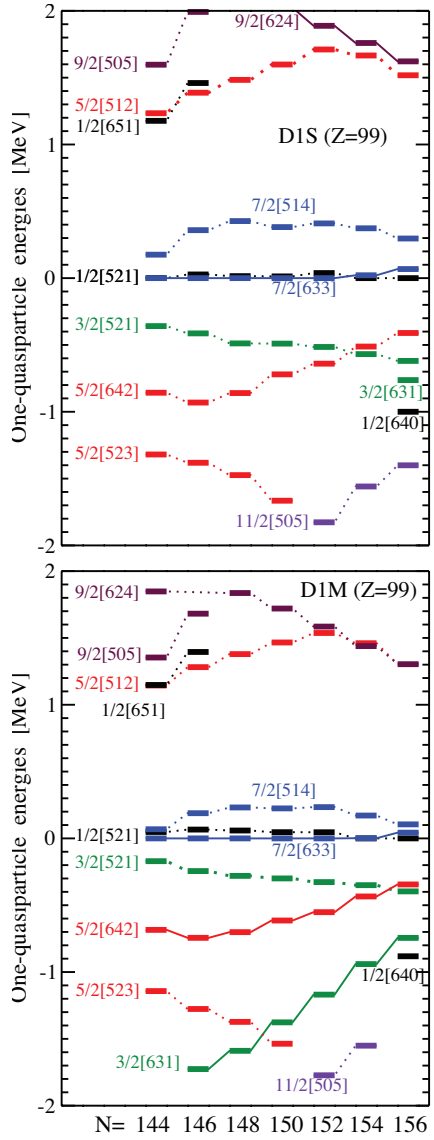
J. Dobaczewski, A. V. Afanasjev,M. B., L. M. Robledo, and Yue Shi, arXiv:1504.03245

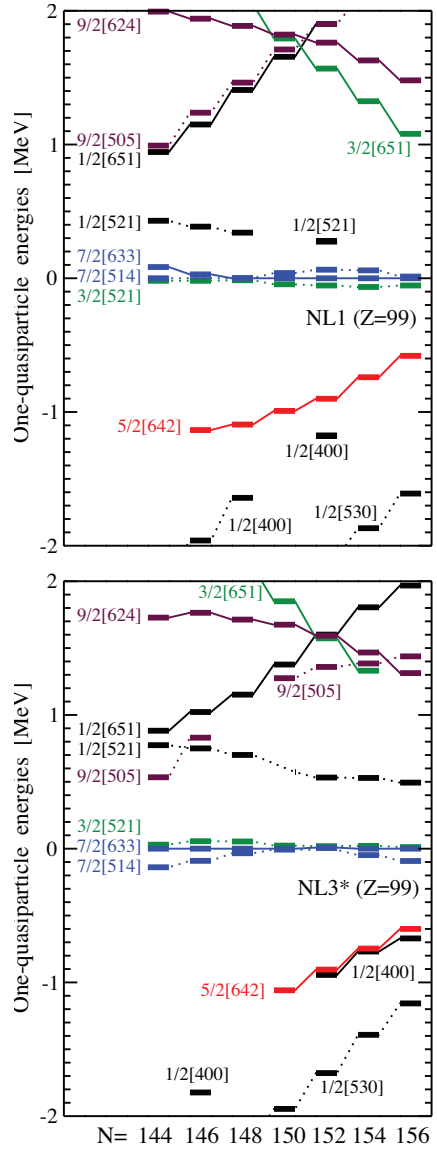
One-quasiparticle states (bandheads) in the $Z = 99$ chain

J. Dobaczewski, A. V. Afanasjev,M. B., L. M. Robledo, and Yue Shi, arXiv:1504.03245



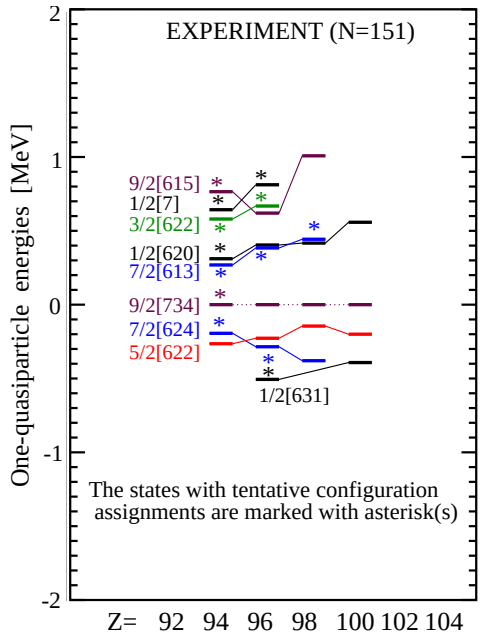


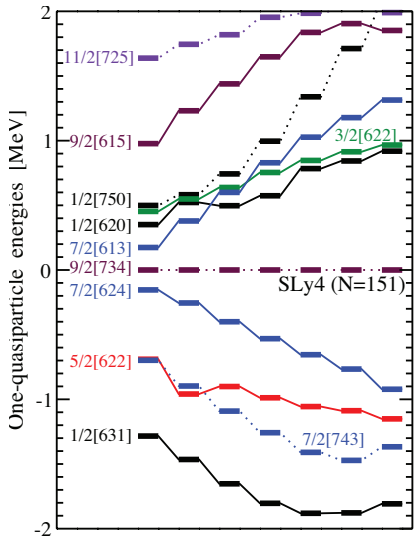


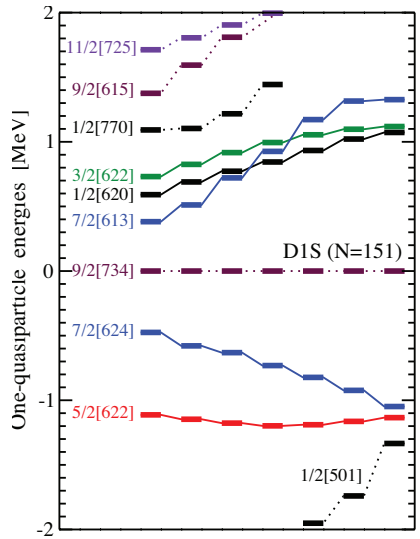


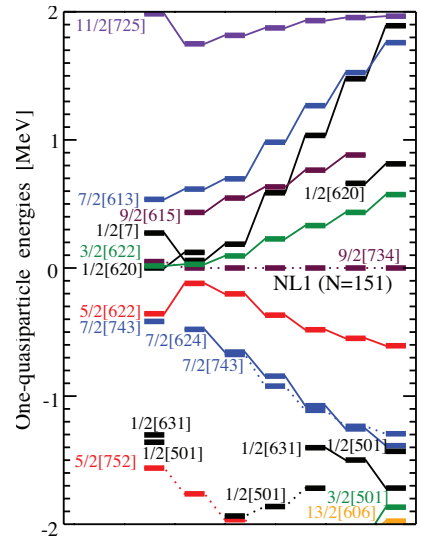
One-quasiparticle states (bandheads) in the $N = 151$ chain

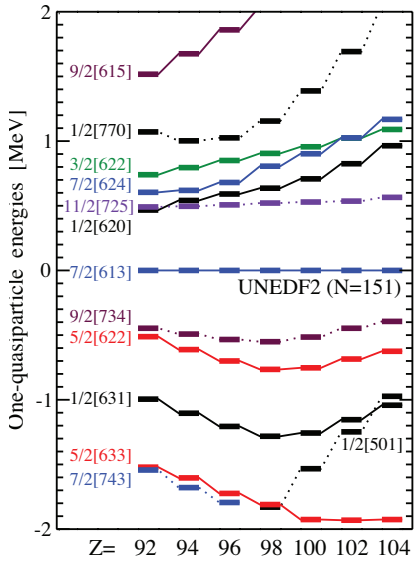
J. Dobaczewski, A. V. Afanasjev,M. B., L. M. Robledo, and Yue Shi, arXiv:1504.03245

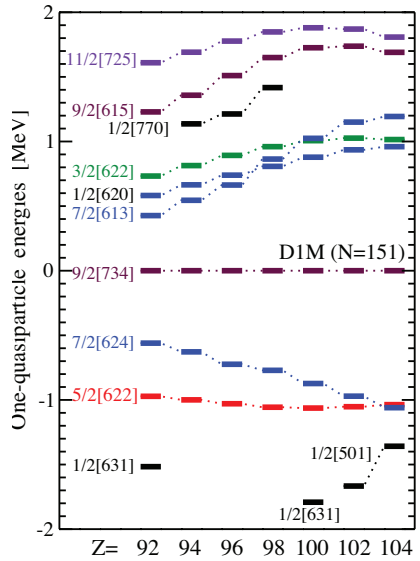


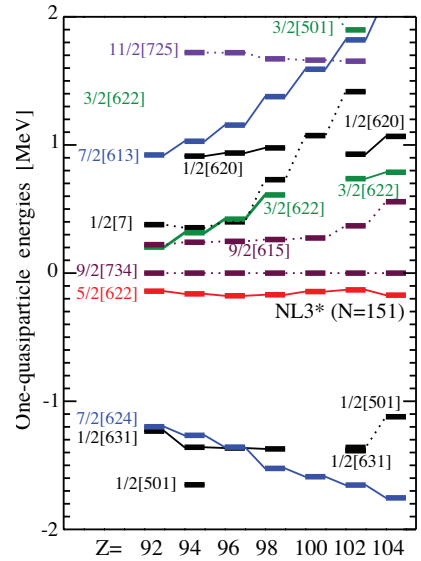








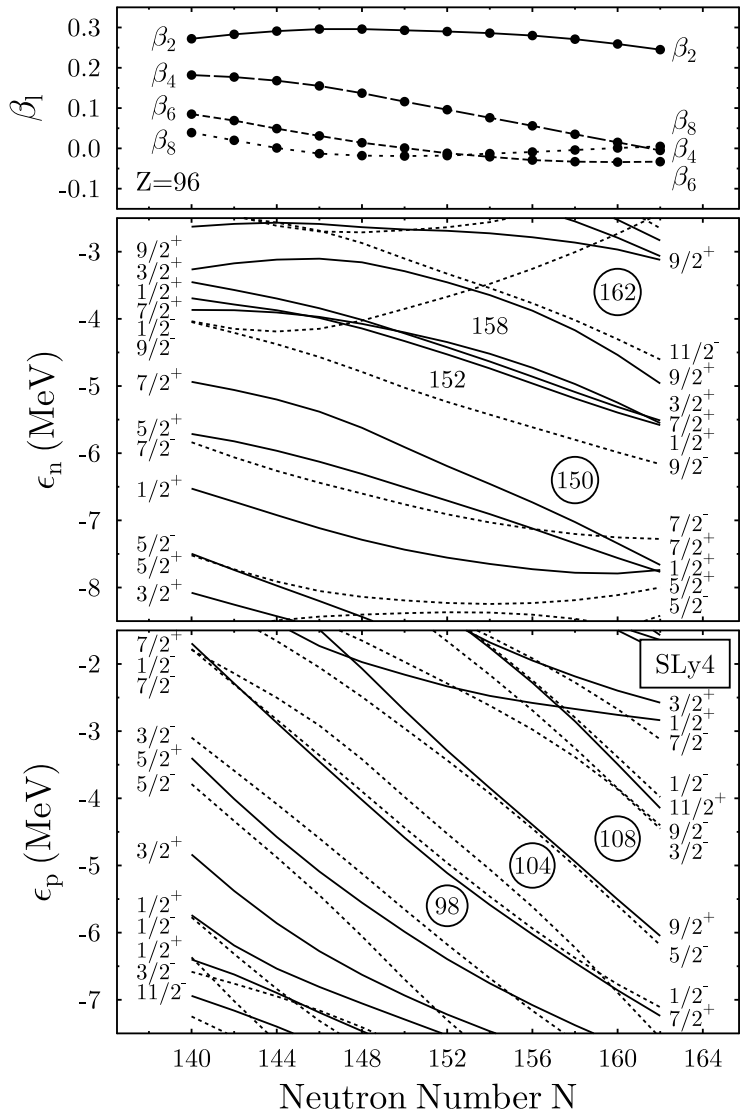




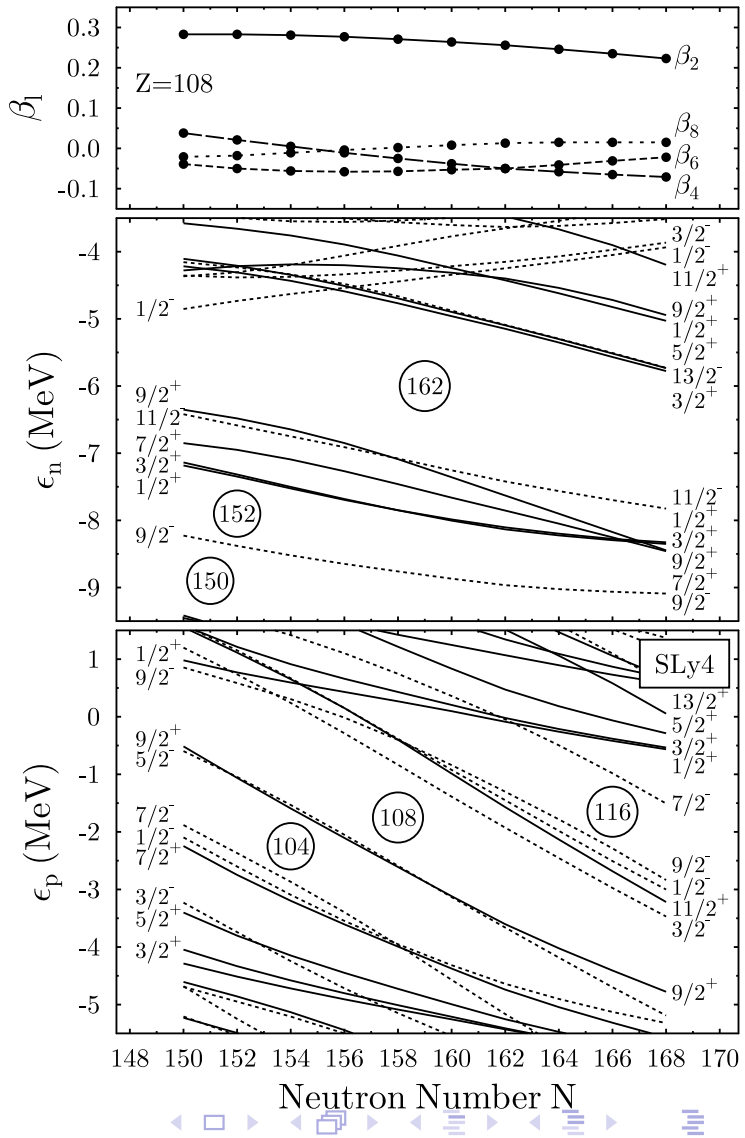
Evolution of deformed shells

M. B. and Heenen, to be published

$Z = 96$



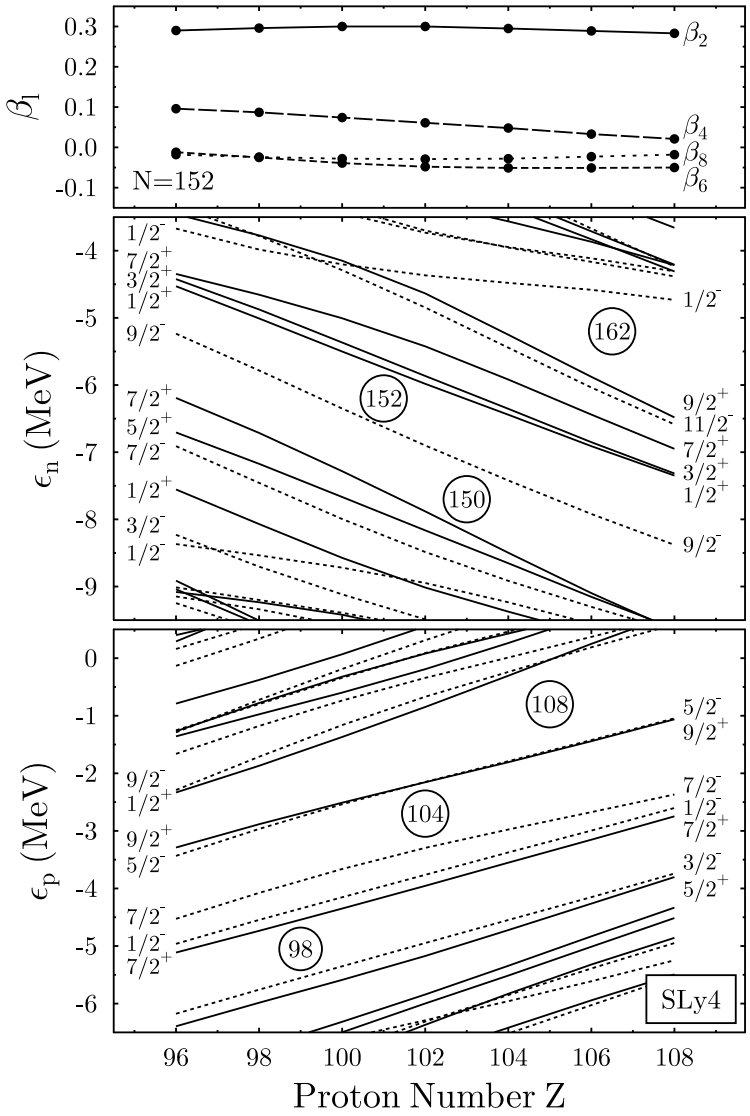
$Z = 108$



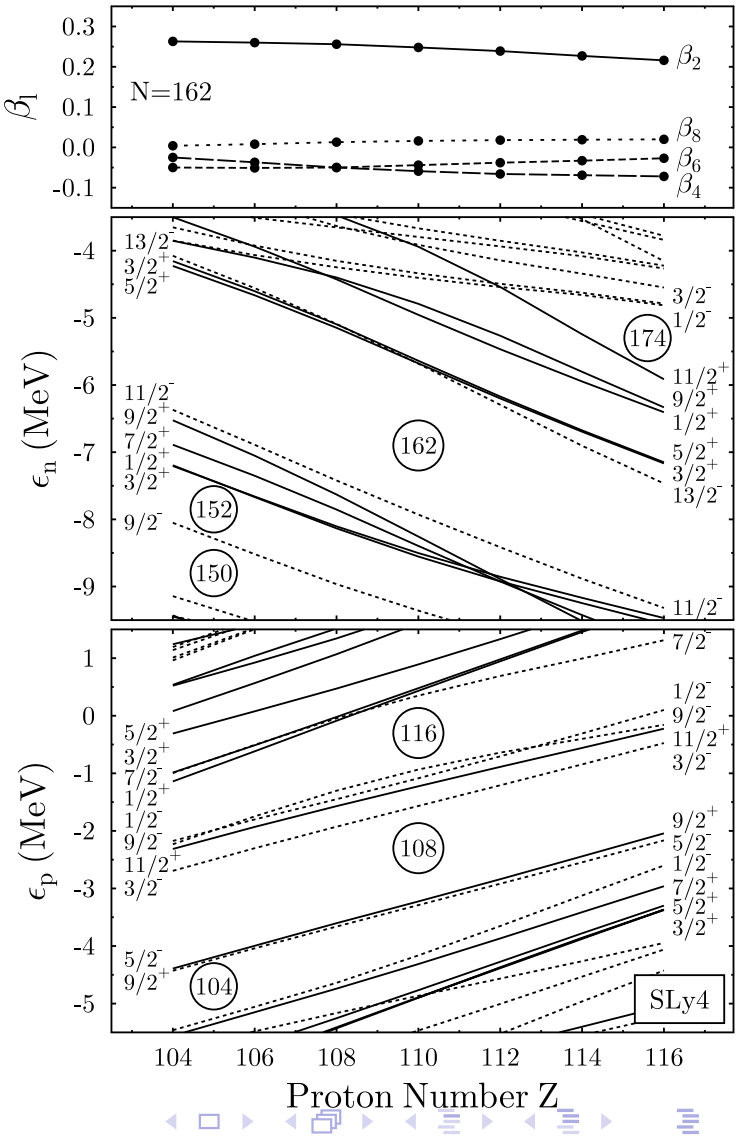
Evolution of deformed shells

M. B. and Heenen, to be published

$N = 152$

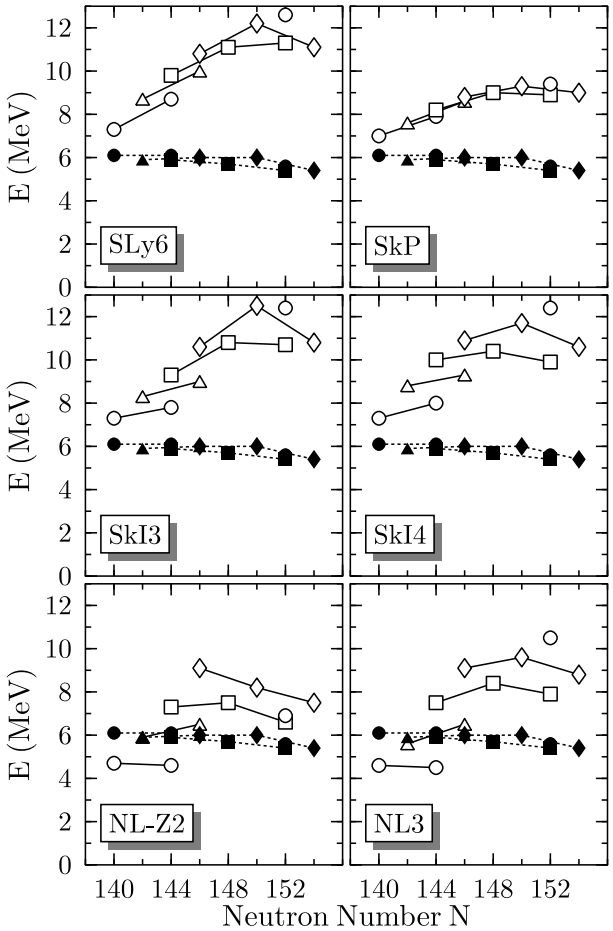


$N = 162$

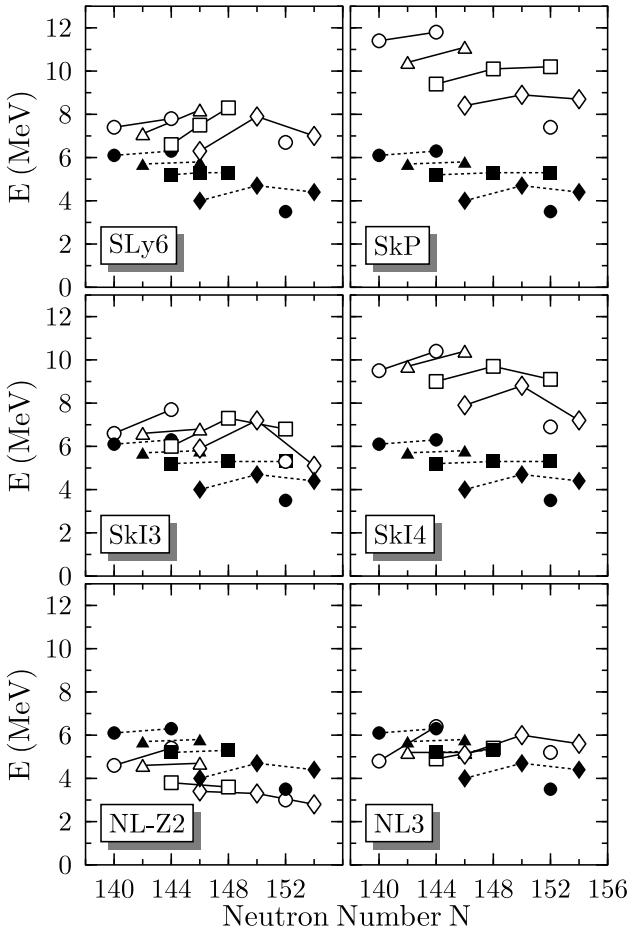


Need for better control of the surface tension

inner barrier



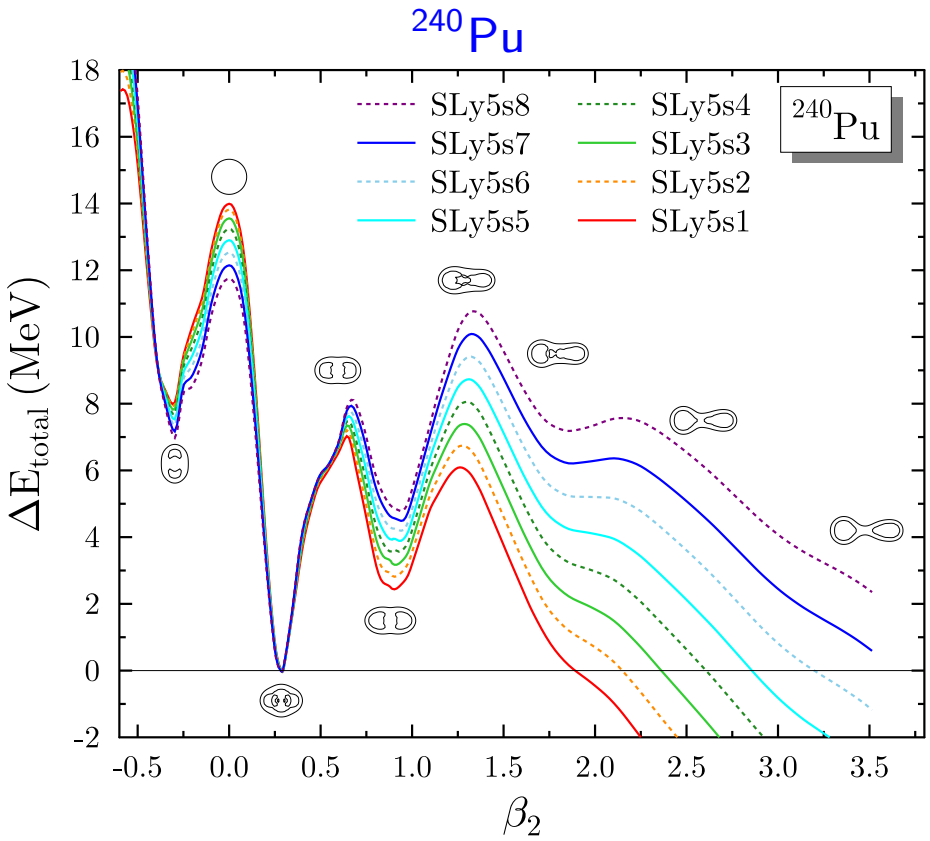
outer barrier



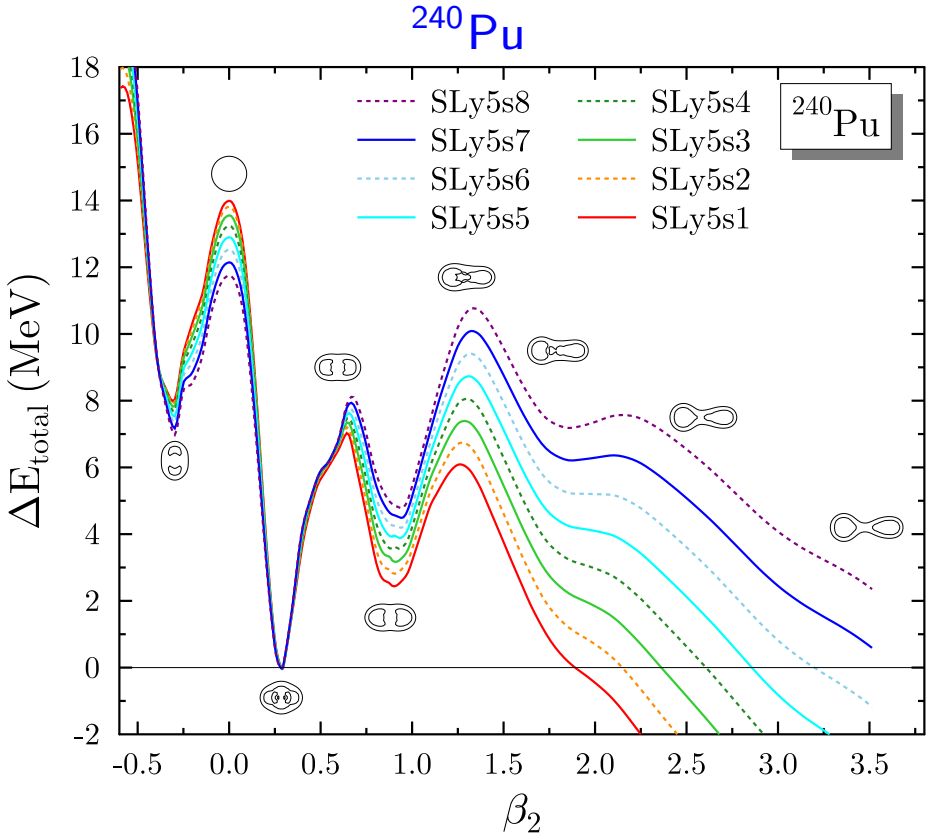
- open symbols: calculated values for various isotopic chains
- filled symbols: experimental values for various isotopic chains

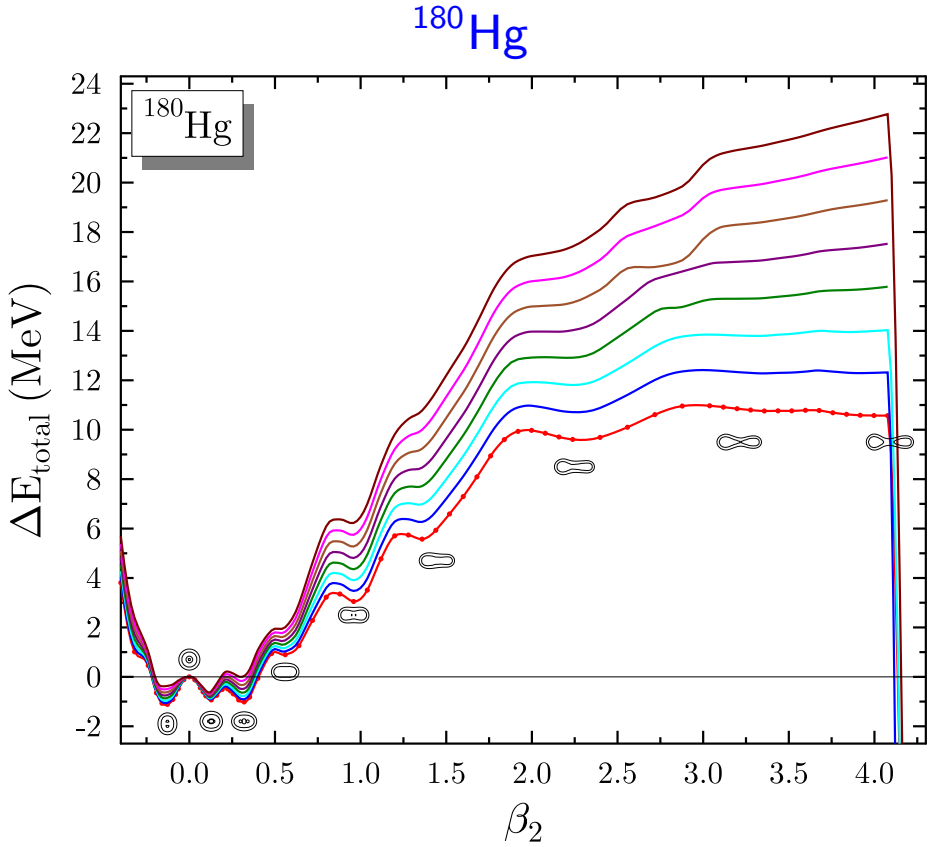
Bürvenich, M. B., Maruhn, Reinhard, PRC 69 (2004) 014307

Better control of the surface tension - The SLy5sX family of fits



Better control of the surface tension - The SLy5sX family of fits





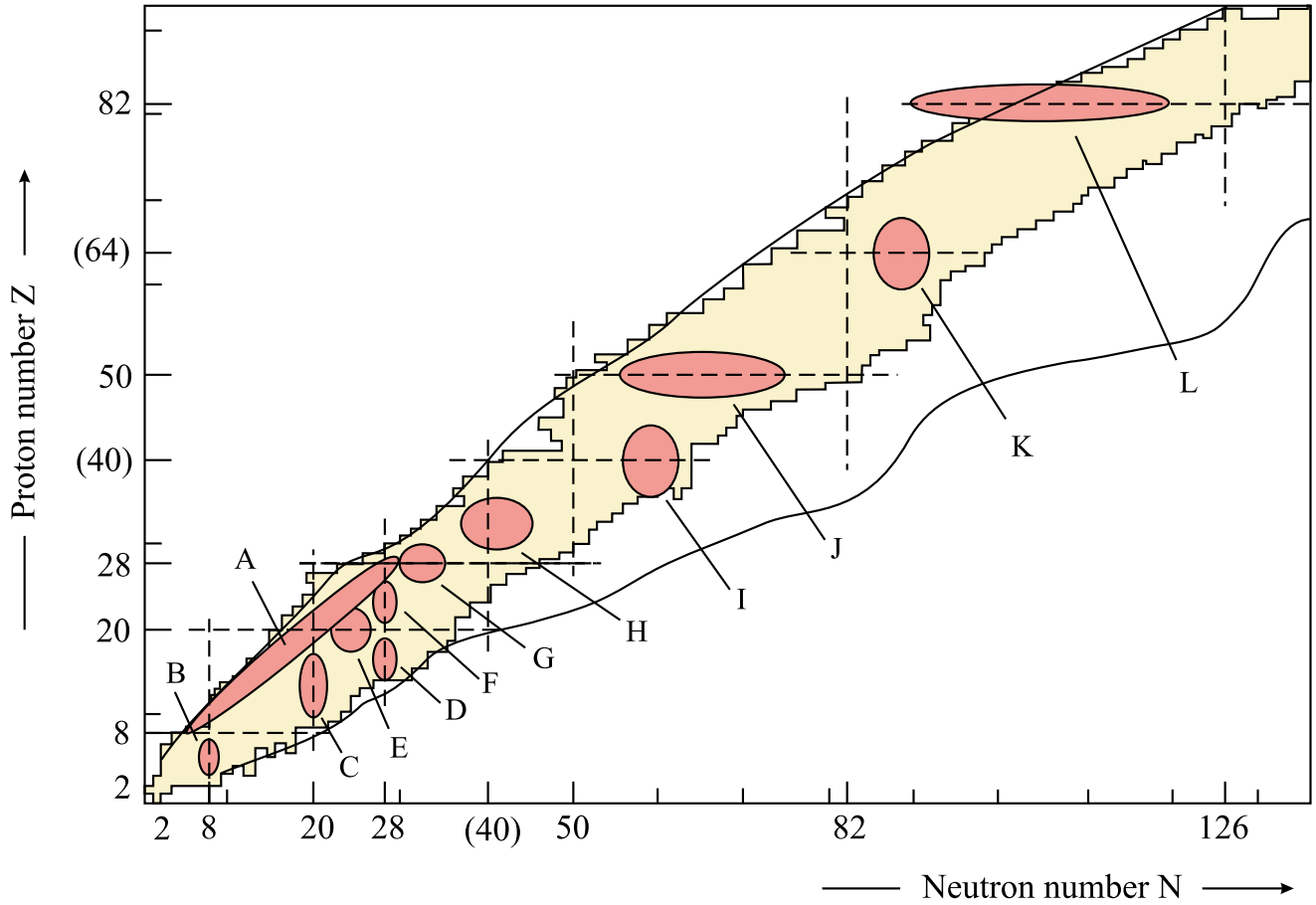
- constraint on an efficient estimate for the surface energy coefficient added to the fit protocol

R. Jodon, thesis, Lyon (2014)

Jodon, Bennaceur, Meyer, M. B., in preparation.

Shape coexistence throughout the chart of nuclei

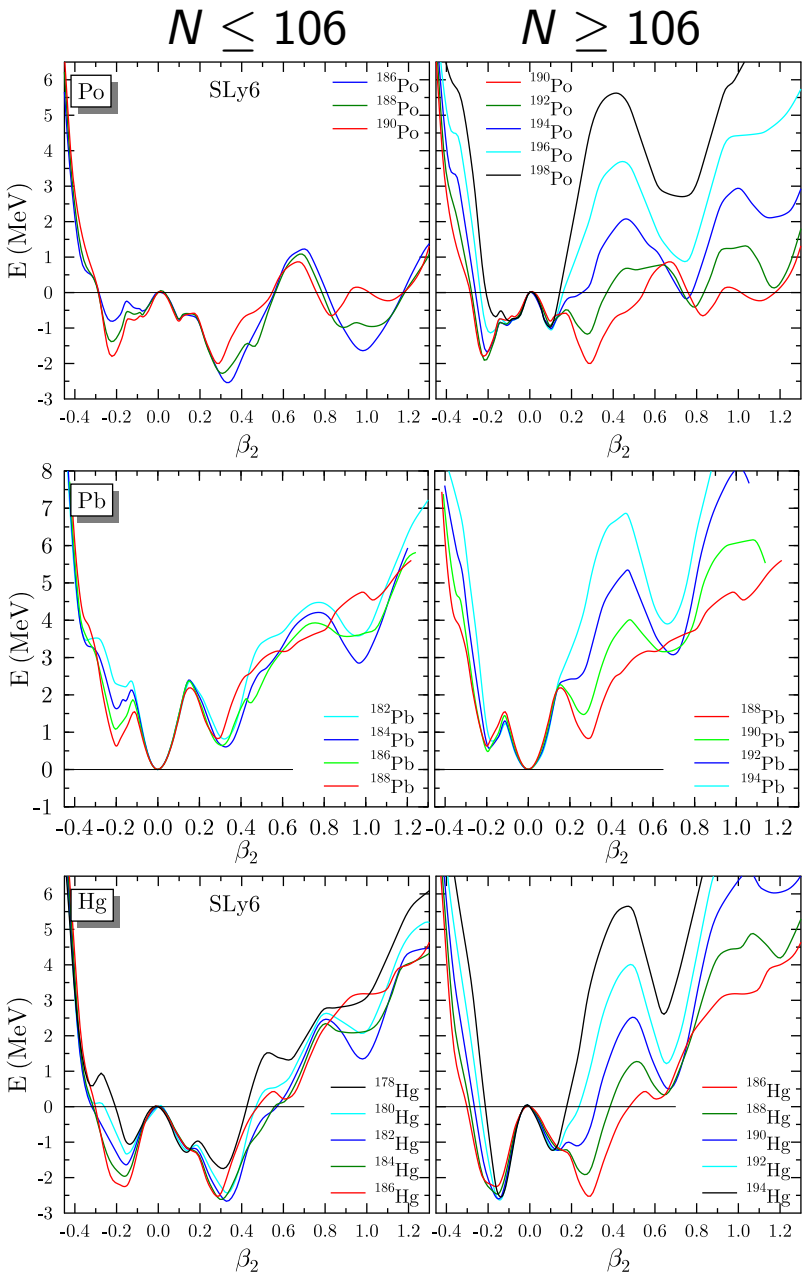
K. Heyde and J. L. Wood, Rev. Mod. Phys. 83 (2011) 1467

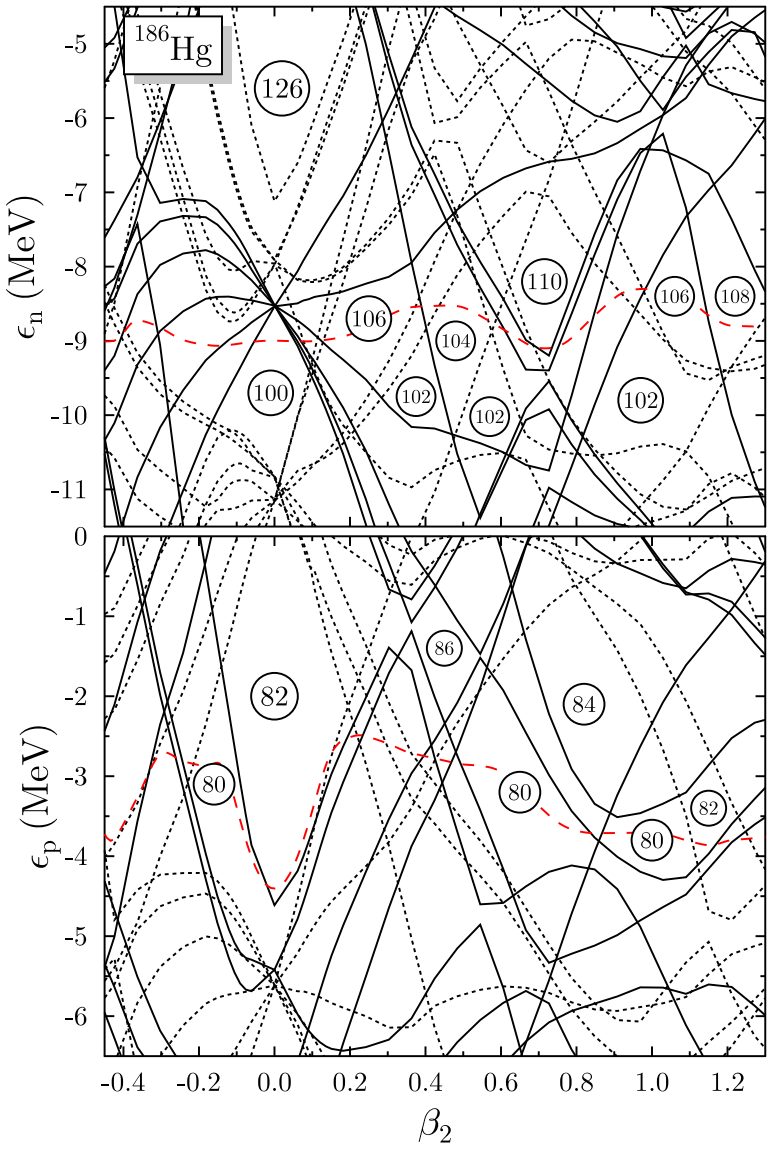


What about shape coexistence phenomena in SHE?

S. Ćwiok, P.-H. Heenen, W. Nazarewicz, Nature 433 (2005) 709

Shape coexistence in the (normal-heavy) $Z = 82$ region

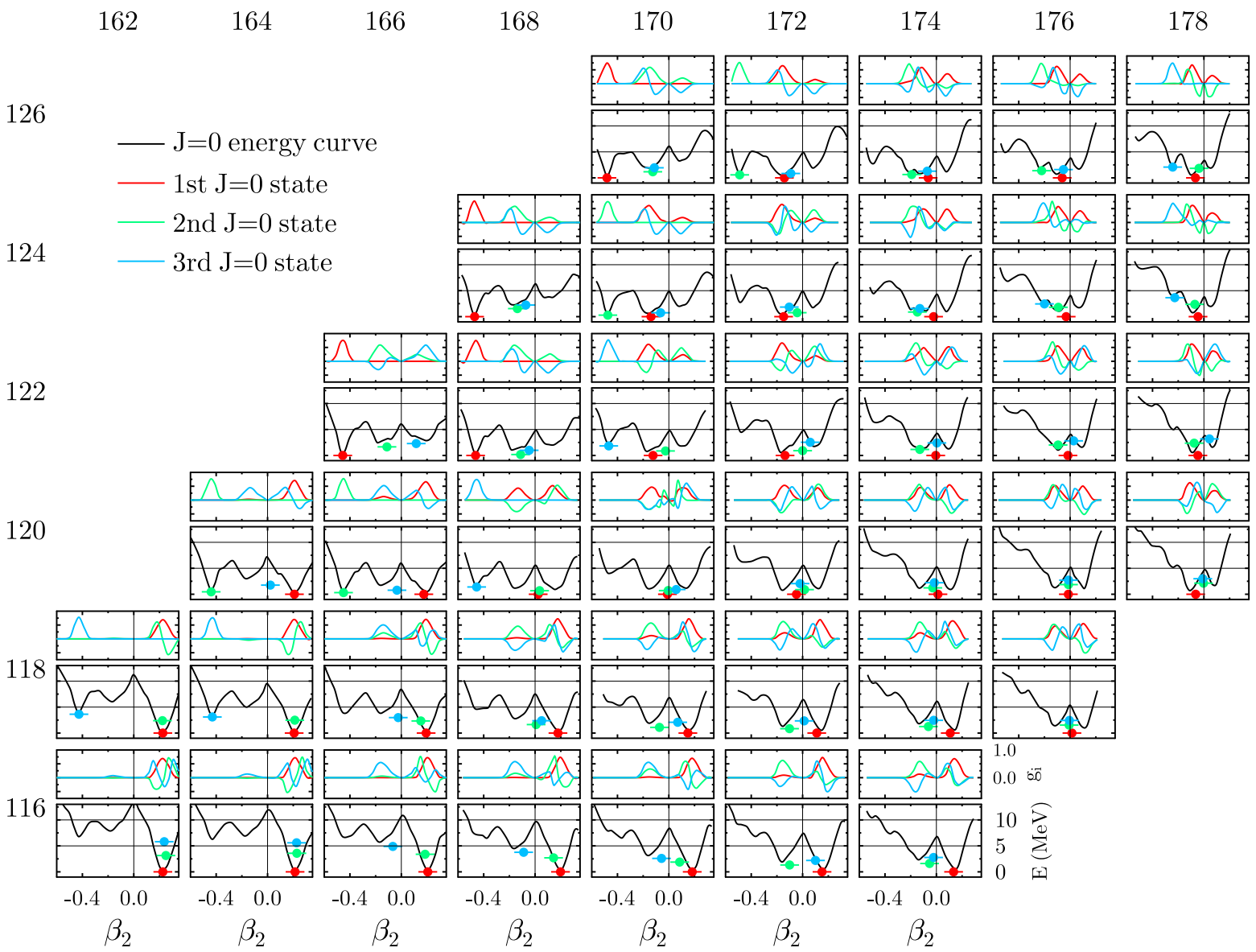




M. B. and P.-H. Heenen, unpublished

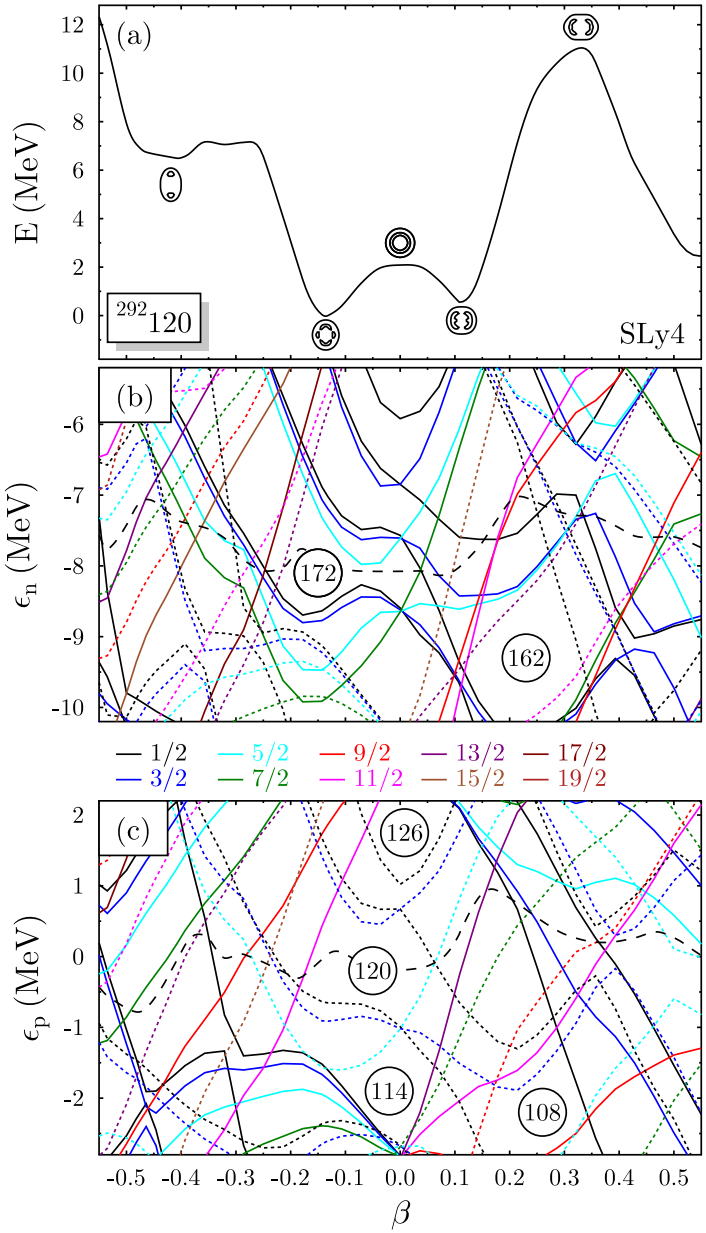
J. Yao, M. B., and P.-H. Heenen, PRC 87 (2013) 034322

Configuration mixing for superheavy nuclei



M. B. and Heenen, to be published
extension of M. B., Bertsch, Heenen, PRC 73 (2006) 034322 to heavier nuclei

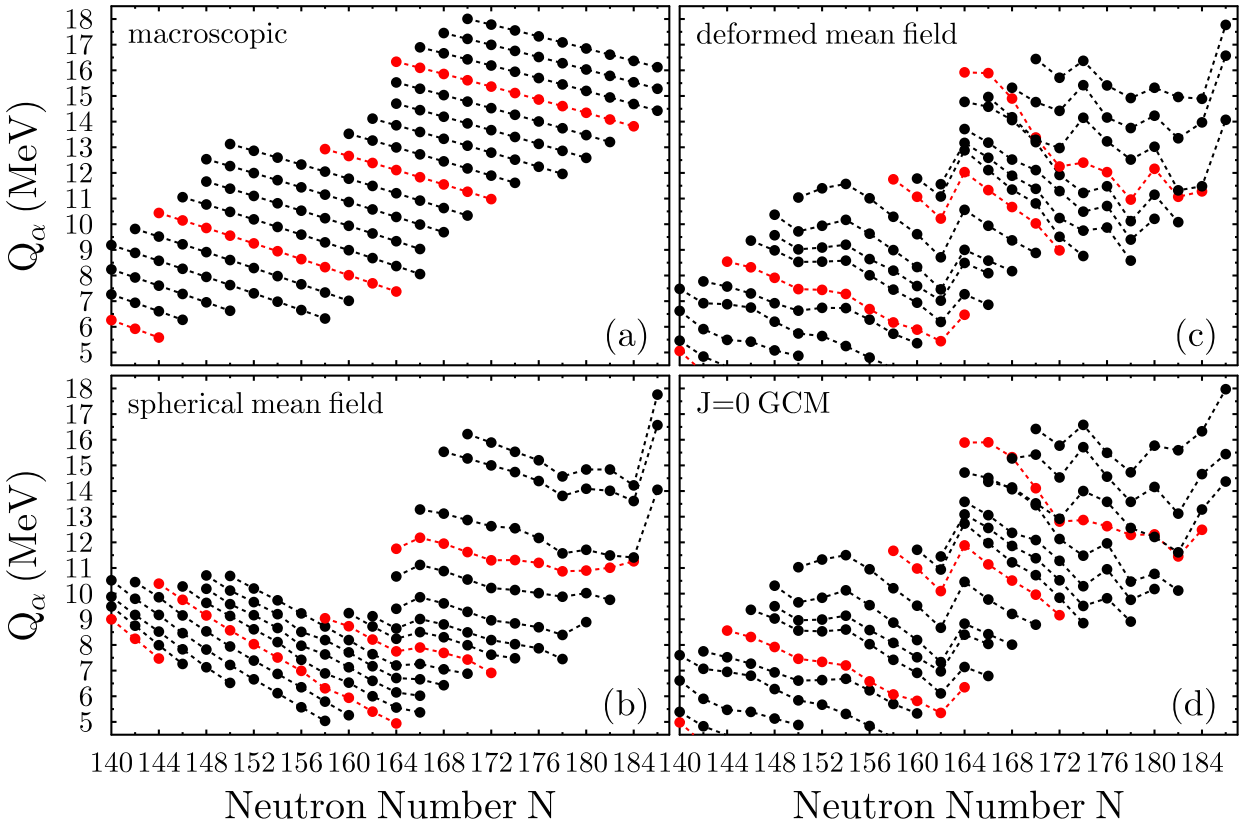
Shape coexistence



- many intruder/extruder levels cross the fermi energy when going to
- possibility for (oblate) high-K isomers

Q_α values of even-even nuclei

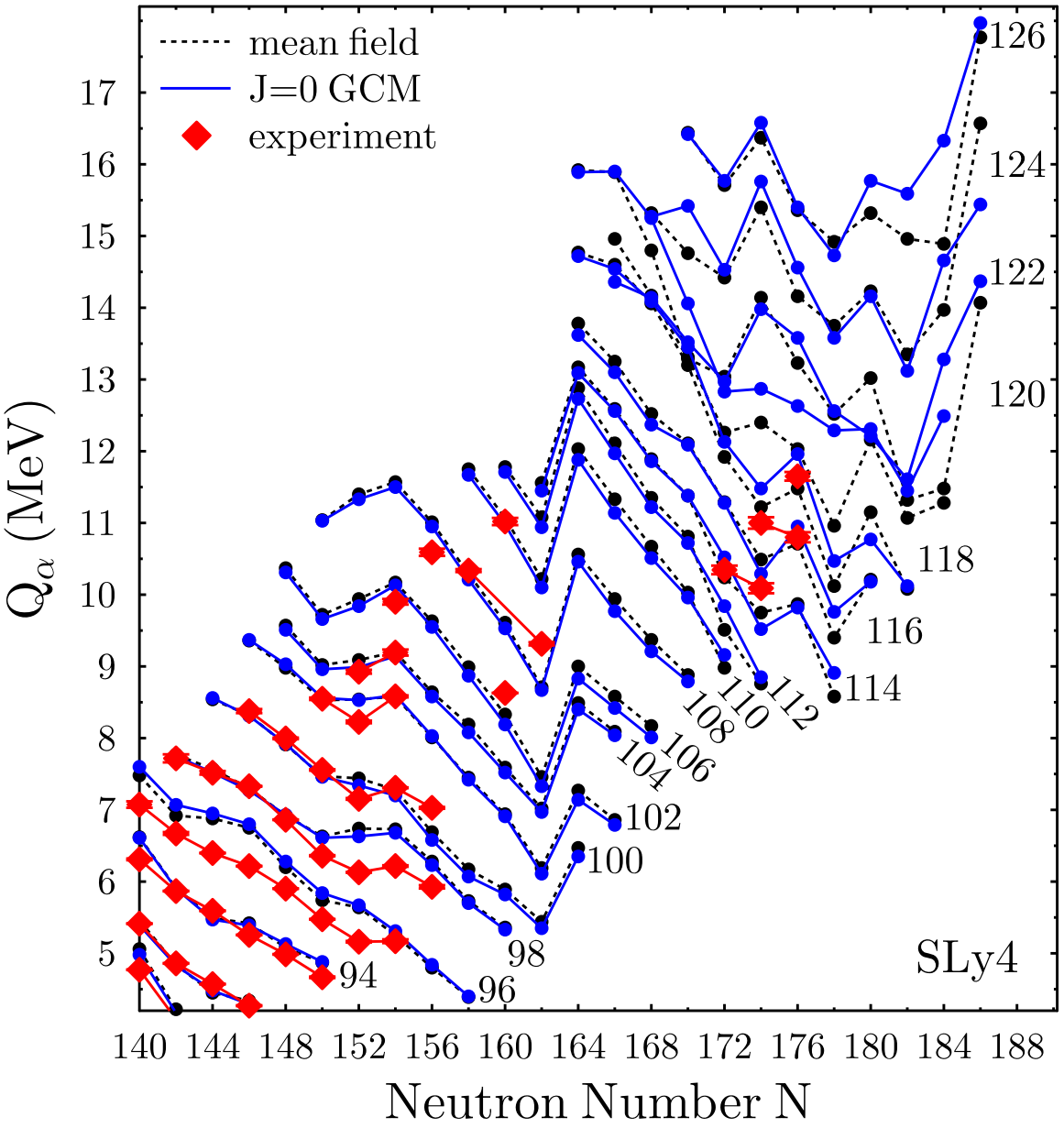
M. B. and P.-H. Heenen, to be published



Q_α values calculated from

- spherical liquid drop with parameters derived from SLy4 (a)
- spherical self-consistent mean field with SLy4 (b)
- deformed self-consistent mean field with SLy4 (c)
- $J = 0$, N and Z projected GCM of axial states with SLy4 (d)
- isotopic chains $Z = 90$, 100, 110, 120 shown in red

Q_α values of even-even nuclei: Role of correlations beyond the mean field



- quadrupole correlations beyond the mean field only play a minor role for ground states in the region where spectroscopic studies are underway and/or planned
- they might have some impact in the region of the heaviest known addressed by synthesis experiments

Take-away messages

- exiting parameterizations are of overall similar quality, with significant differences in detail.
- It is highly unlikely that the differences with experiment concerning shell structure in the $A \approx 250$ region can be resolved within the existing forms of the EDFs in use. This constitutes one of the motivations to construct EDFs of different form and/or containing higher-order terms.
- one can expect multiple shape coexistence in superheavy elements when approaching $Z = 120$.
- different shapes at small deformation might in many cases be strongly mixed in the ground state for the $Z \gtrsim 114$ nuclides within experimental reach.
- there are exotic shapes at large oblate deformation that appear to be decoupled from the shapes at small deformation
- possibility of oblate and very oblate high-K isomers.
- strong evolution of *deformed* shell closures in the transfermium region with N and Z.
- shopping list for theoretical developments: less symmetry-constrained calculations – better functionals (performance-wise and usability-wise regarding going beyond the mean field)