Global octupole deformation and Schiff moment

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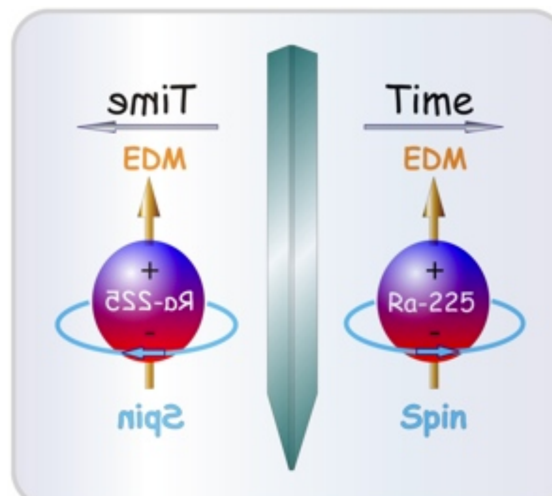
- The Standard Model CP-violation is too small to explain the **matter / antimatter asymmetry** in the universe

- Beyond Standard Model theories require **additional CP-violation**

- **Non-zero** Electric Dipole Moment (**EDM**) of a **neutral particle** indicates T-violation (thus CP-violation)

- **Schiff moment relates / enhances** atomic EDM to fundamental P-, T-violating coupling constants



Measured atomic EDMs limits

↓

Constraints on Schiff moments

↓

Constraints on fundamental P-,T-violating coupling constants

- **Theory relates atomic EDM (limit) to Schiff moment, eg. for ^{199}Hg:**

$$\mathbf{d}_{\mathrm{Hg}} = -2.4 \times 10^{-4} \mathbf{S}_{\mathrm{Hg}} / \mathrm{fm}^2$$

- **Measured atomic EDM limit constrains Schiff moment**

$$|S_{\mathrm{Hg}}| < 3.1 \times 10^{-13} \ e\,\mathrm{fm}^3 \quad (95\%\mathrm{C.L.}).$$

-B. Graner et al., *Phys. Rev. Lett.* **116**, 161601(2016)

- **Schiff moment is related to the P-, T- violating coupling constants through** $\hat{V}_{\not{P}\not{T}}$

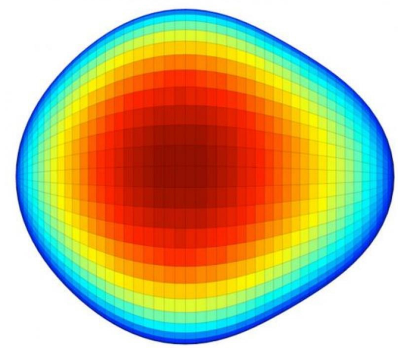
Definition (to first order):

$$S \equiv \langle \Psi_0 | \hat{S}_z | \Psi_0 \rangle = \sum_{i \neq 0} \frac{\langle \Psi_0 | \hat{S}_z | \Psi_i \rangle \langle \Psi_i | \hat{V}_{\mathrm{PT}} | \Psi_0 \rangle}{E_0 - E_i} + \mathrm{c.c.}$$

$$\hat{S}_z = \frac{e}{10} \sum_p \left(r_p^2 - \frac{5}{3} \bar{r}_{\mathrm{ch}}^2 \right) z_p$$

Large Z nuclei

Parity doublets: Near degenerate energy levels, commonly found in **octupole deformed odd** nuclei

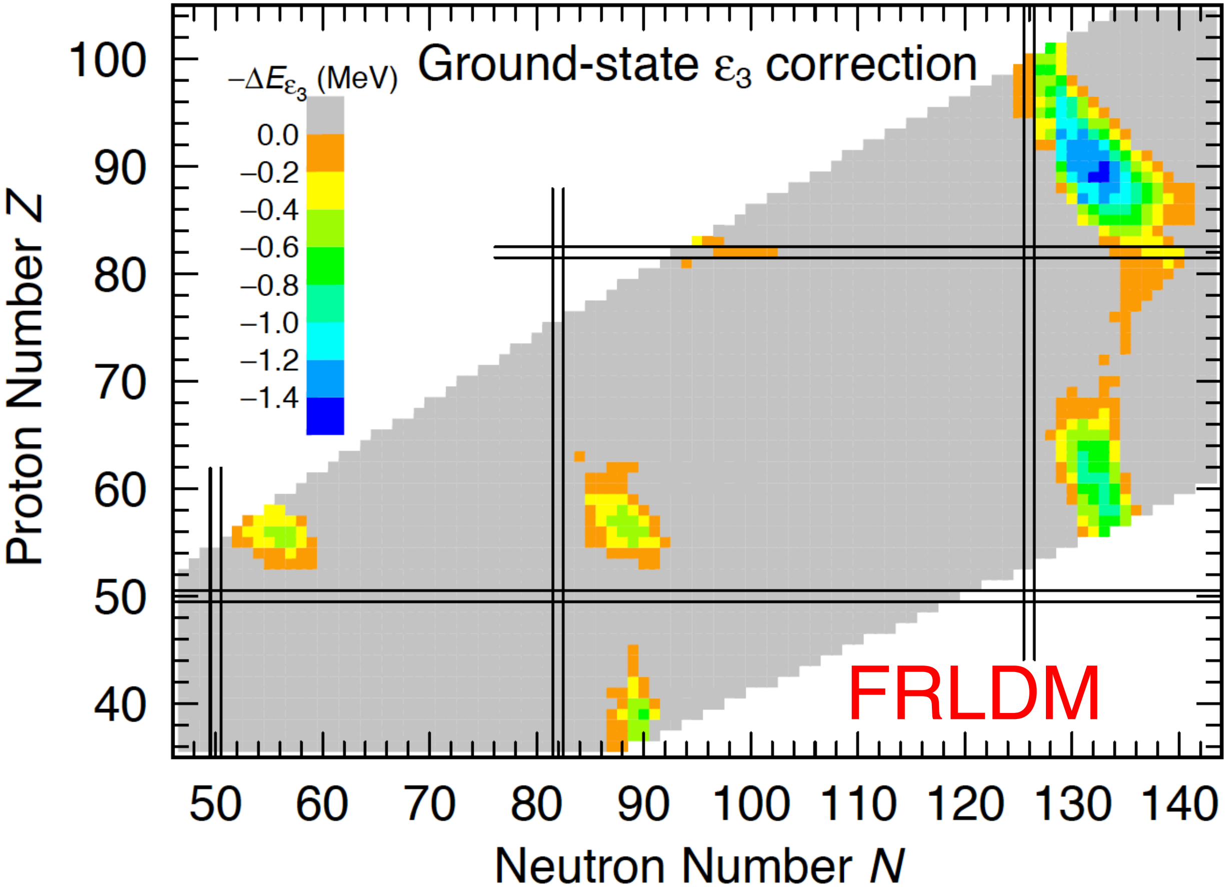


$$S_{\mathrm{Hg}} = 0.0004 g \bar{g}_0 + 0.055 g \bar{g}_1 + 0.009 g \bar{g}_2 \quad (e\ \mathrm{fm}^3)$$

$$S_{\mathrm{Ra}}^{\text{zero-range}} = -5.06 g \bar{g}_0 + 10.4 g \bar{g}_1 - 10.1 g \bar{g}_2 \quad (e\ \mathrm{fm}^3)$$

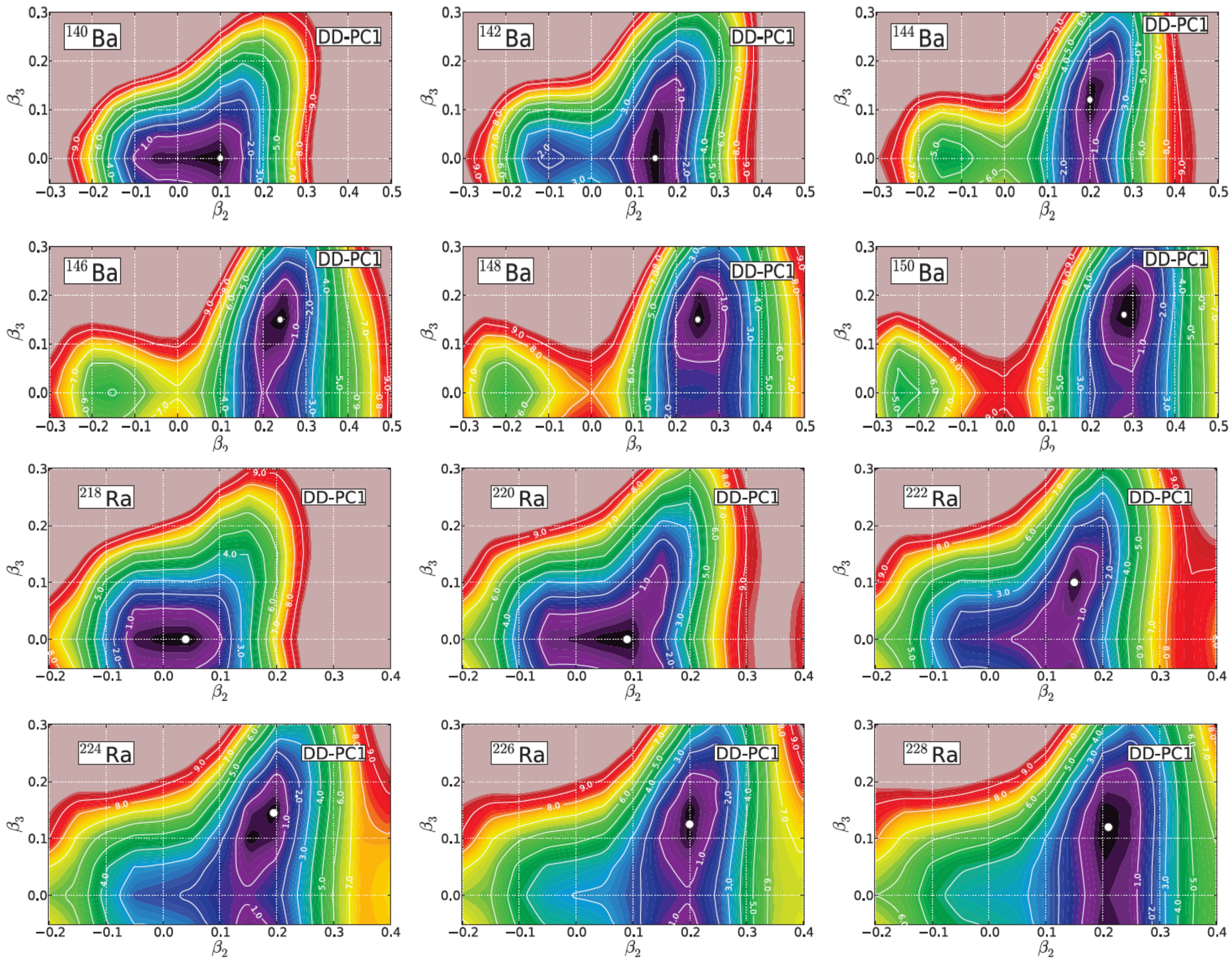
-J. Engel, et al., *Phys. Rev. C* **68** 025501(2003)

-L. P. Gaffney et al., *Nature* 497, 199-204(2013)

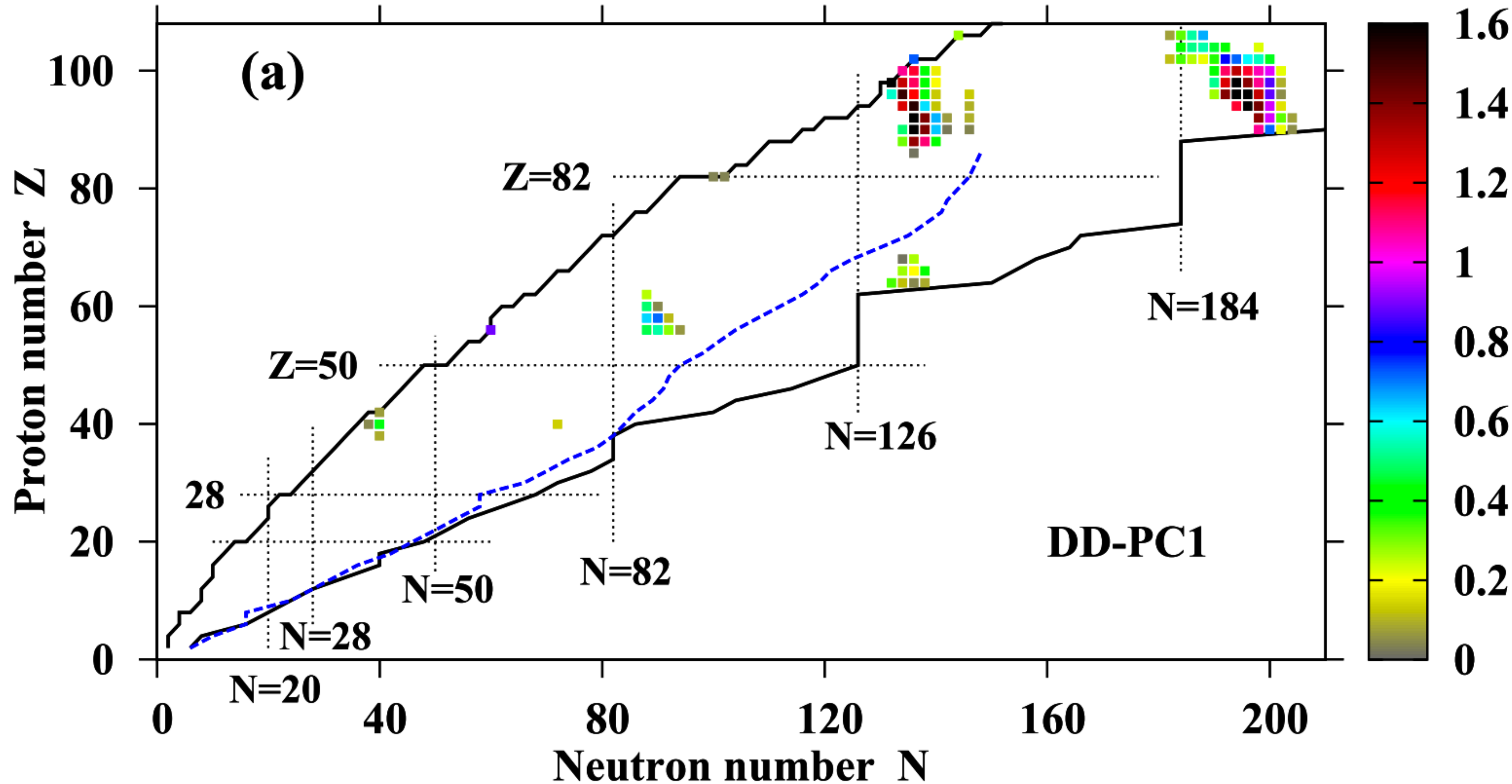


Axial and reflection asymmetry of the nuclear ground state
P. Möller et al, Atomic Data and Nuclear Data Tables 94, 758 (2008)

CDFT:DD-PC1



K. Nomura et al., Phys. Rev. C 89, 024312 (2014)

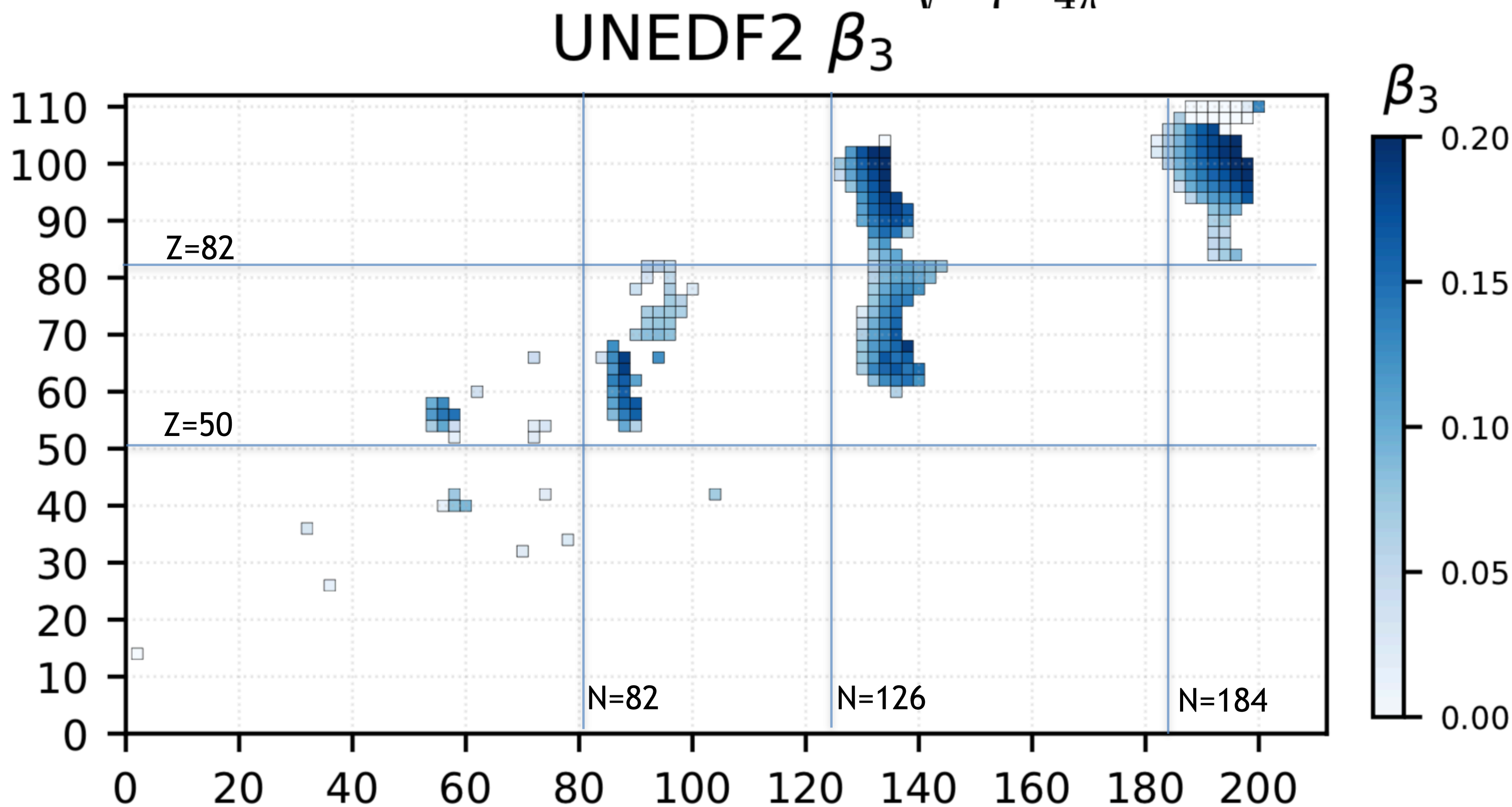


S.E. Agbemava, A.V. Afanasjev, P. Ring, Octupole deformation in the ground states of even-even nuclei: A global analysis within the covariant density functional theory, Phys. Rev. C 93, 044304 (2016)

Skyrme DFT even-even octupole mass-table

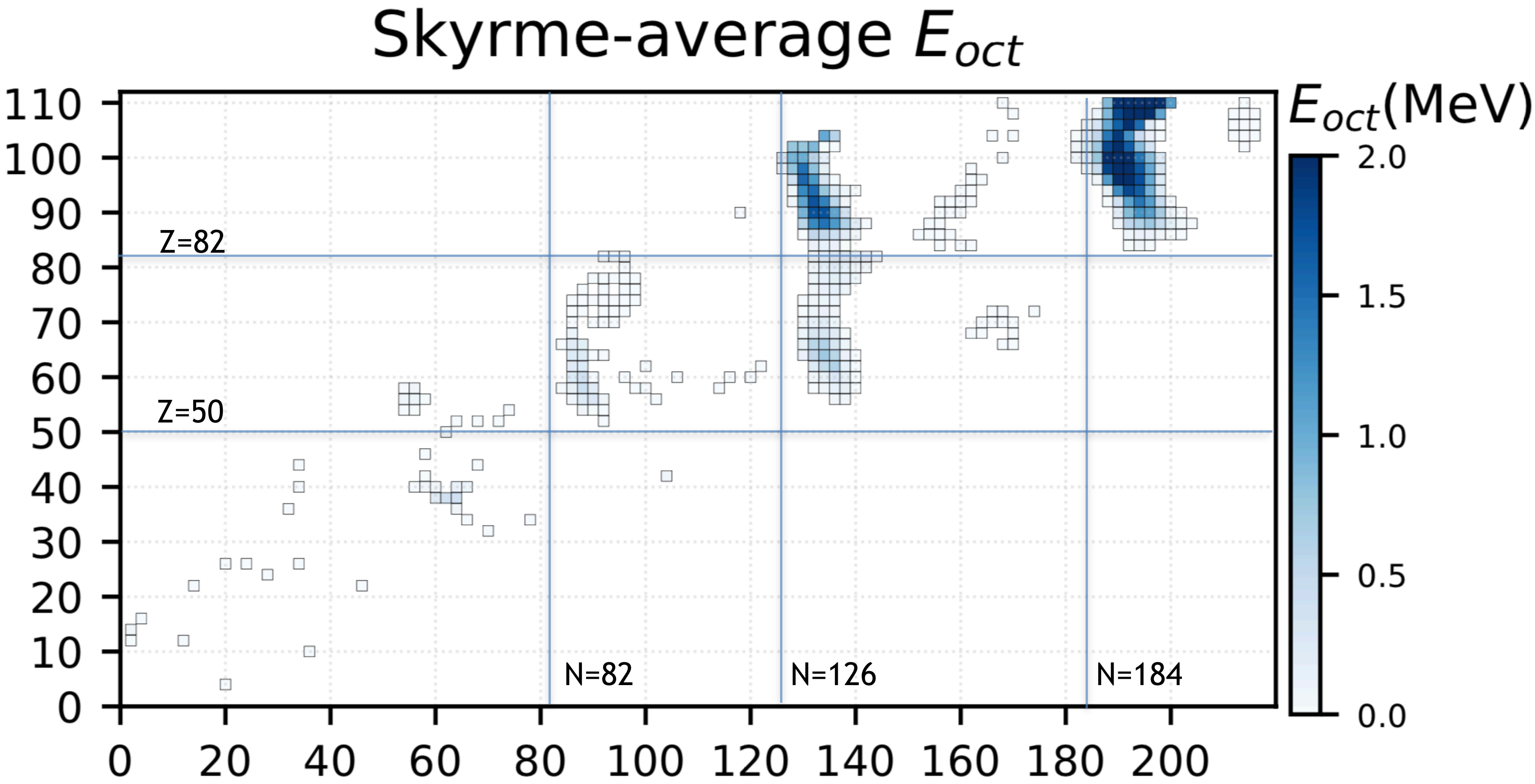
Equilibrium deformation

$$\beta_3 = Q_{30}/(\sqrt{\frac{16\pi}{7}}\frac{3}{4\pi}AR_0^3)$$

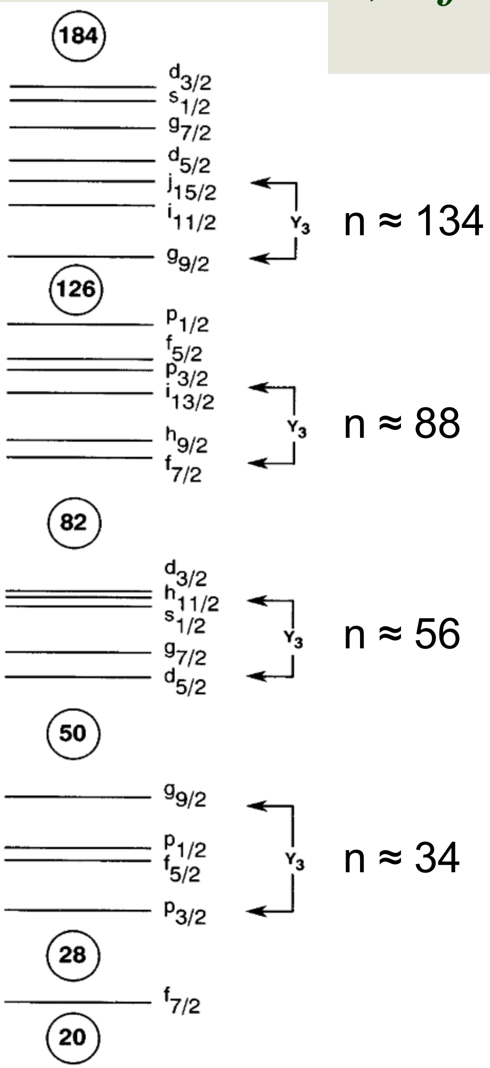


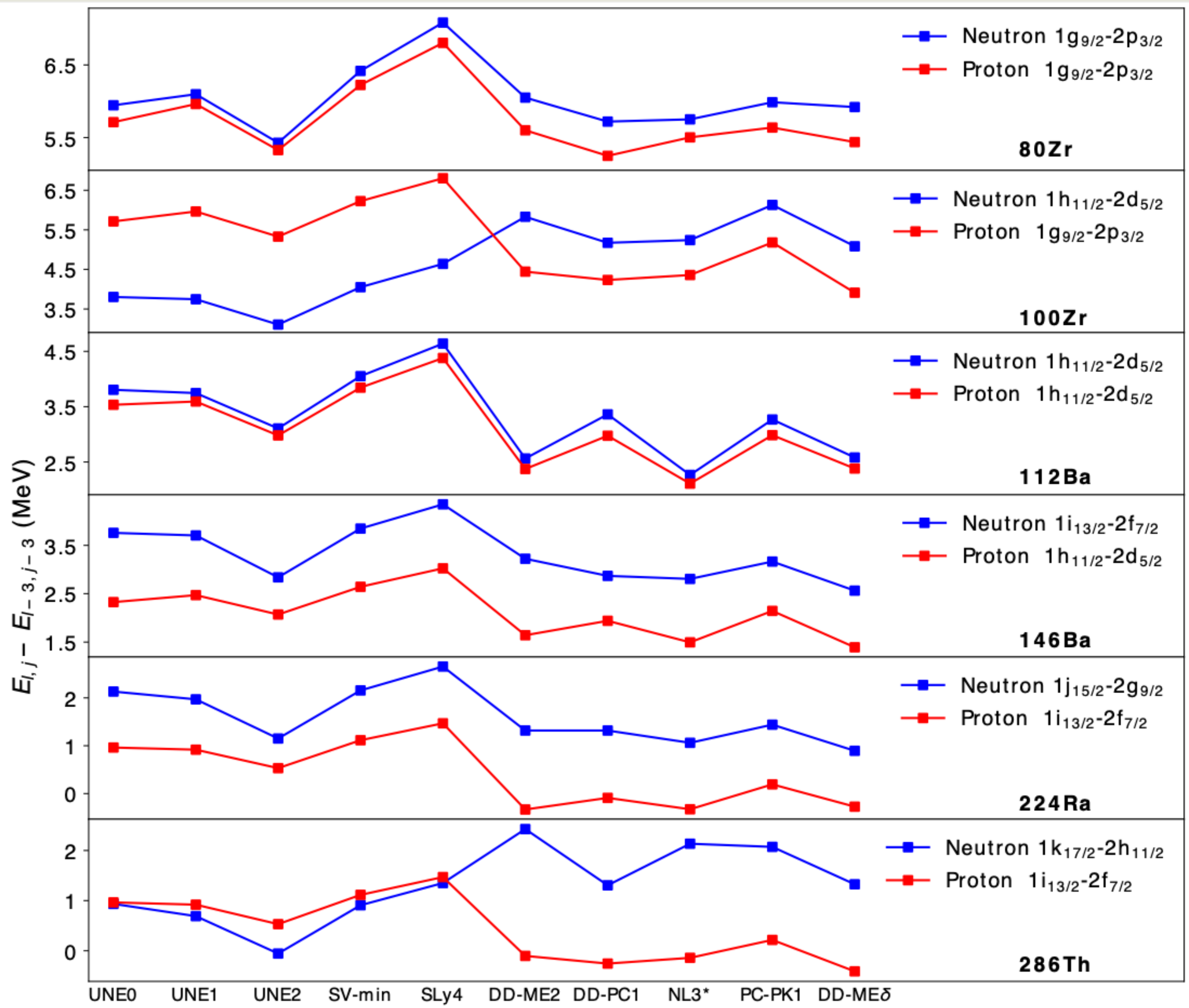
Octupole energy

$$\Delta E_{\rm oct} = E^{\rm oct}(\beta_2, \beta_3) - E^{\rm quad}(\beta_2', \beta_3' = 0)$$



$\Delta l, \Delta j = 3$ single particle levels splitting





P. Butler and W. Nazarewicz,
Rev. Mod. Phys. 68,349 (1996)

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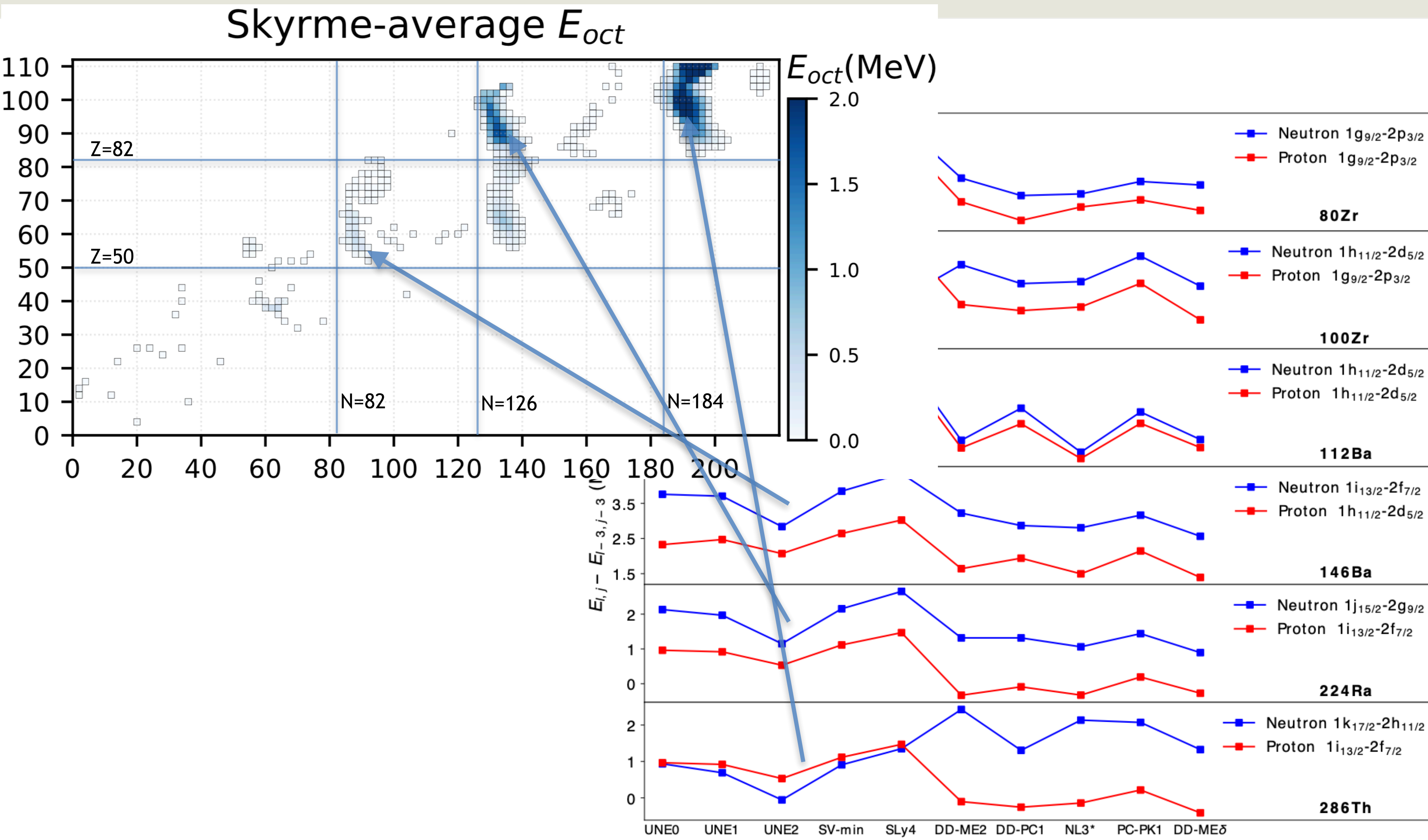
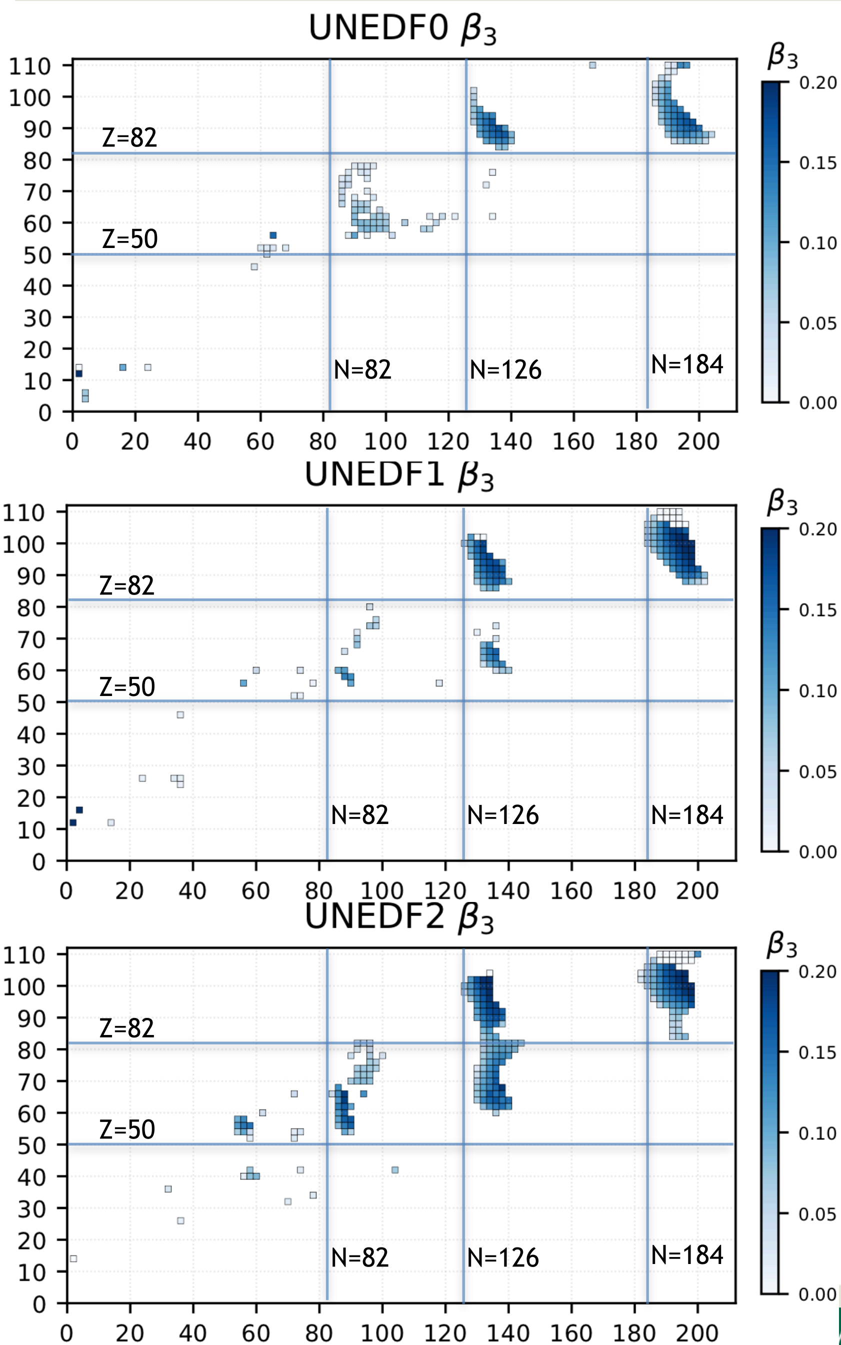
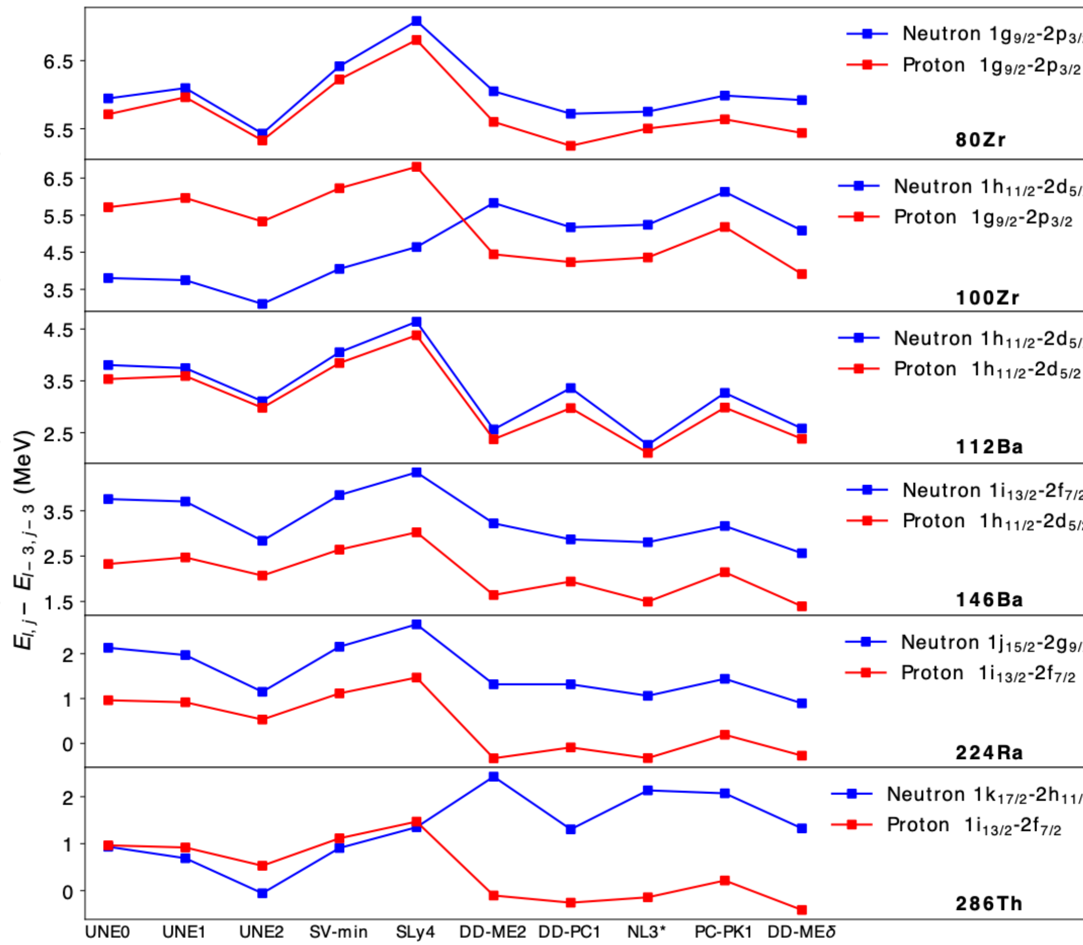
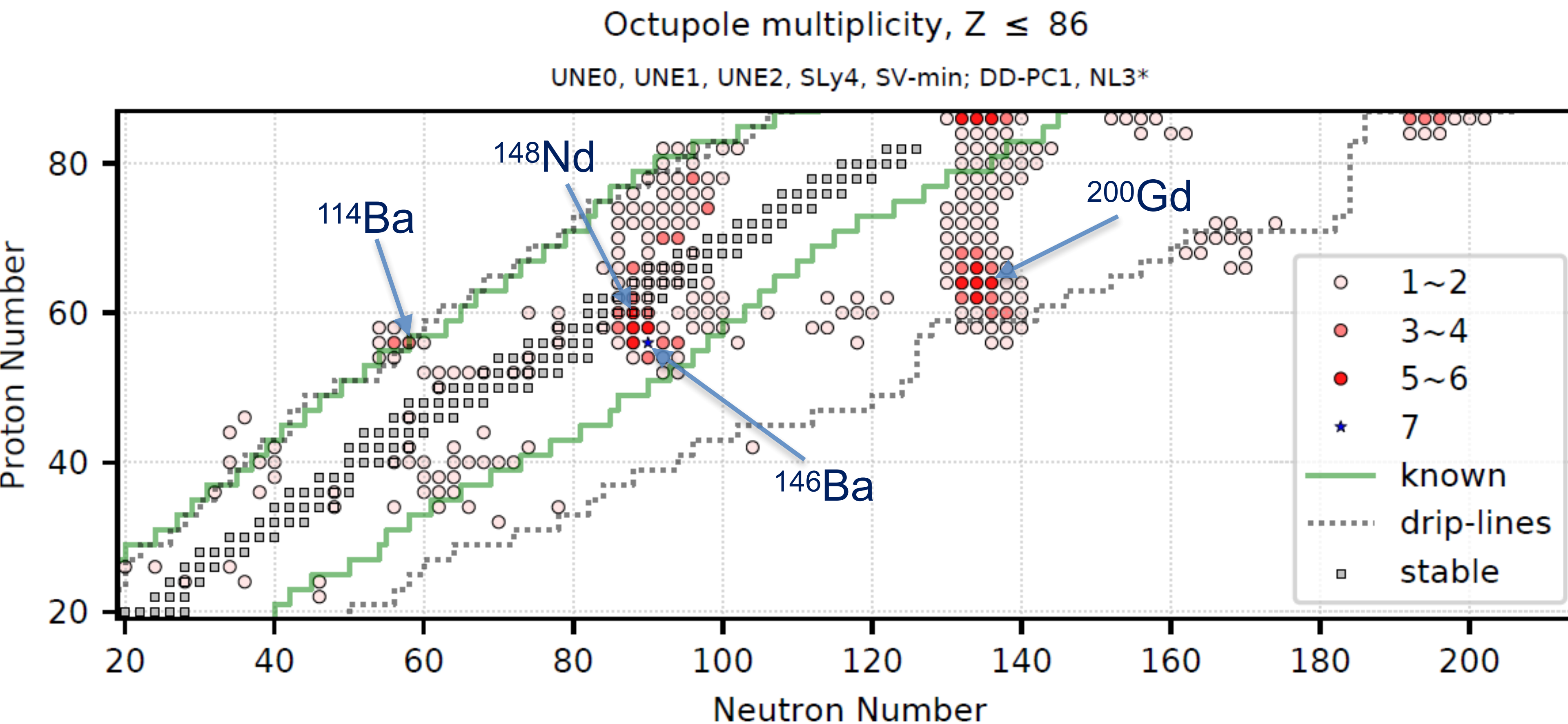


particle levels splitting

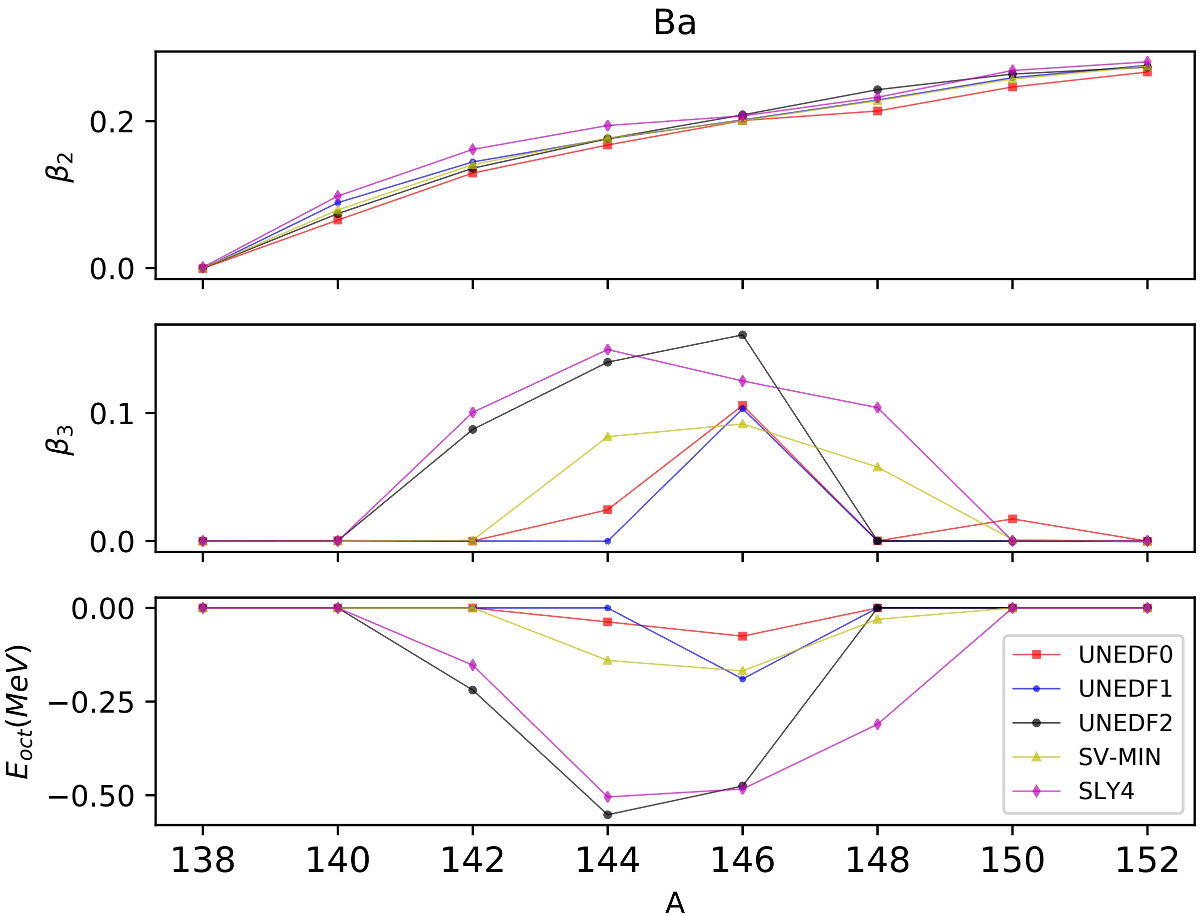


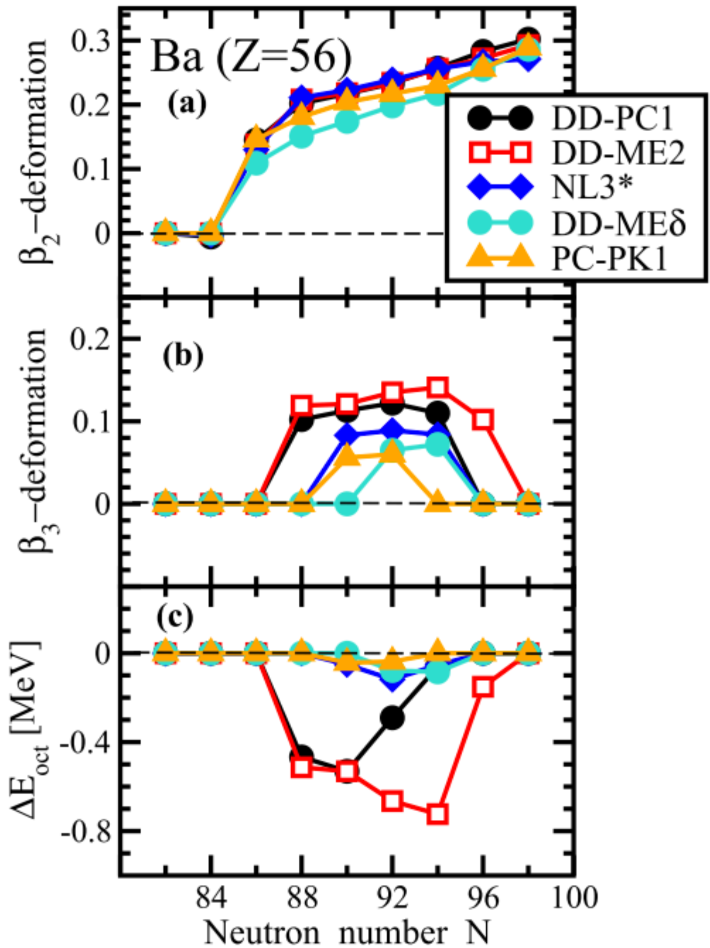


Number of cases, Z<=86 (7 models)



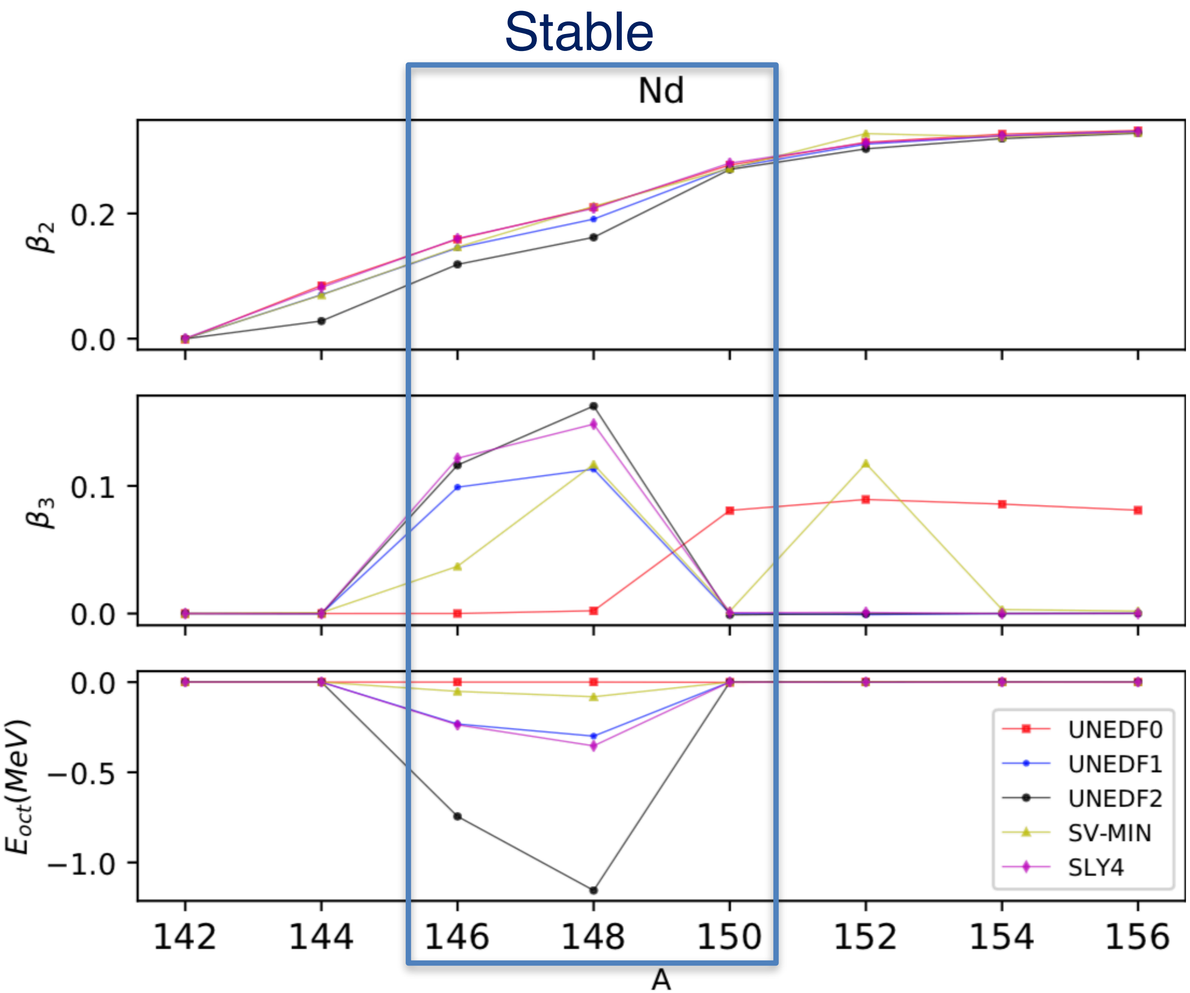
Ba (Z=56)

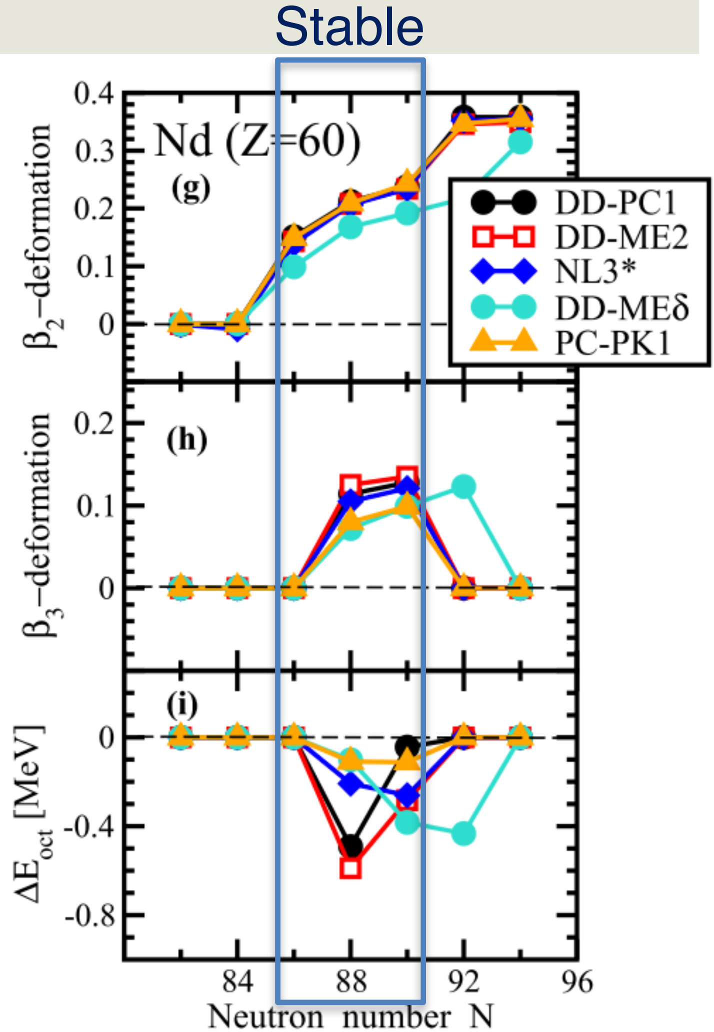




S. Agbemava et al., Phys. Rev. C **93**, 044304 (2016)

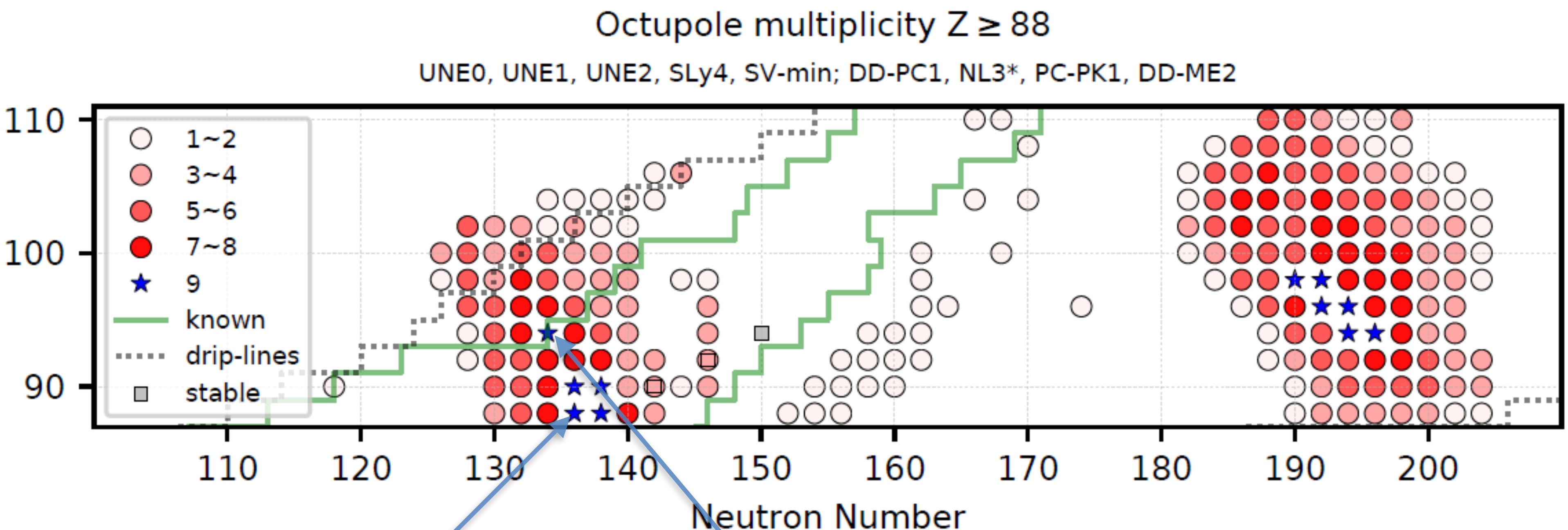
Nd (Z=60)



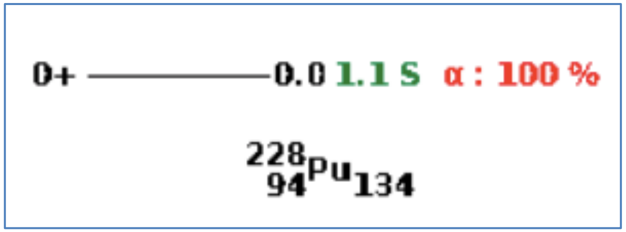


S. Agbemava et al., Phys. Rev. C **93**, 044304 (2016)

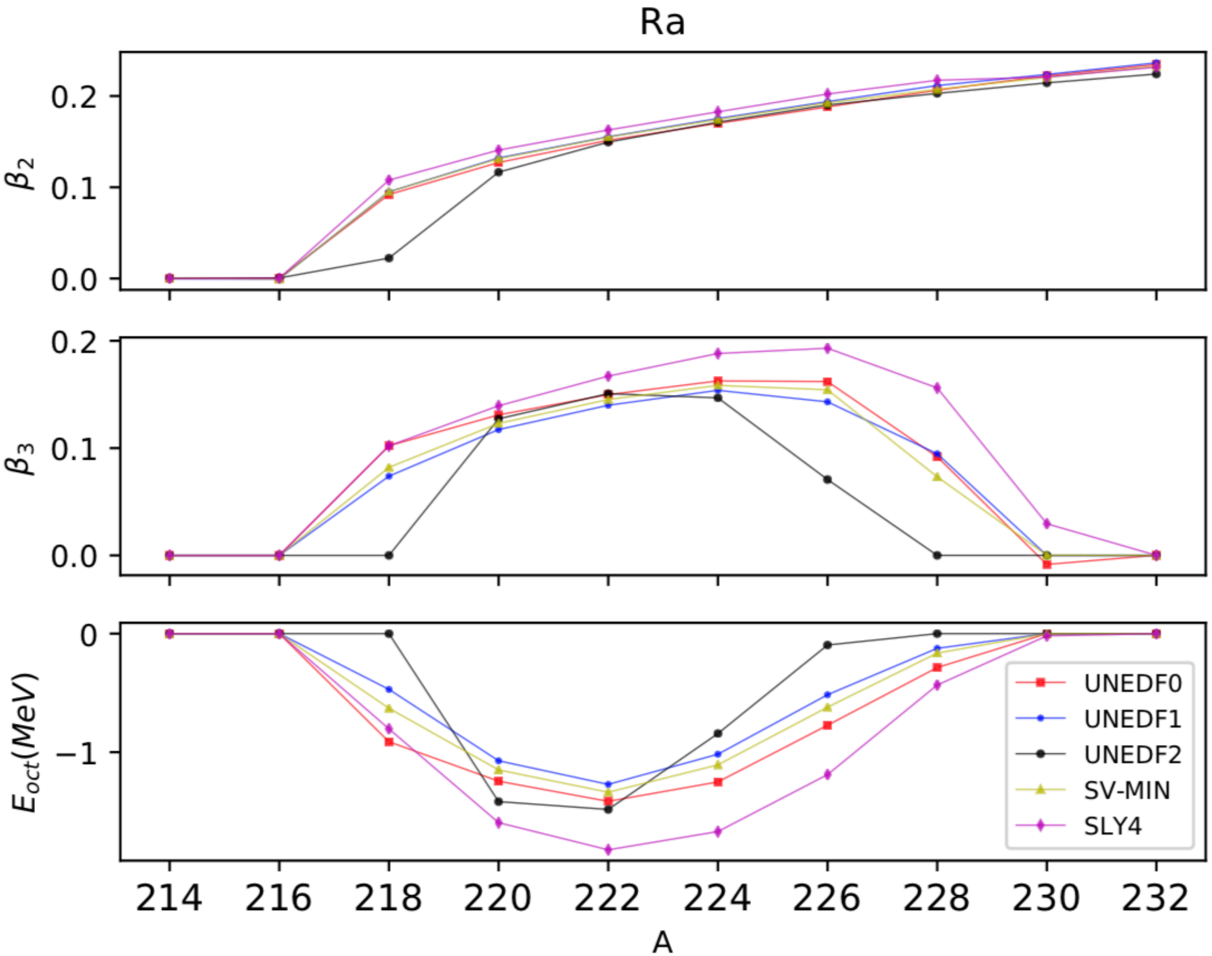
Number of cases, Z>=88 (9 models)

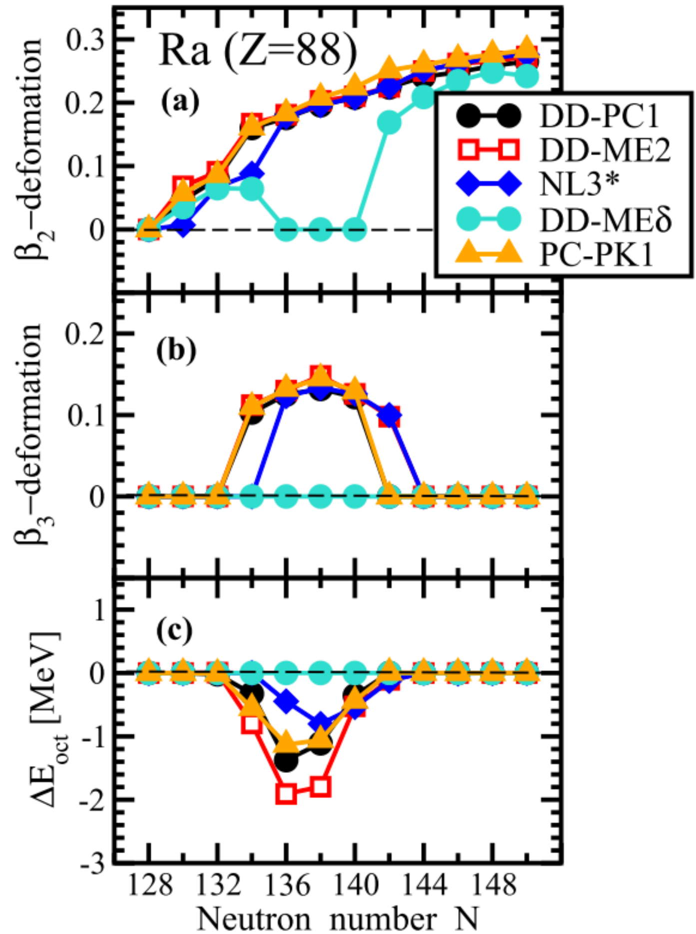


^{224,226}Ra, ^{226,228}Th ^{228}Pu



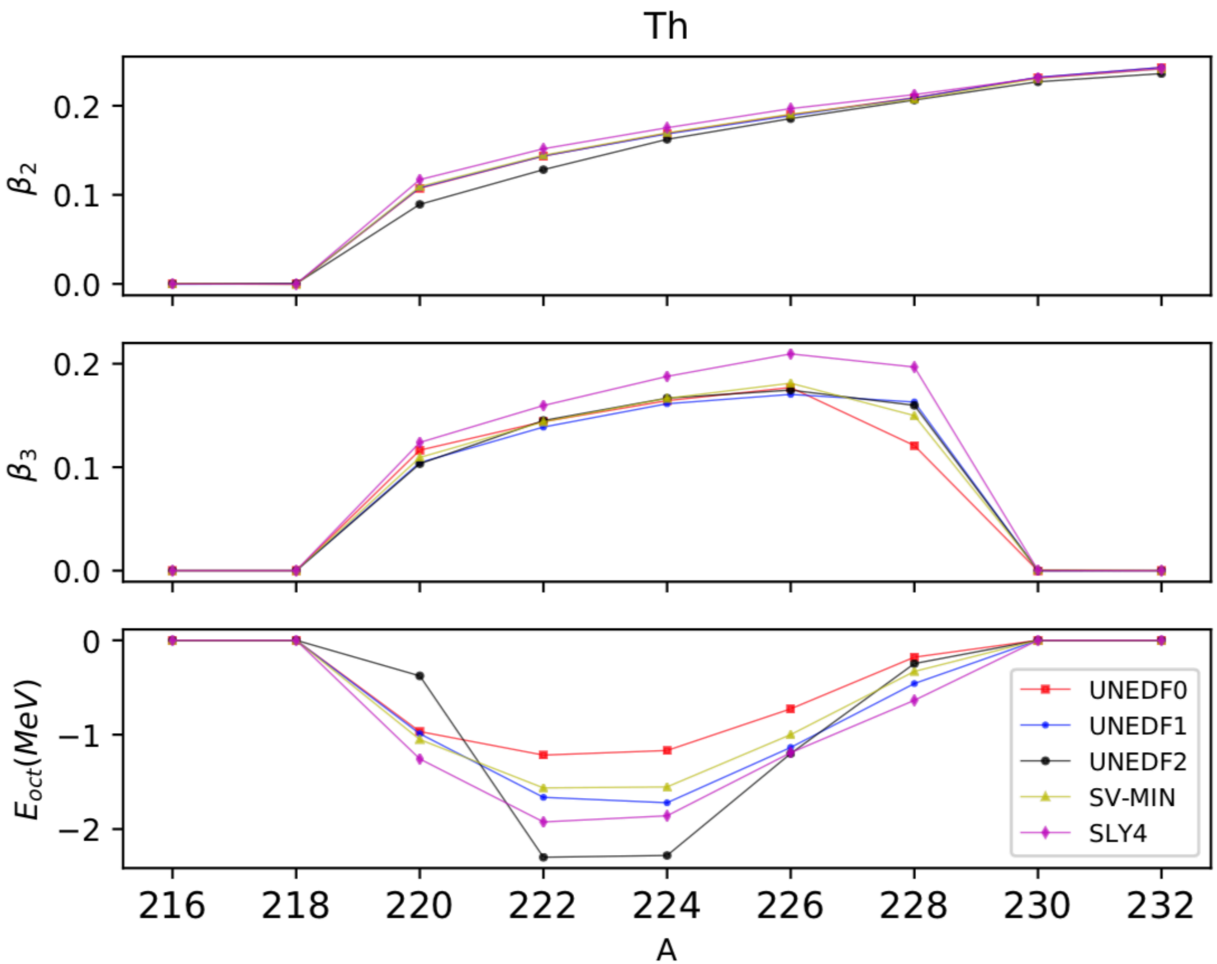
Ra (Z=88)

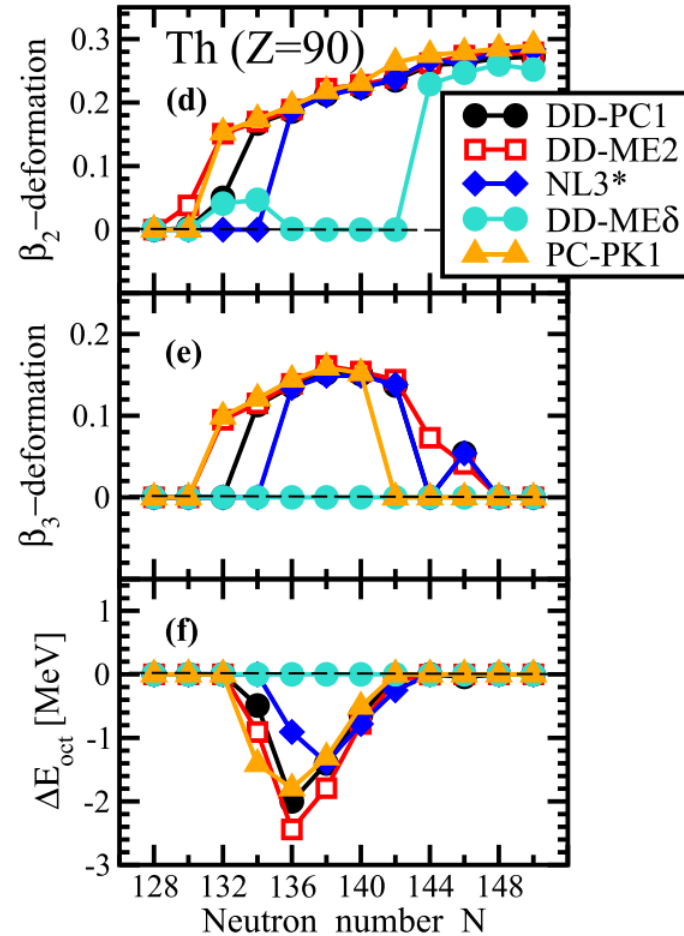




S. Agbemava et al., Phys. Rev. C **93**, 044304 (2016)

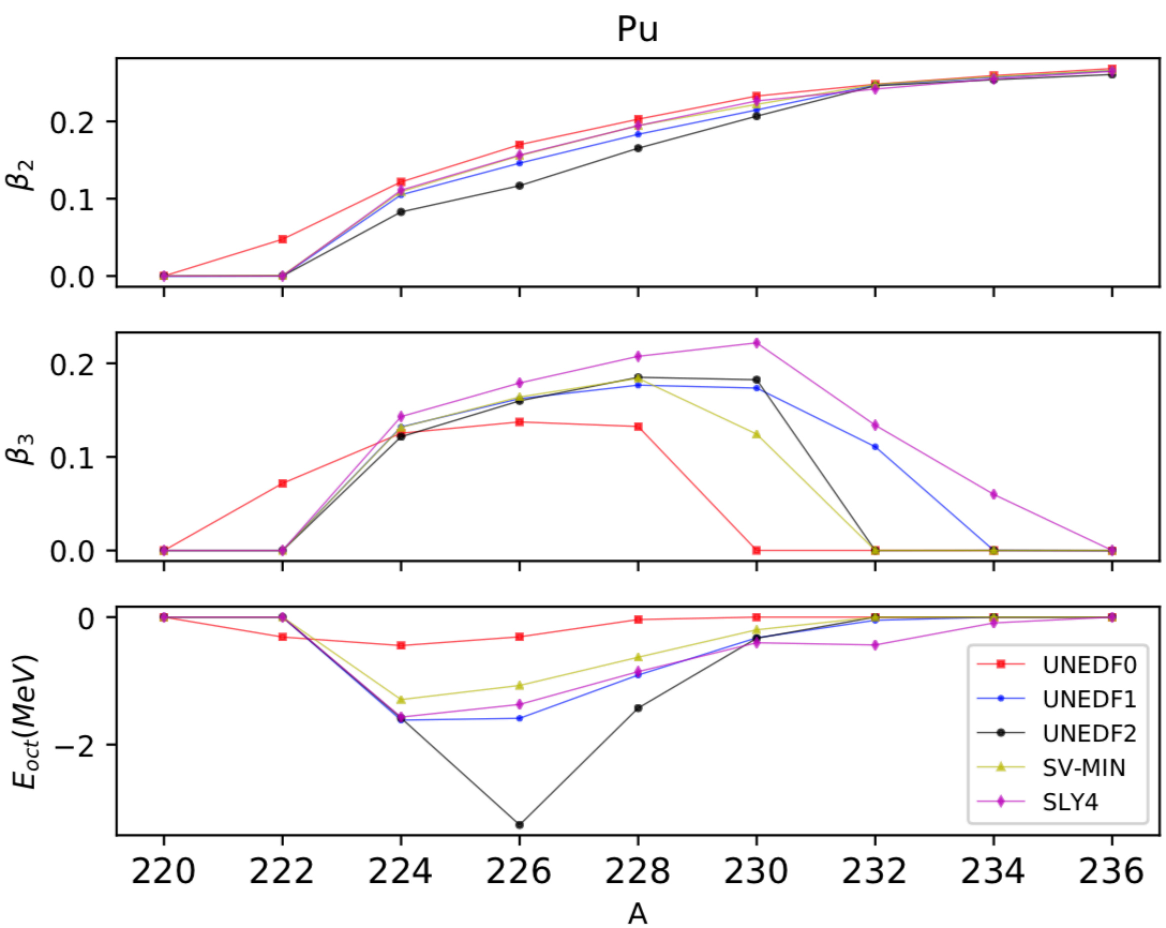
Th (Z=90)

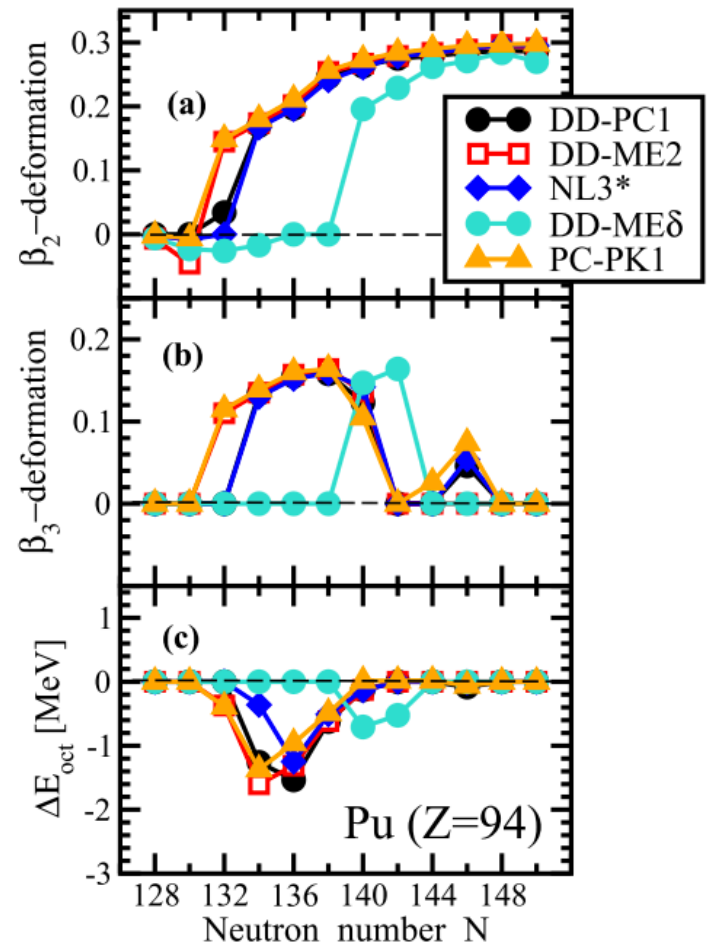




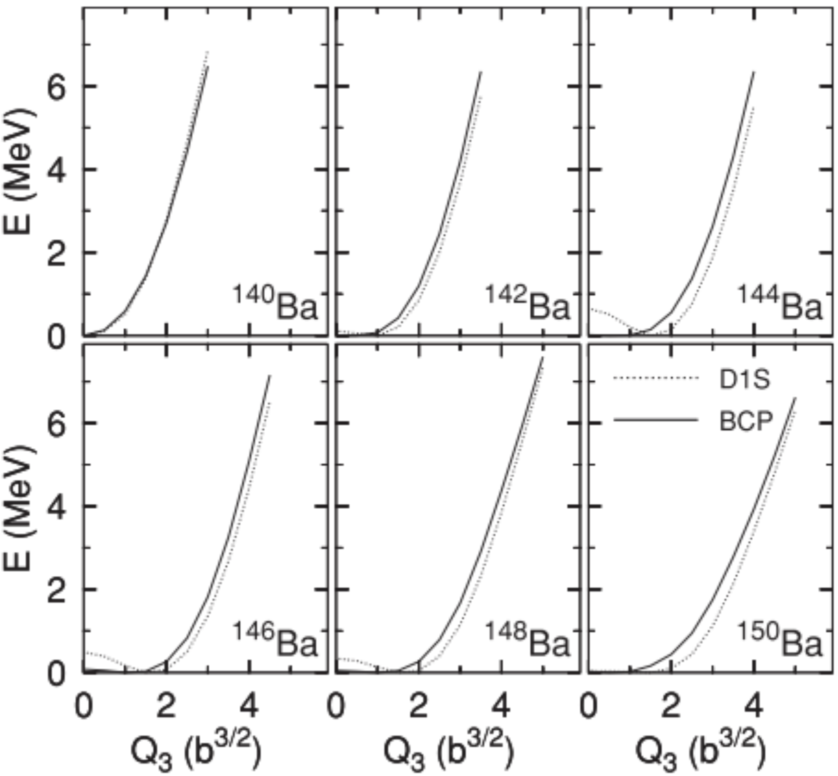
S. Agbemava et al., Phys. Rev. C **93**, 044304 (2016)

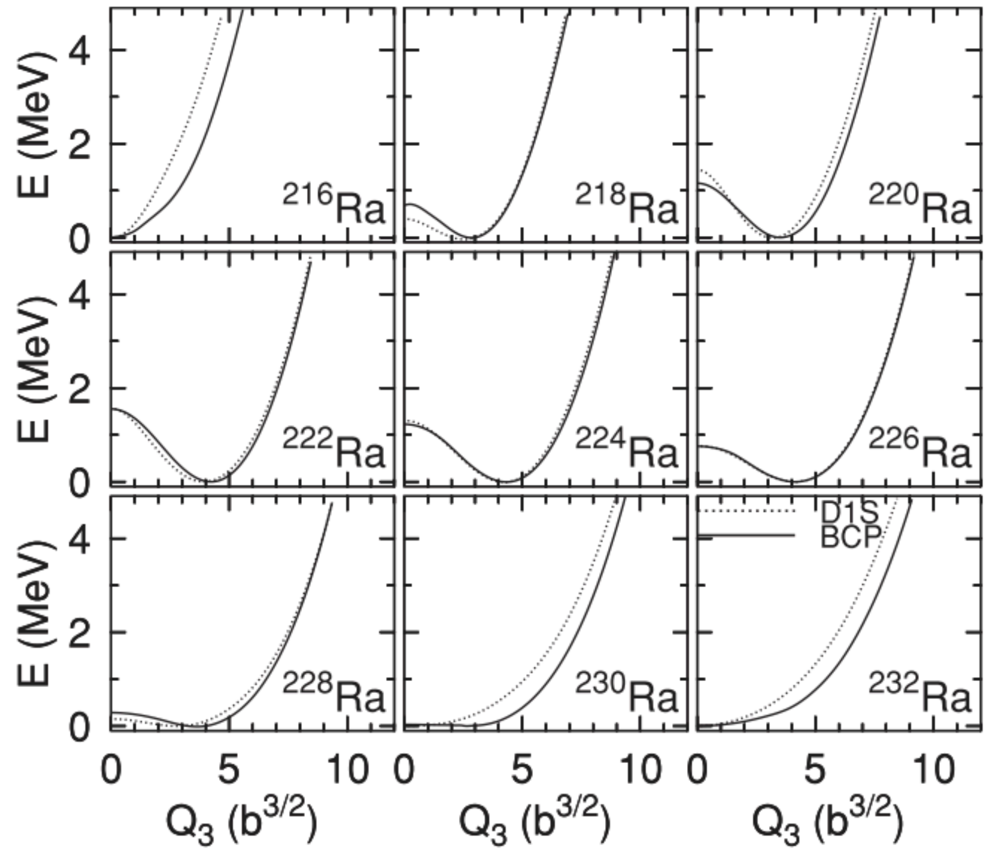
Pu (Z=94)





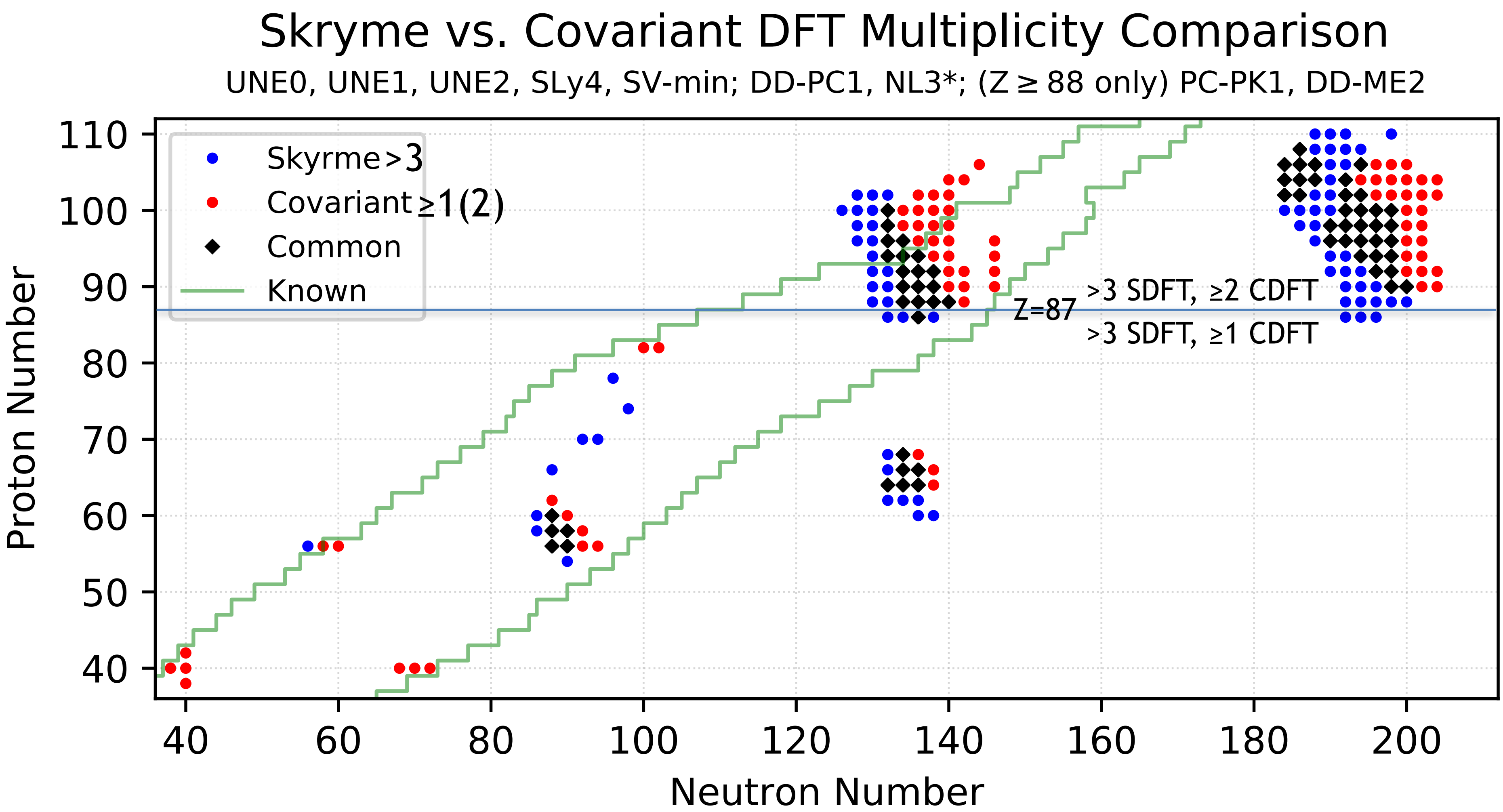
L. M. Robledo et al., J. Phys. G. **39** 105103 (2012)



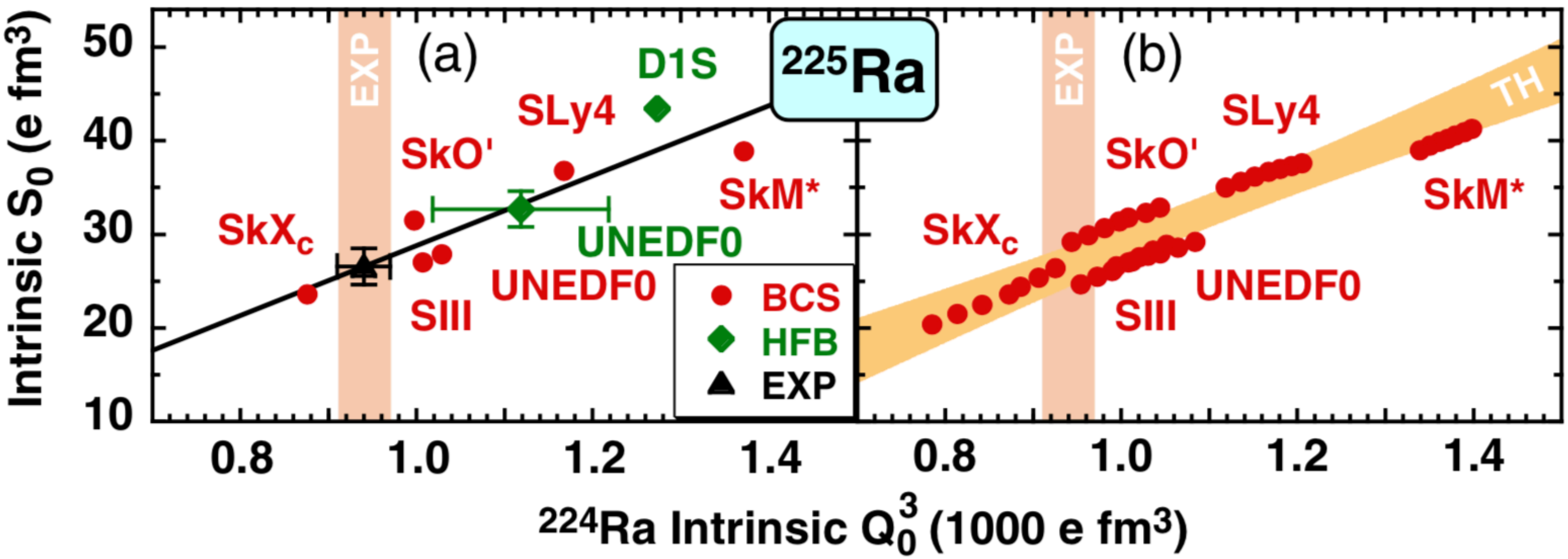


L. M. Robledo et al., J. Phys. G. **39** 105103 (2012)

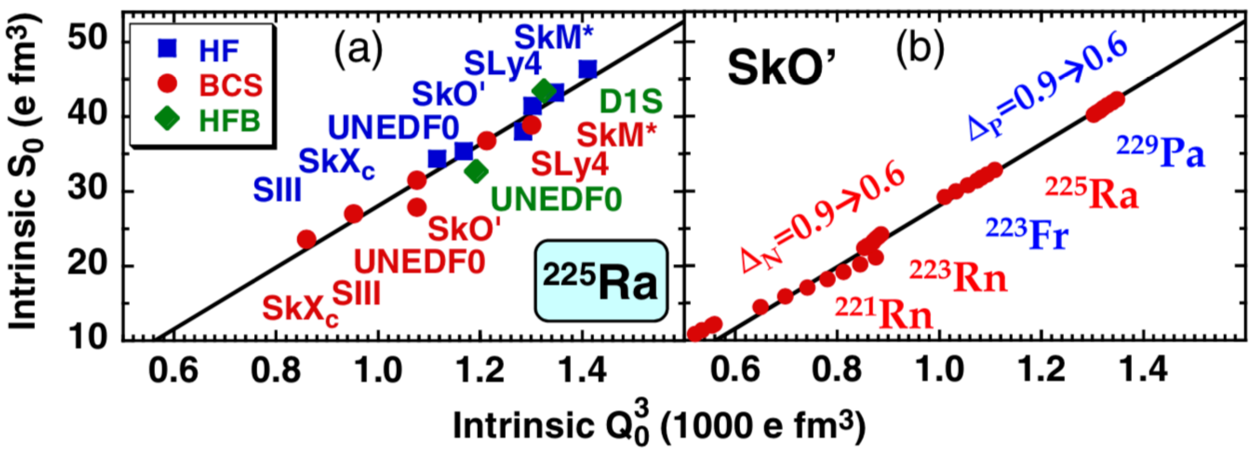
Skyrme vs. CDFT



J. Dobaczewski, J. Engel, M. Kortelainen, P. Becker Phys. Rev. Lett. 121, 232501 (2018)



The result is a dramatically reduced uncertainty in intrinsic Schiff moments. Direct measurements of octupole moments in odd nuclei will reduce the uncertainty even more. The only significant source of nuclear-physics error in the laboratory Schiff moments will then be the intrinsic matrix elements of the time-reversal non-invariant interaction produced by CP-violating fundamental physics.



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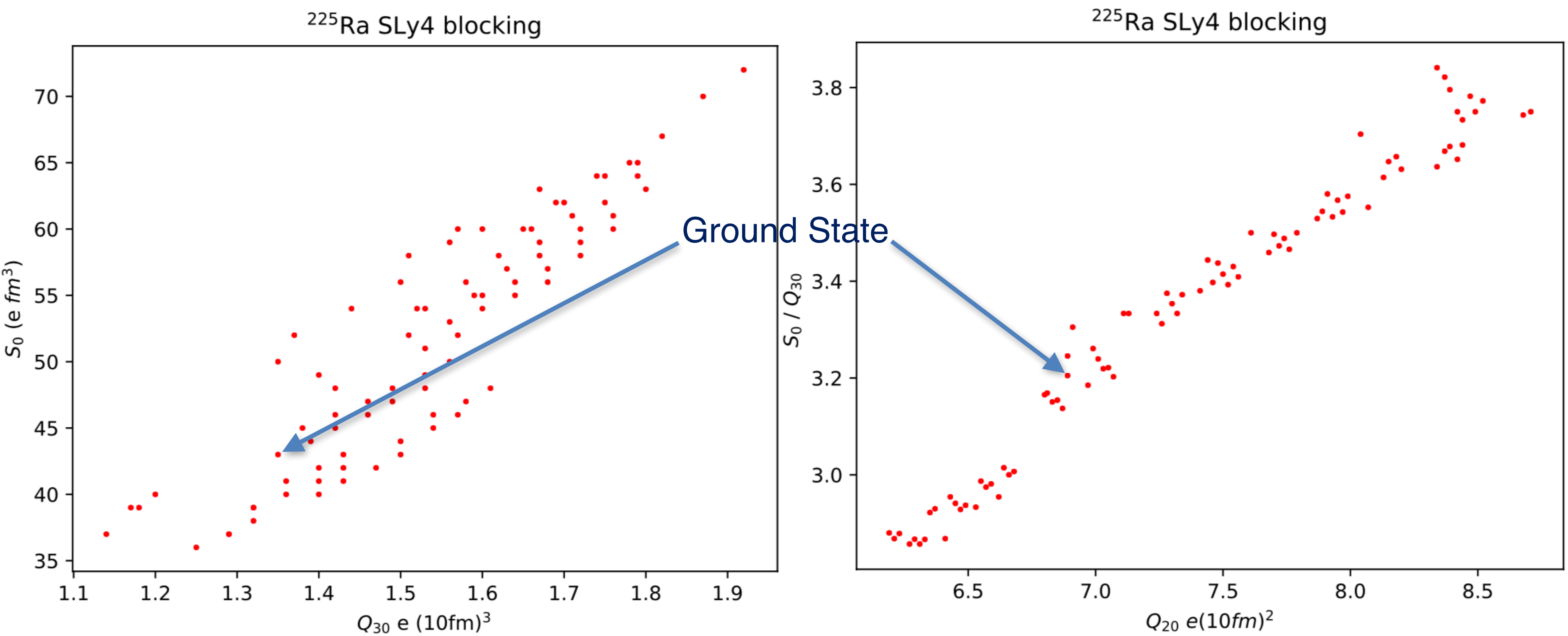

Summary

- Very rich data; need to be fully analyzed.
  - Octupole softness
  - Systematic uncertainties
- The usual suspects remain the best cases
- To be done:
  - Search for best parity doublet candidates in odd-A nuclei
  - Schiff moment calculations

Collaboration:

W. Nazarewicz, E. Olsen, J. Dobaczewski, N. Schunck

S. Agbemava