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On the nature of the shape coexistence phenomenon in the lead region

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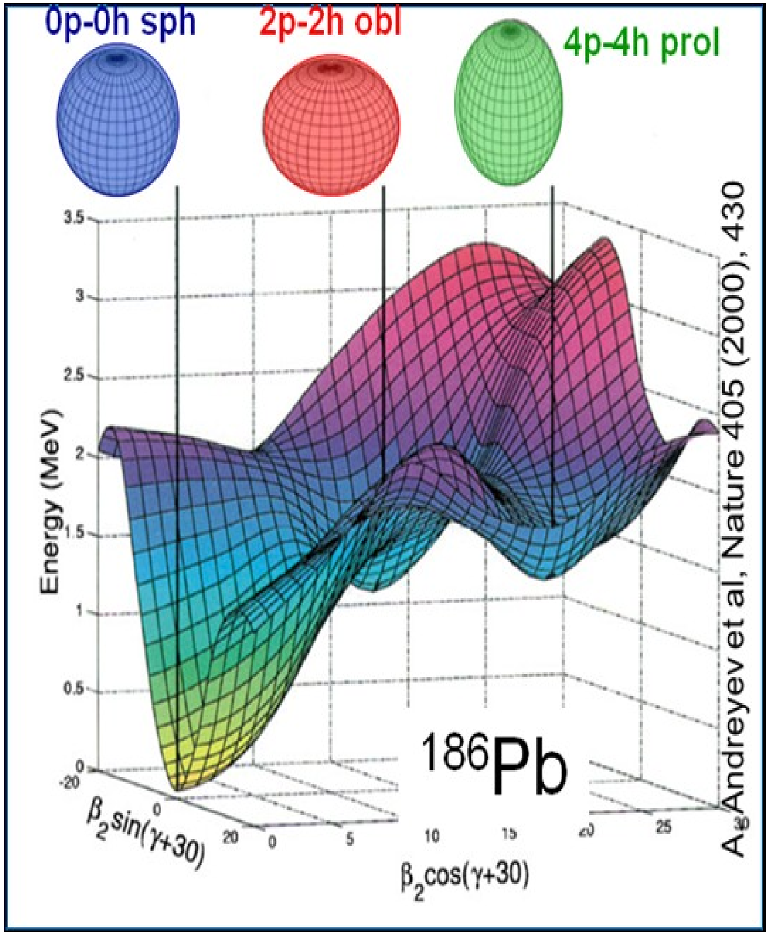
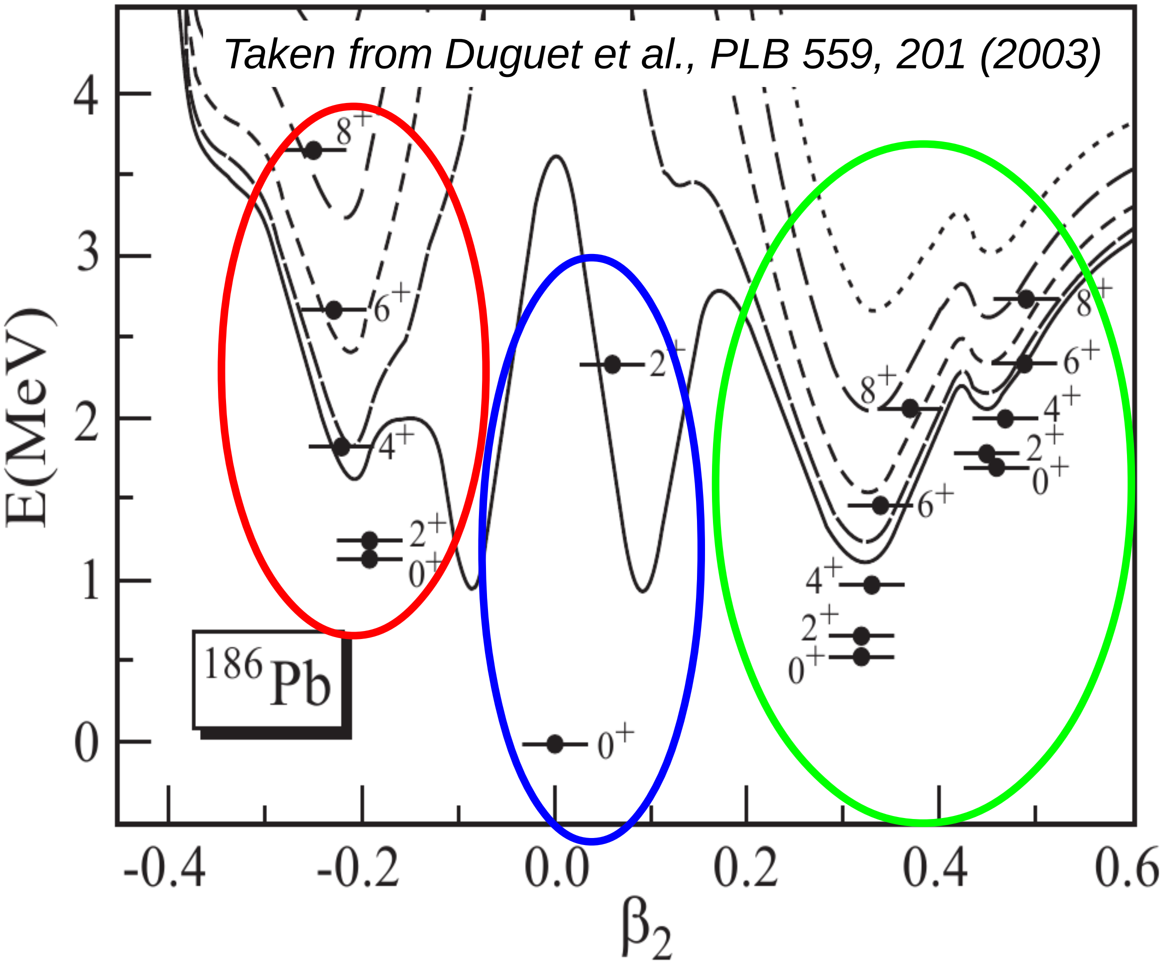
Shape coexistence

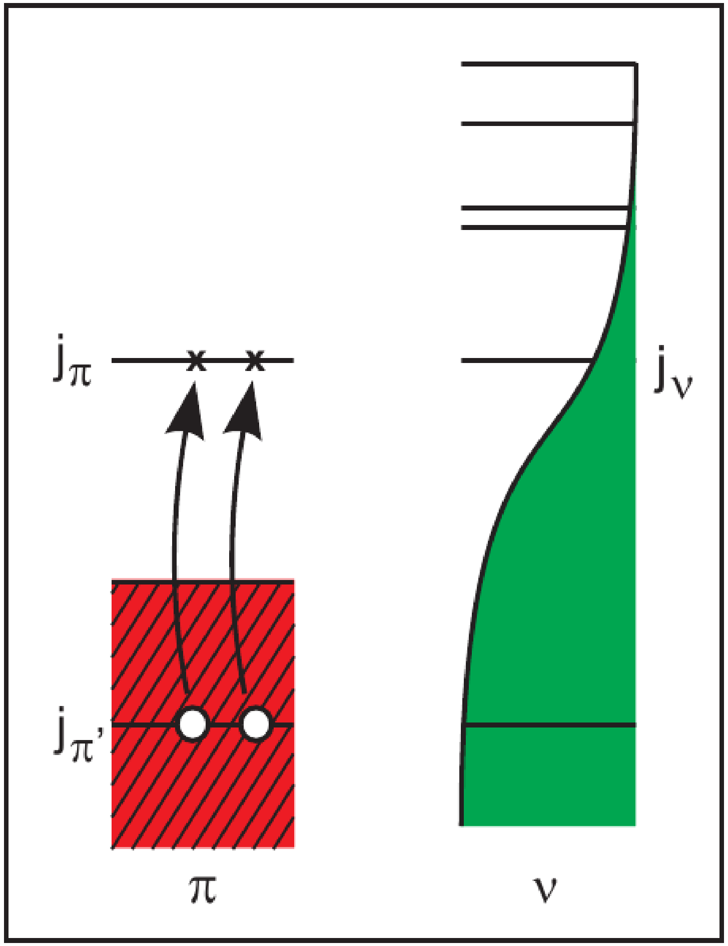
It appears in quantum systems where eigenstates with very different density distribution coexist.

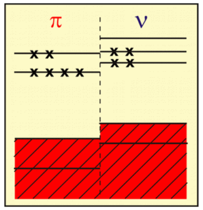


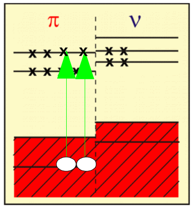


Shell Model/Interacting Boson Model

- For nuclei near to closed shells, either for neutrons or for protons, it can be energetically favorable to have excitations of 2p-2h, 4p-4h … crossing the energy gap.
- The np-nh excitations have a lower excitation energy than expected due to the correlation energy: pairing and deformed correlations.
- Restricted to light and medium-heavy nuclei, at present.



$\phi(J,M) = a(J,M)$ 

$+ \; b(J,M)$ 

In heavy nuclei the huge model space imposes some kind of truncation: symmetry dictated truncation.

What is a Quantum Phase Transition (QPT)?

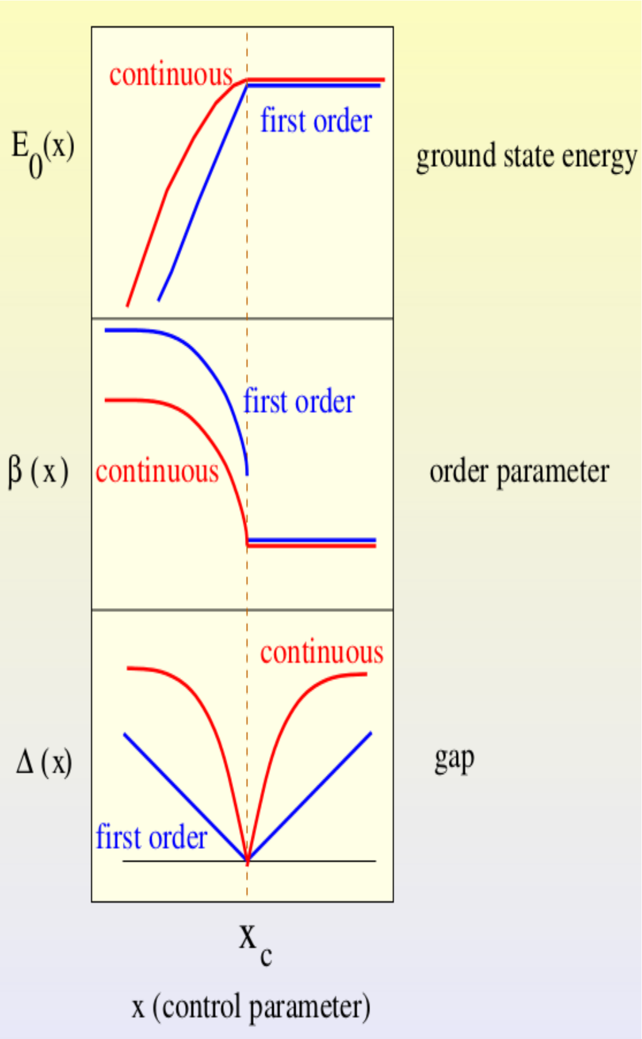
QPT occurs at some critical value, x_c, of the control parameter *x* that controls an interaction strength in the system's Hamiltonian *H(x)*. It is implicit zero temperature.

$$H = x H_1 + (1-x) H_2$$

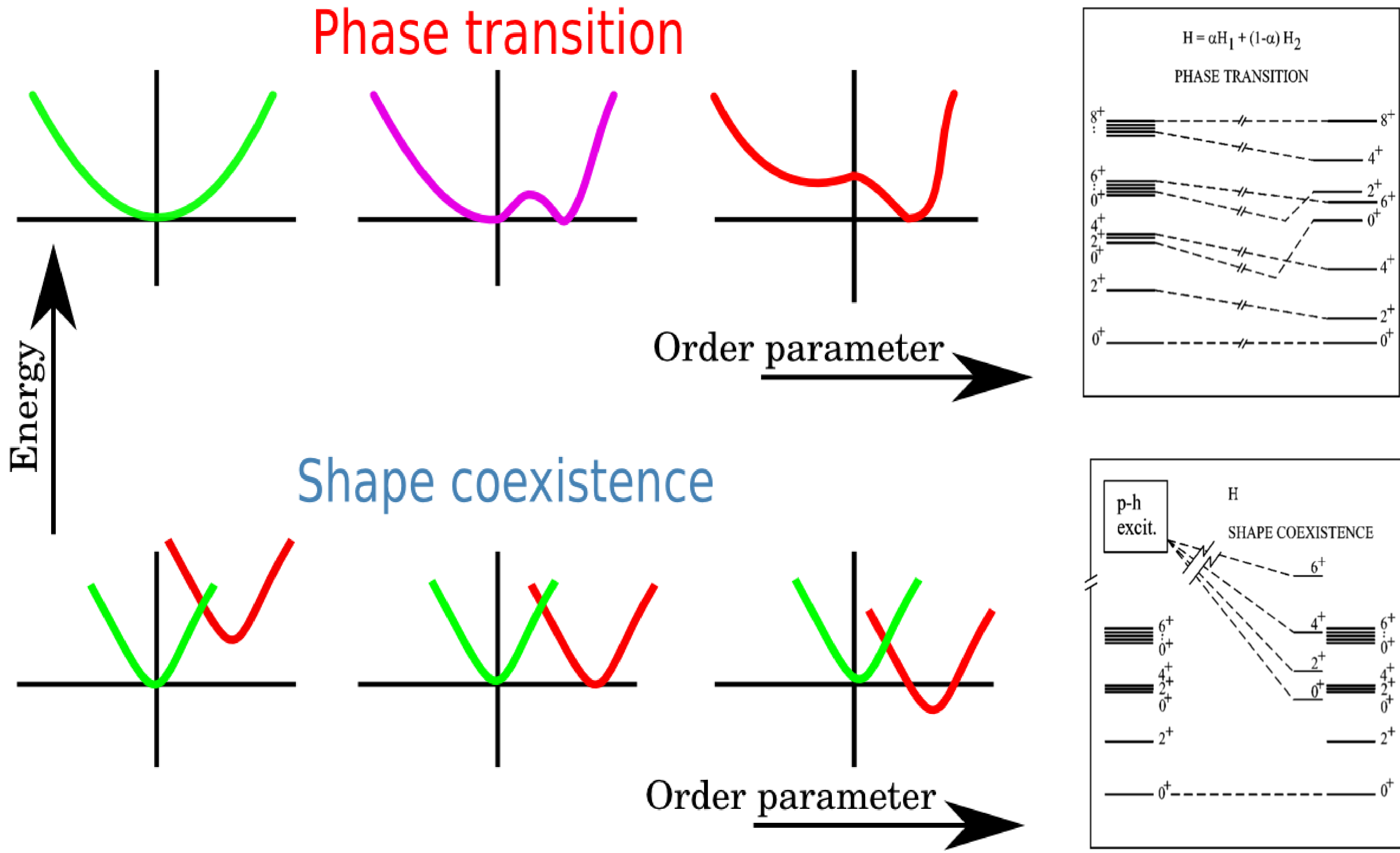
The value of the *order parameter (deformation)* suddenly changes when crossing the critical point.

At the critical point:

•The ground state energy is nonanalitic.
•The energy gap between the first excited state and the ground state vanishes.

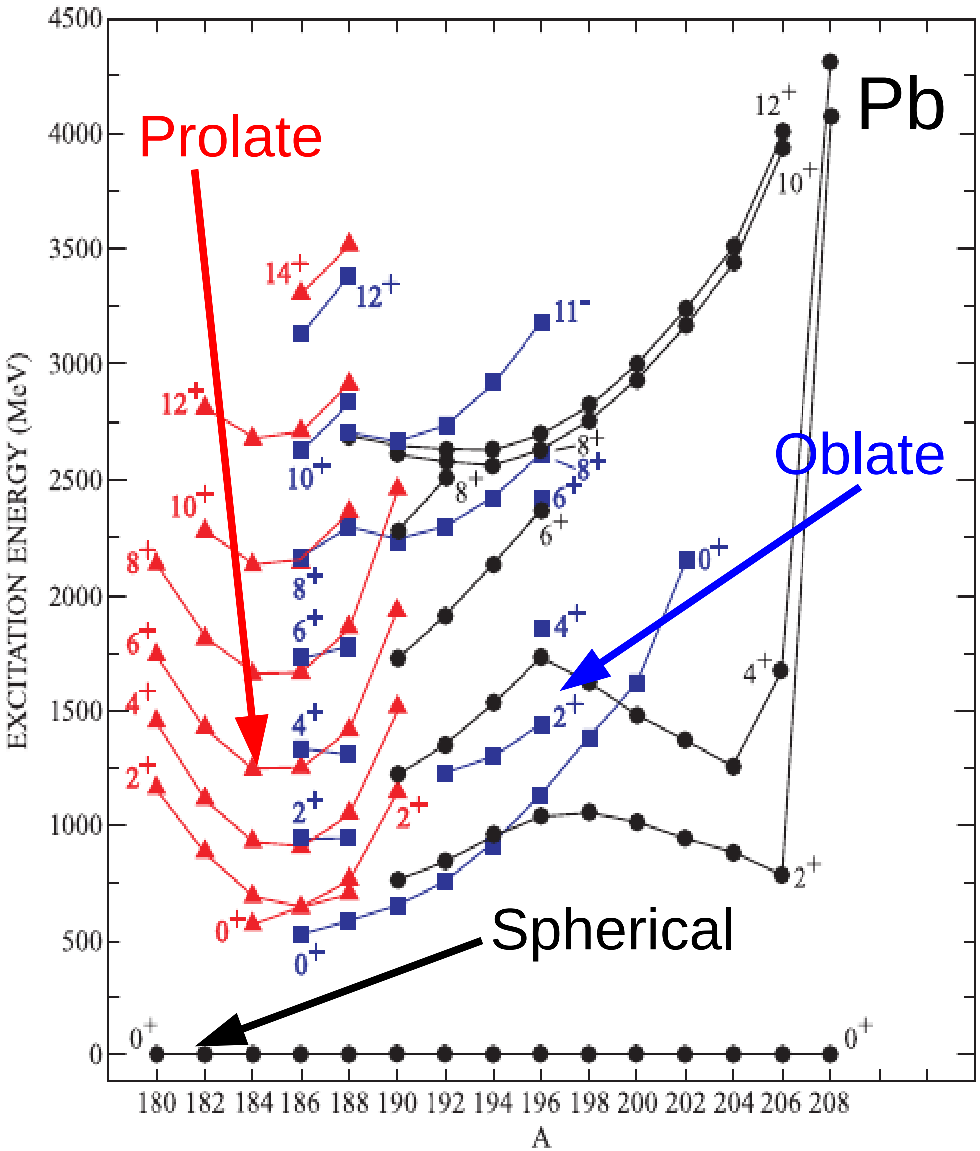


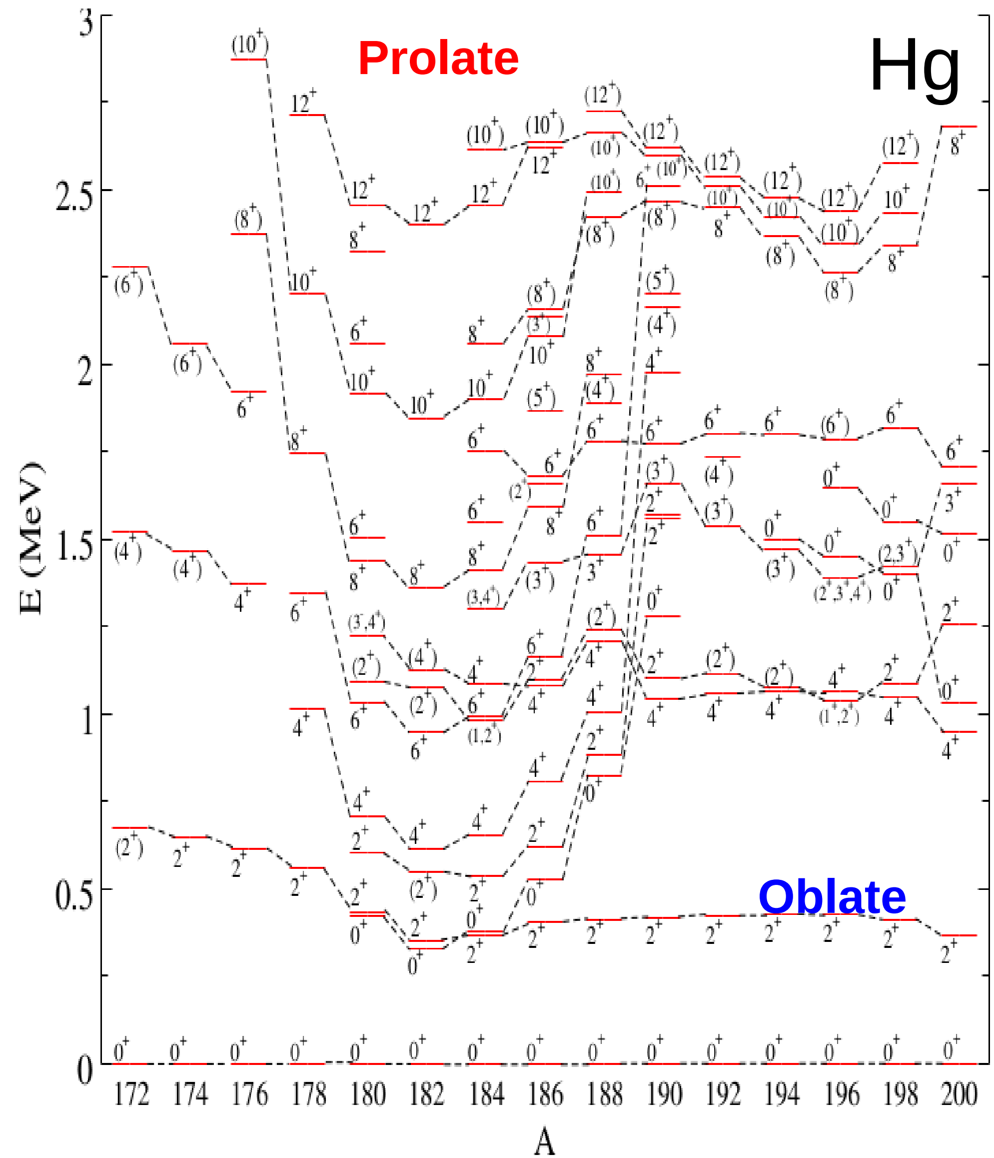
A schematic comparison



PRC 69, 054304 (2004)

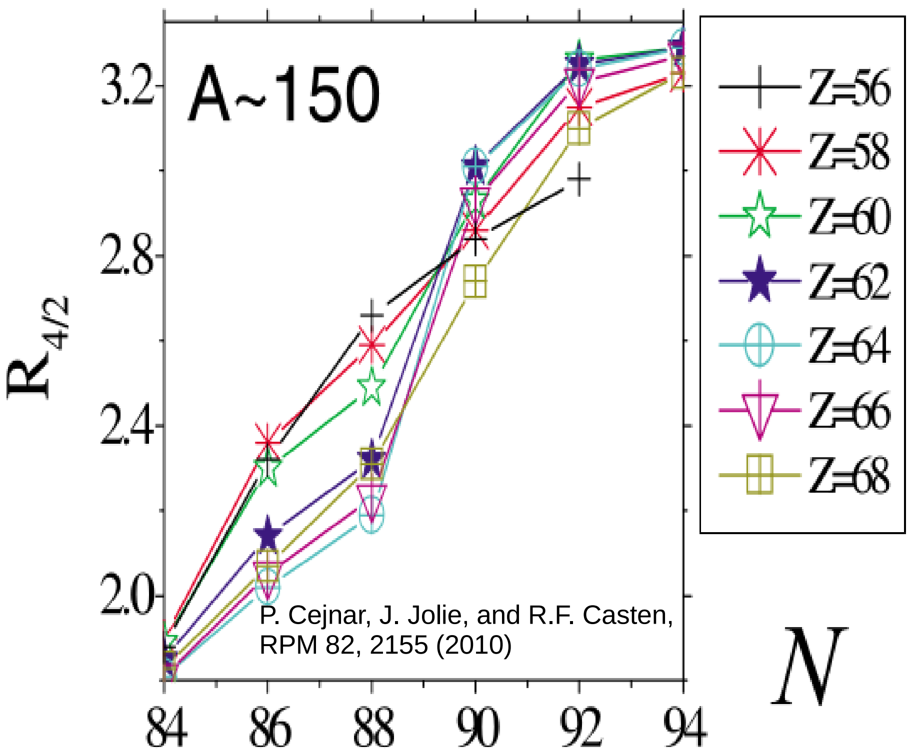
Shape coexistence key indicators

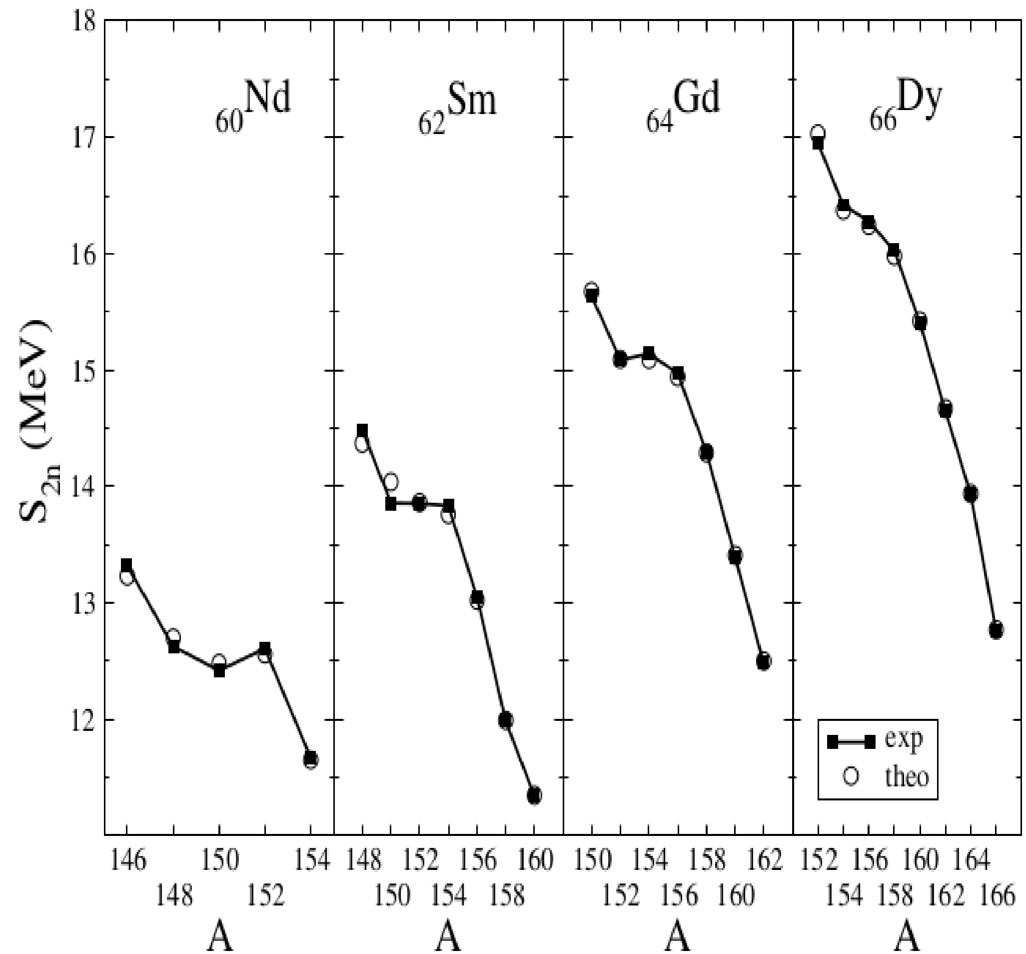




JEGR and K. Heyde, PRC 89, 014306 (2014)

QPT key indicators



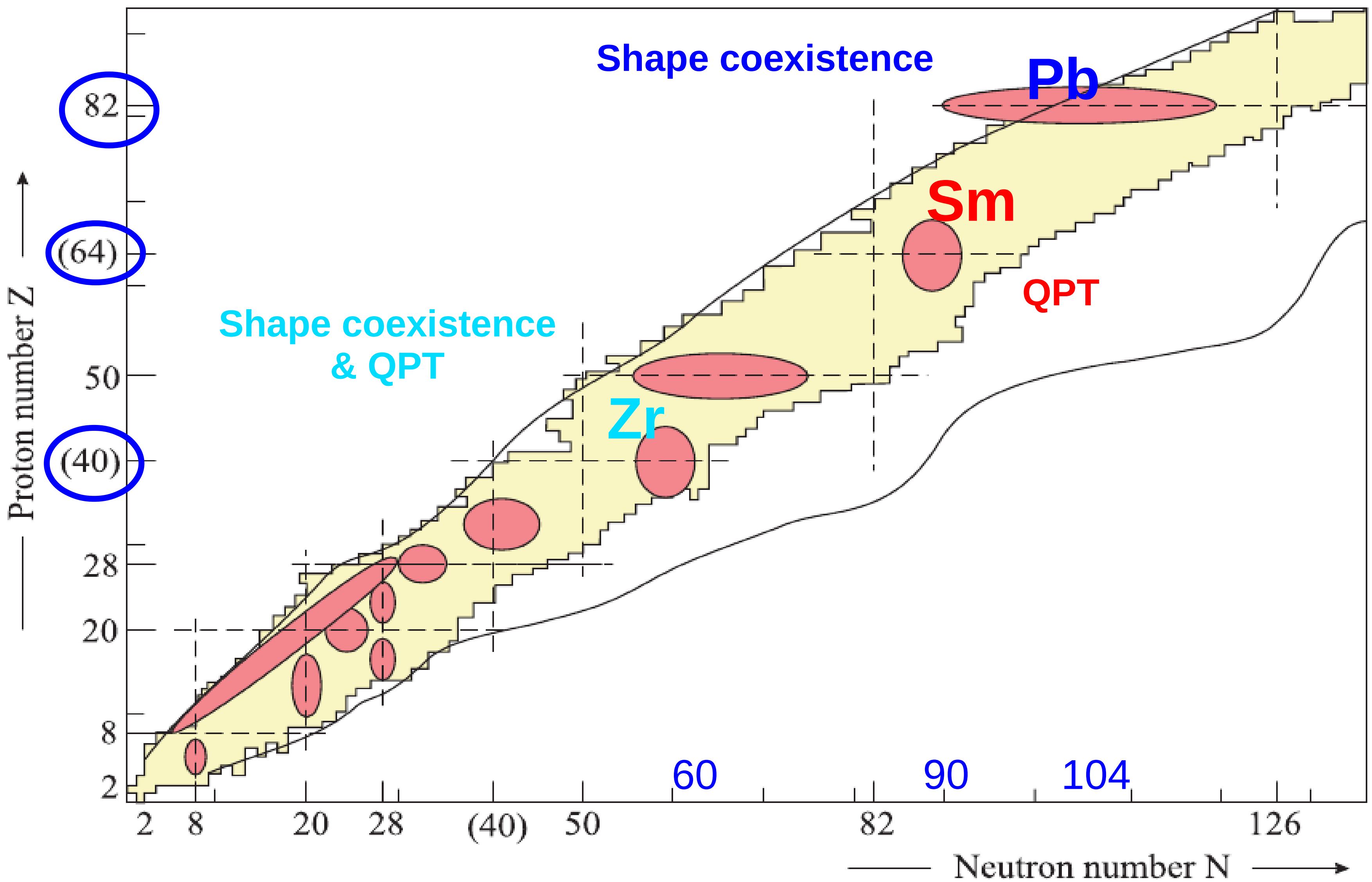


E(4+)/E(2+) can be used as an order parameter and, therefore is a key observable to find where a QPT develops.

Some open questions

- In both cases there is a rapid change in the deformation of certain states.
- Are both approaches compatible in an unified way?
- Can a Quantum Phase Transition be described in terms of the onset of intruder configurations?
- Is shape coexistence always present “before” a Quantum Phase Transition sets in?

Regions of reference



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

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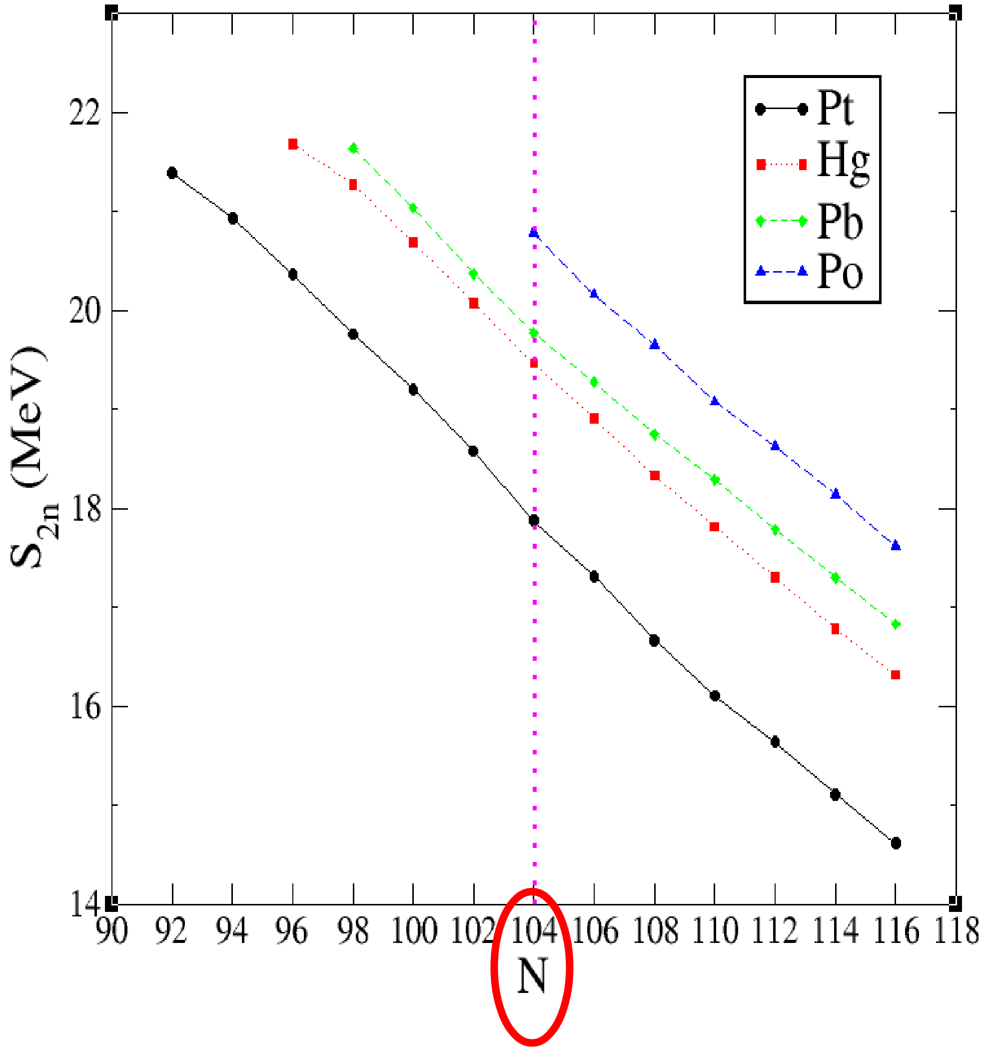
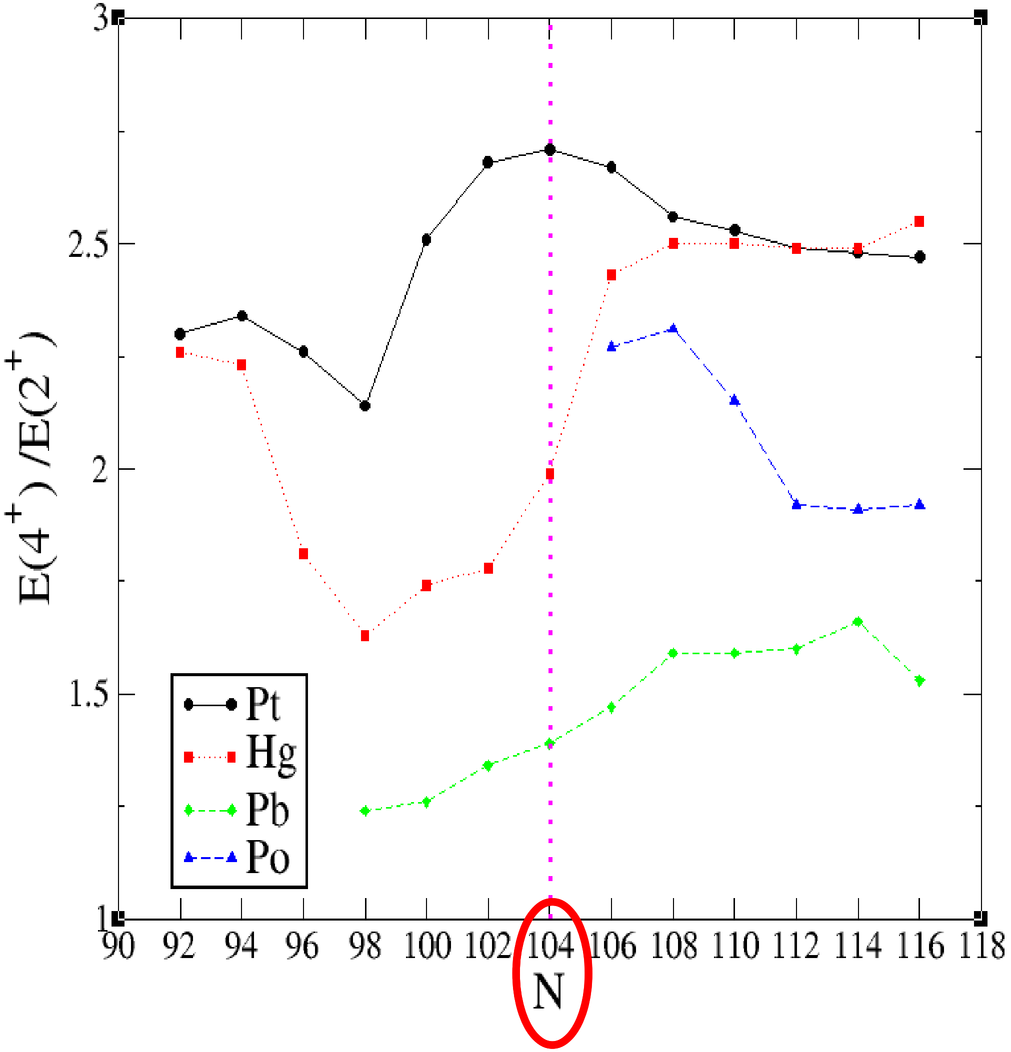
Pb region

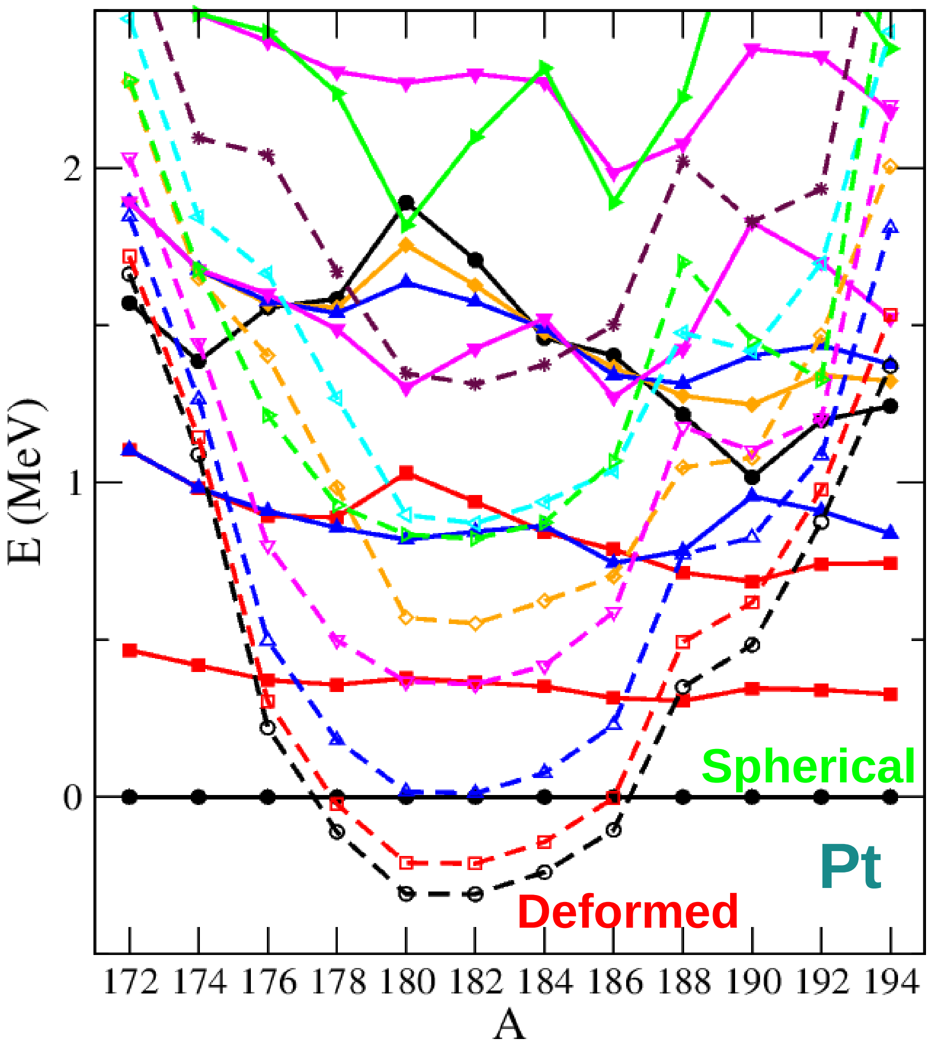




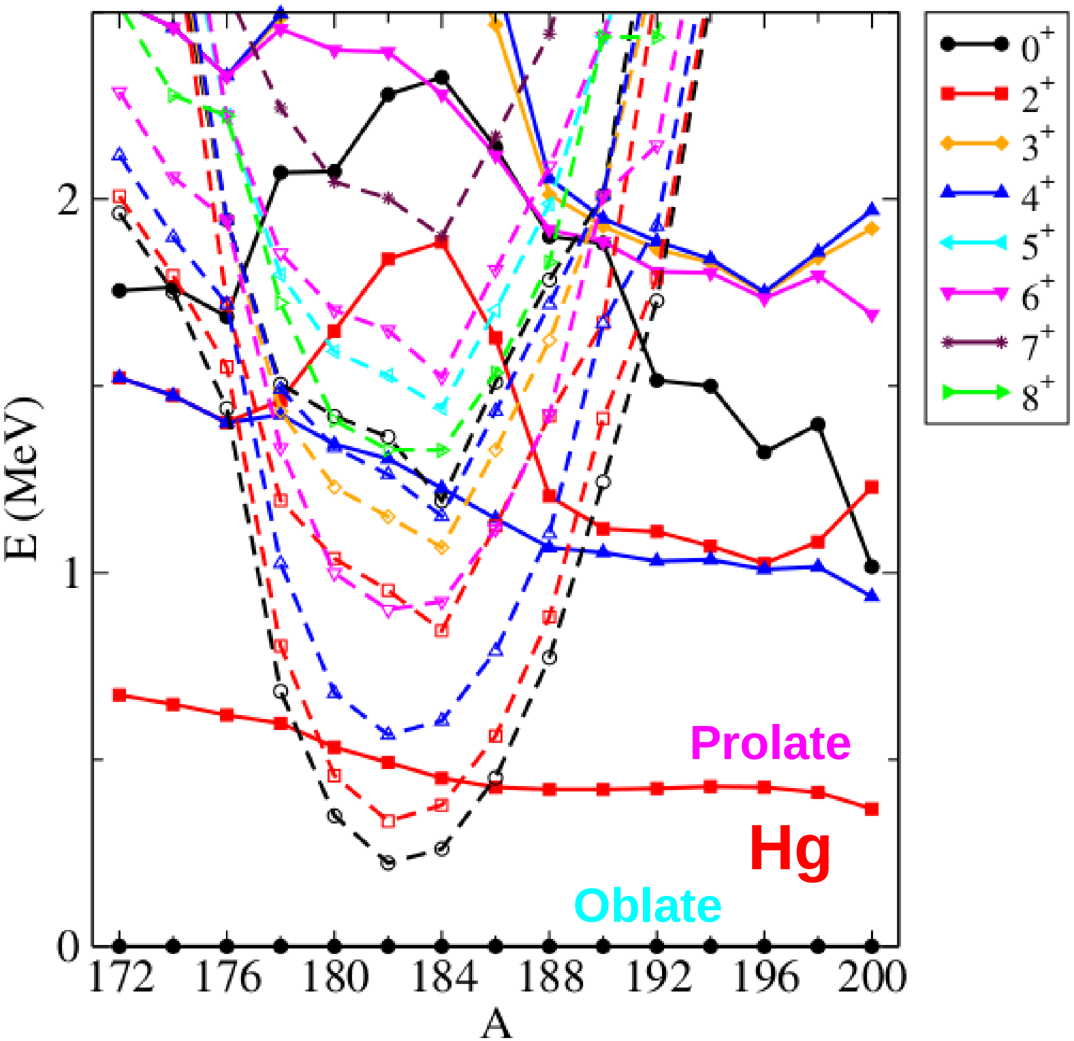
Unperturbed energies (IBM-CM)

Change in the ground state structure

No change in the ground state structure



JEGR and K. Heyde, NPA 825, 39 (2009)



JEGR and K. Heyde, PRC 89, 014306 (2014)

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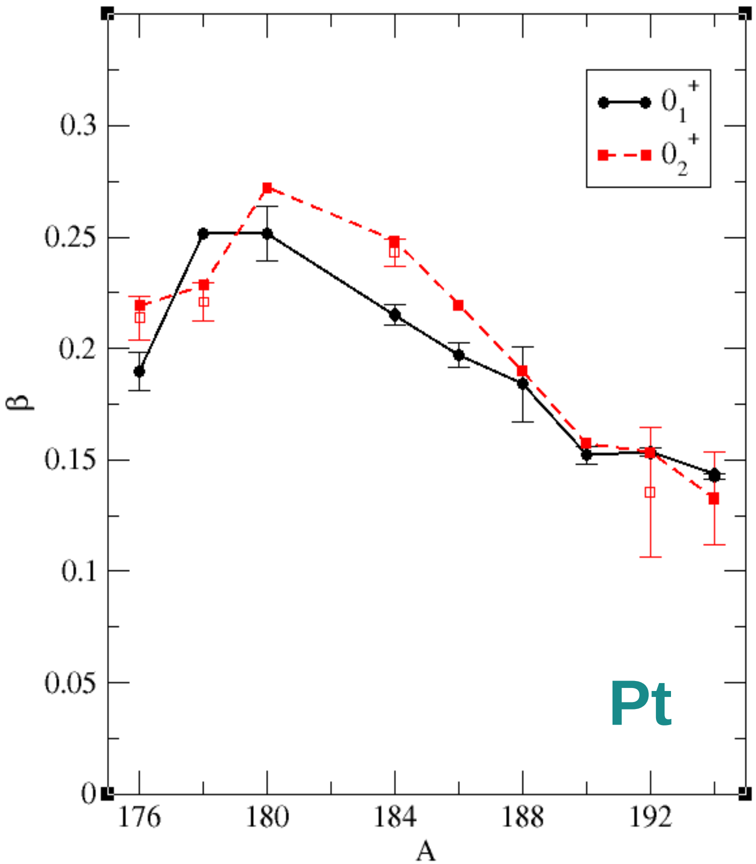
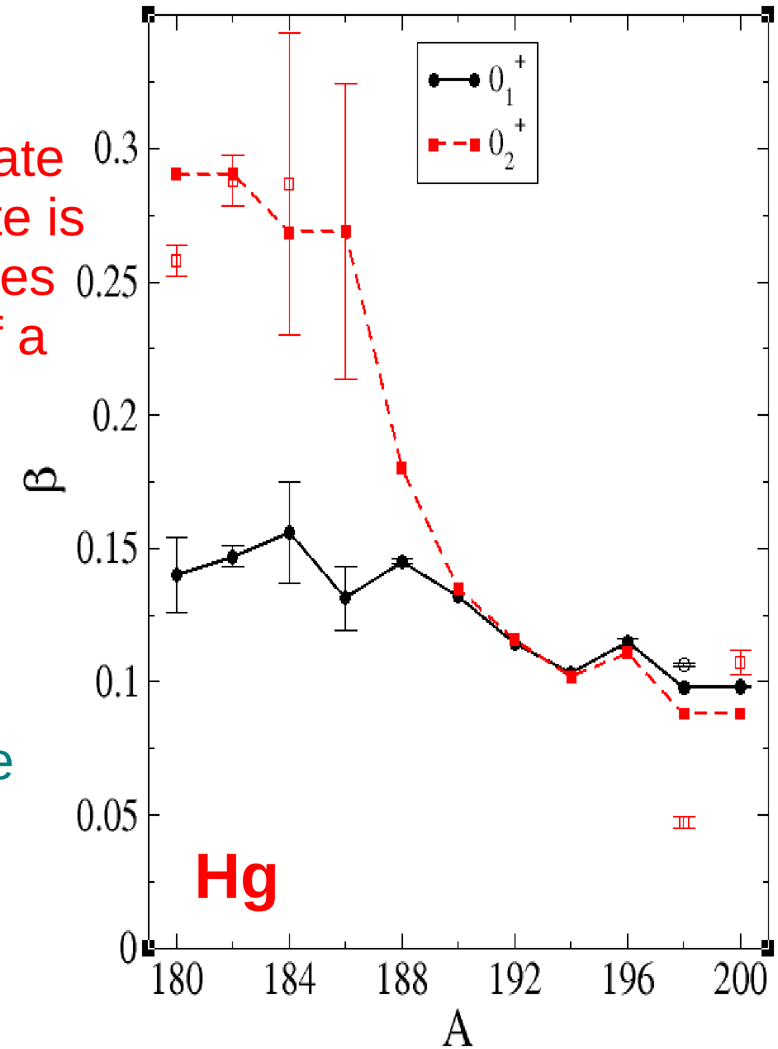
What a about the relation between QPT and shape coexistence in Pb region

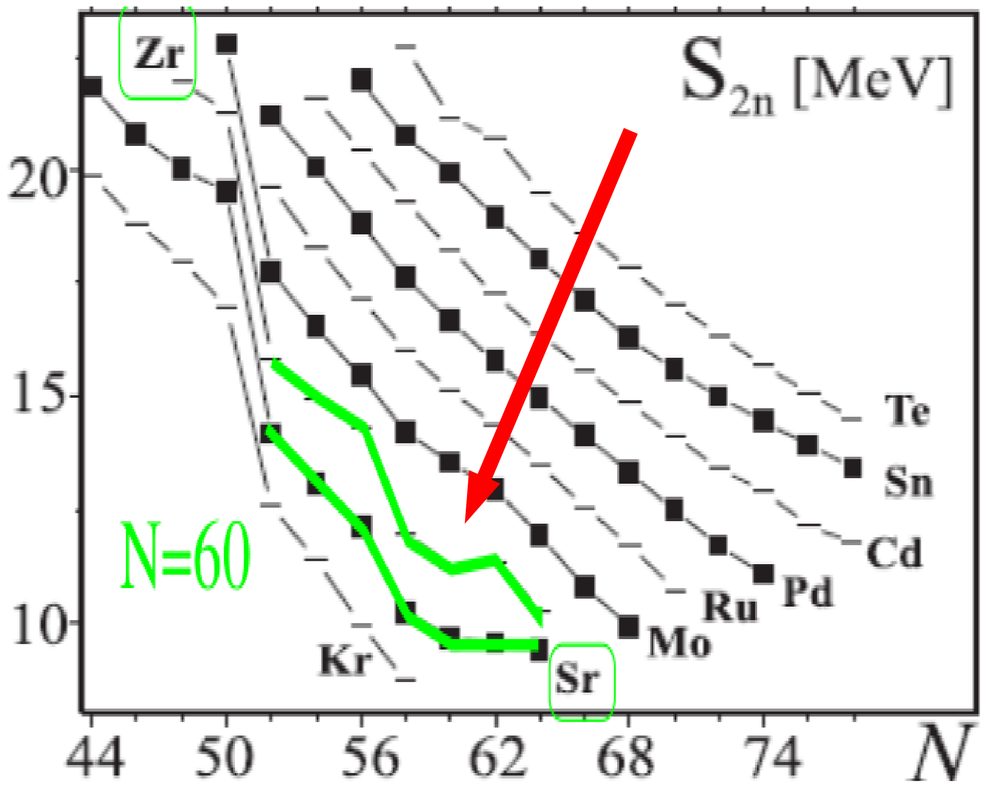


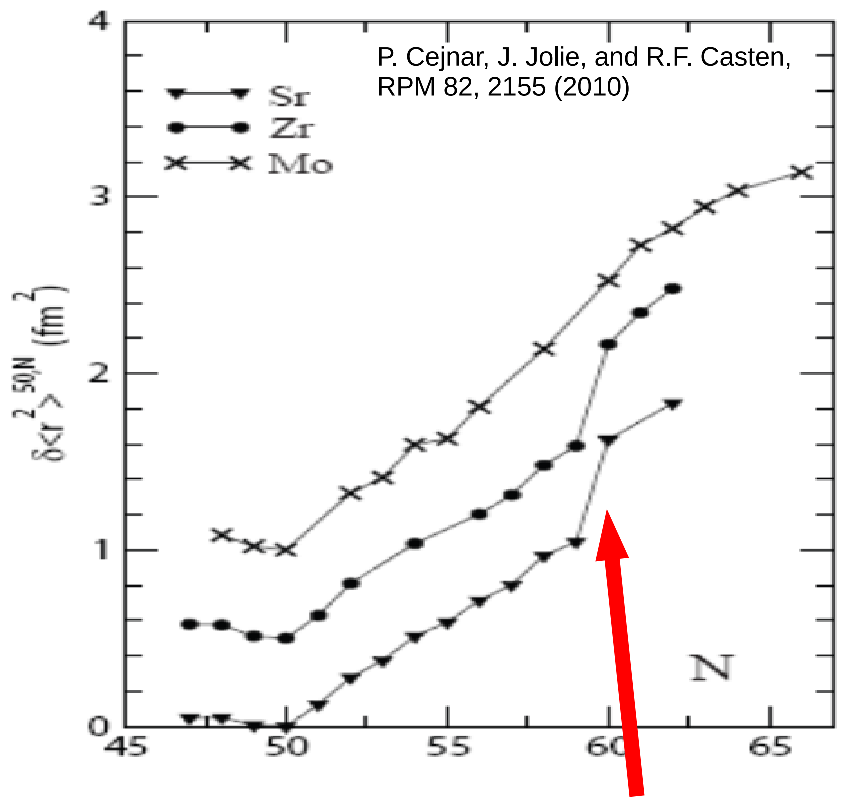
Hg:The ground state never changes its character and the influence of the closest intruder state on the ground state is small: this precludes the appearance of a QPT.



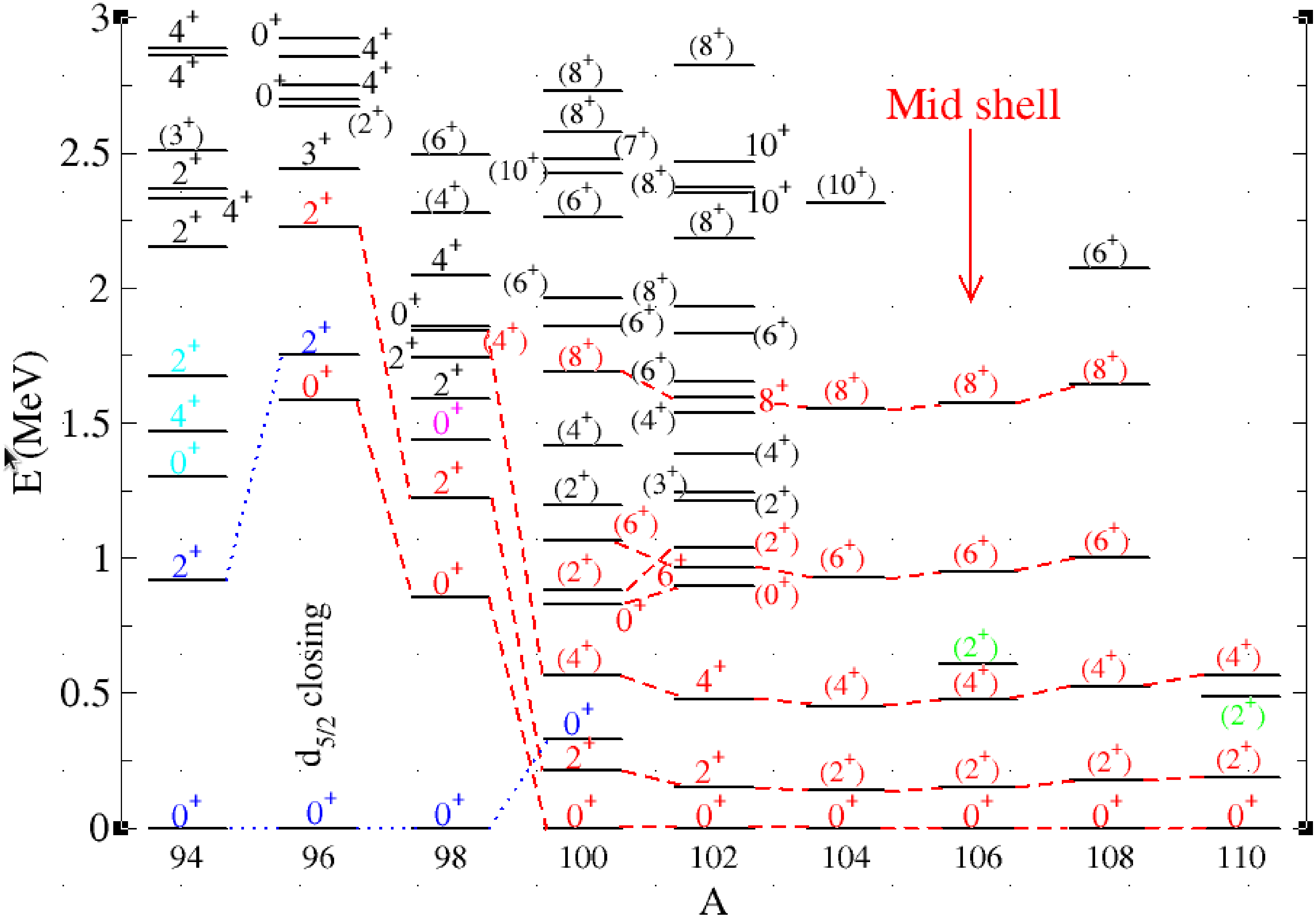
Pt: An intruder becomes ground state and therefore deformation should suddenly changes, however, a large mixing between intruder and regular configurations smooth out the effects of any QPT.

Z=40 subshell closure, A=100





Energy systematics



Shape coexistence

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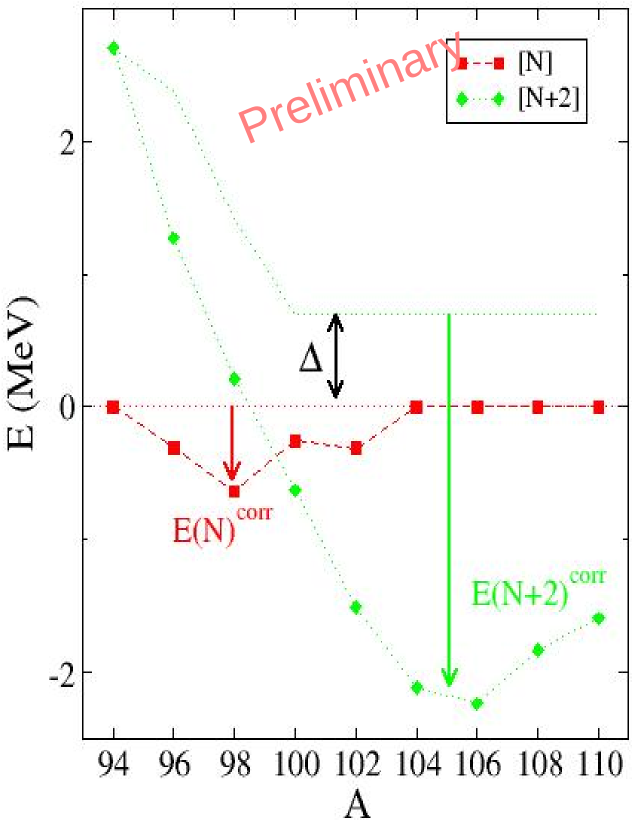
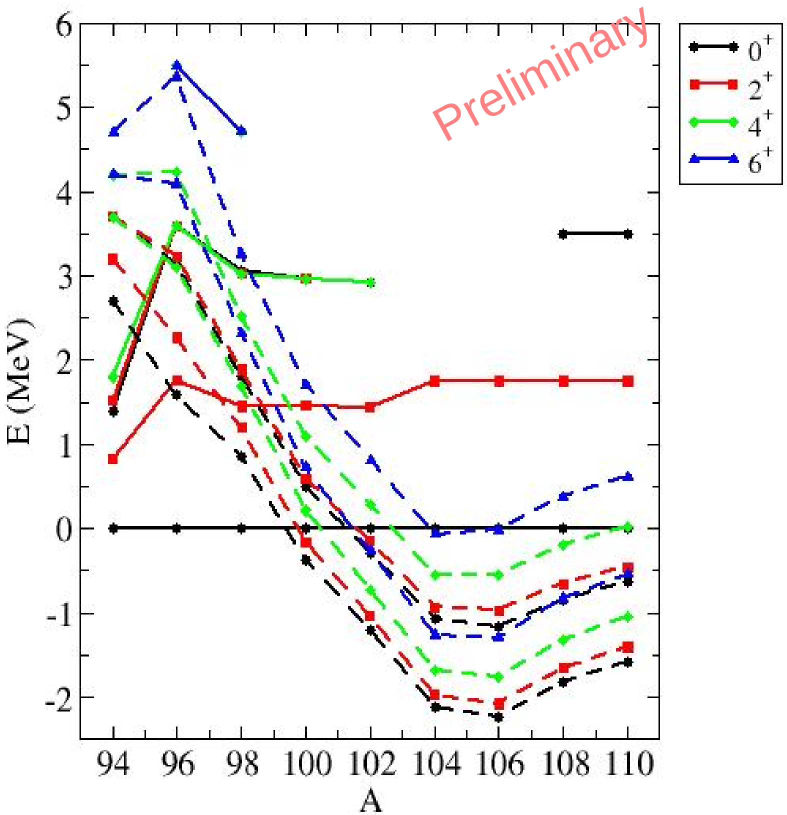
IBM with configuration mixing calculation with two types of configurations (no interaction between the regular and the intruder configuration)





This phenomenon can also be explained in terms of type II shell evolution in *Togashi et al PRL 117, 172502 (2016)*, or in terms of the effect of paring and proton-neutron residual interaction, as in *Heyde et al NPA 466, 189 (1987).*

E0 transitions point towards a large mixing between regular and intruder states around ^{100}Zr, $\rho^2(E0)=108(19)\ 10^{-3}$.

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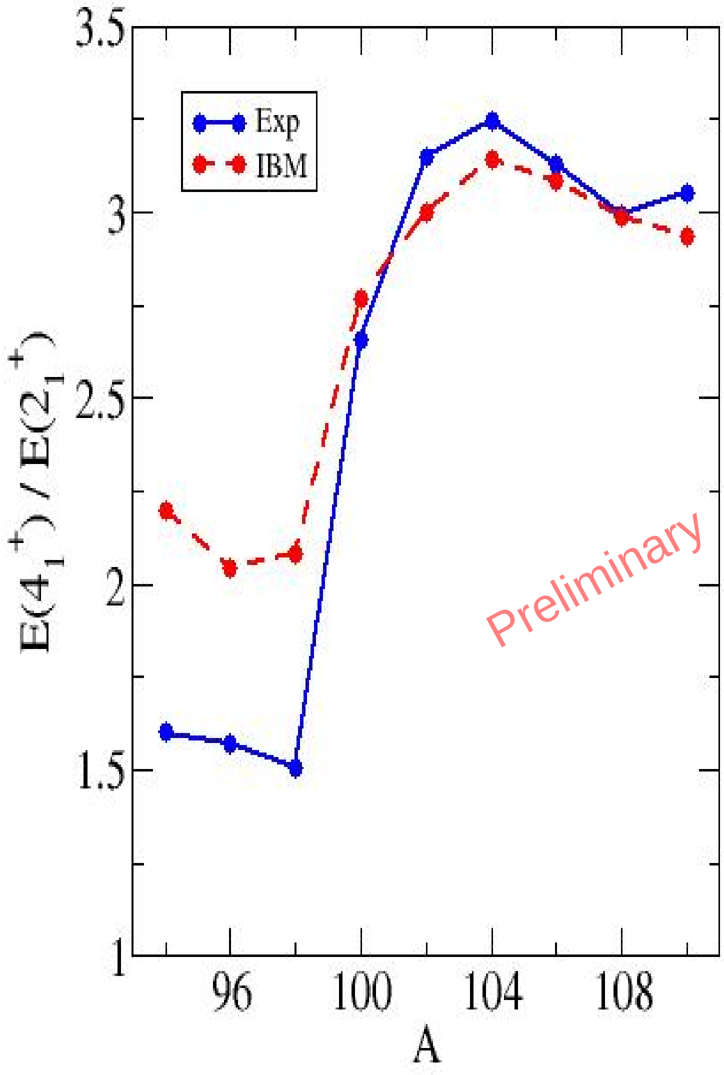
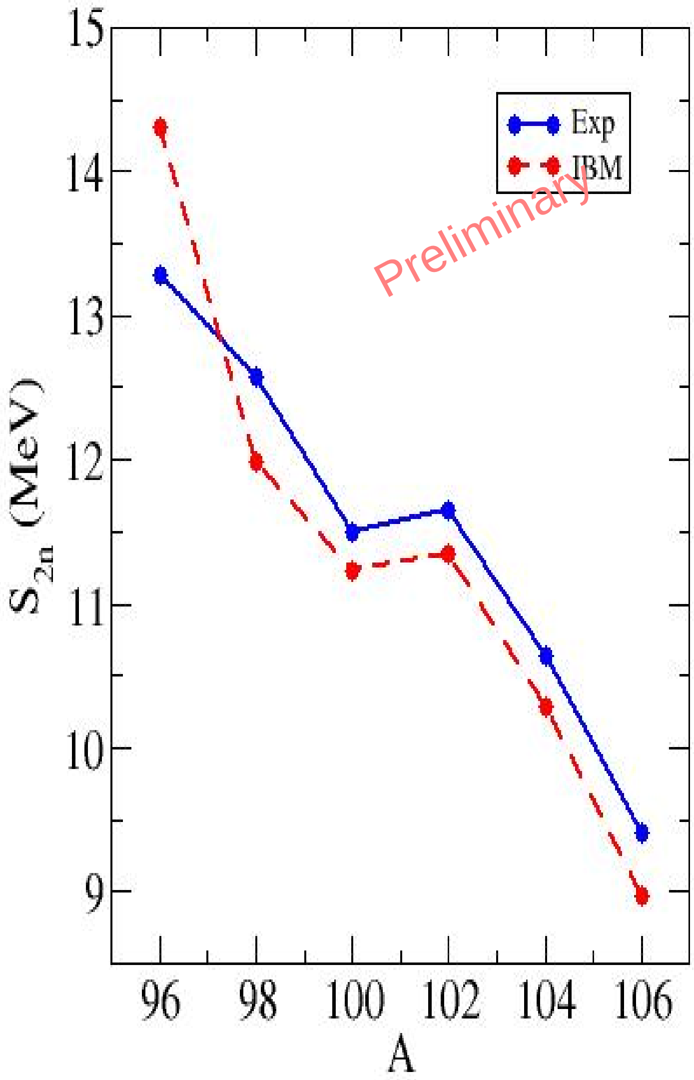
Quantum Phase Transition





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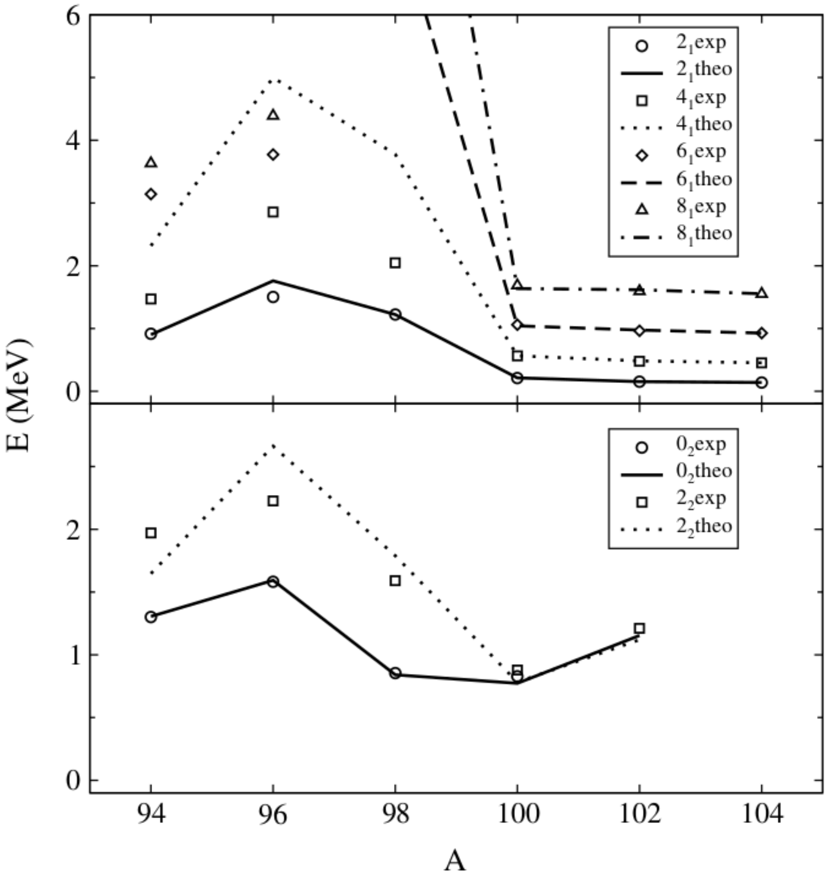
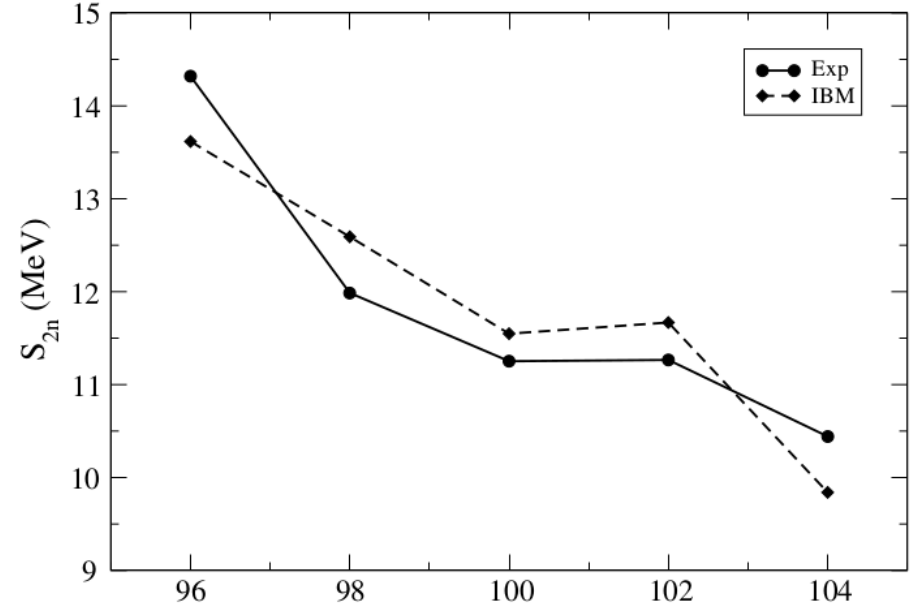
... however ...



JEGR et al EPJ A 26, 221 (2005)



$$\hat{H} = \varepsilon_d \hat{n}_d - \kappa \hat{Q} \cdot \hat{Q} + \kappa' \hat{L} \cdot \hat{L},$$

$$H = x\,H_1 + (1 - x)\,H_2$$

a single configuration can also describe, though in an effective way, what happens in Zr, without the need of shape coexistence.

Summary and conclusions

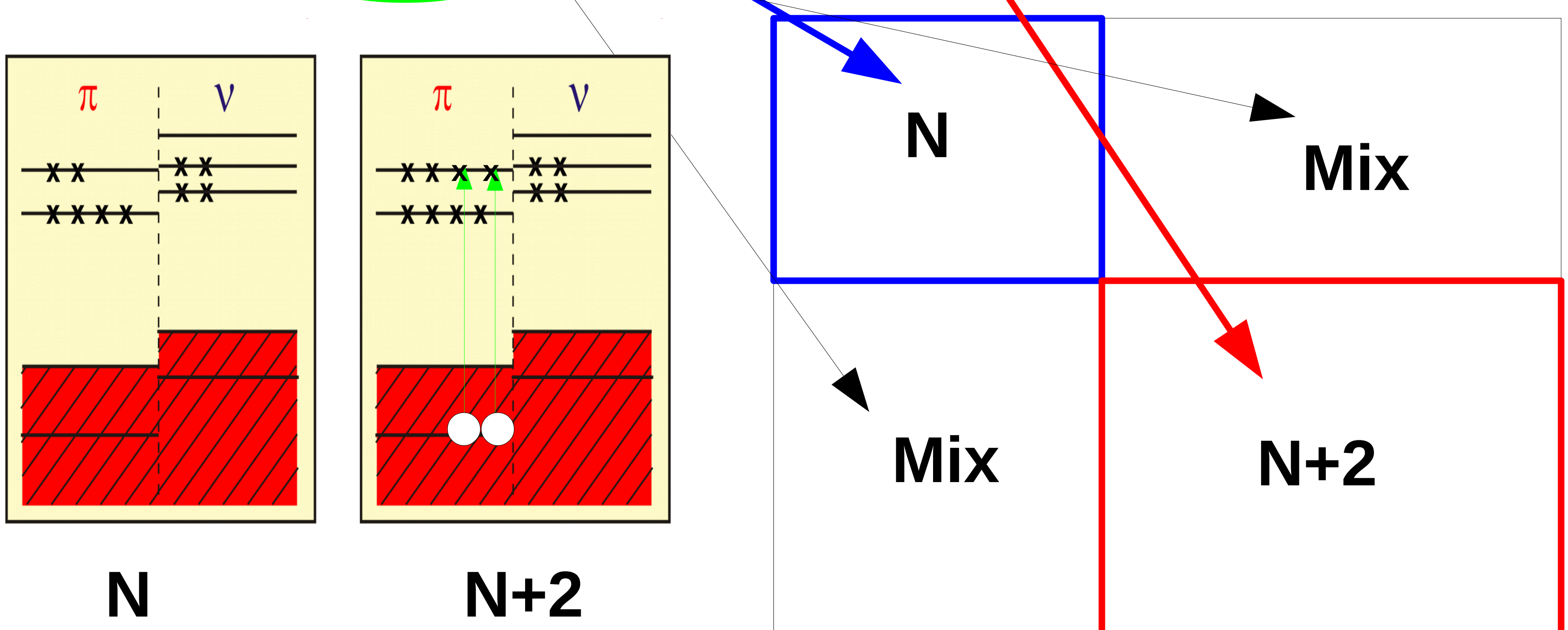
- We have tried to establish a link between two seemingly (un)related phenomena: Shape Coexistence and Quantum Phase Transition.
- In Pt-Pb-Hg two (or even three) configurations coexist, one slightly deformed (or spherical) and of gamma unstable character, corresponding to the regular states and a more deformed one of oblate (prolate) character corresponding to the intruder ones. **No indication of QPTs are observed.**
- In Zr two (or even three) configurations coexist, one of spherical character while the other(s) deformed. **QPT is observed.**
- The crossing of configurations can induce a QPT but the strong interaction between configuration precludes it, in Pt, but not in Zr.

Thank you

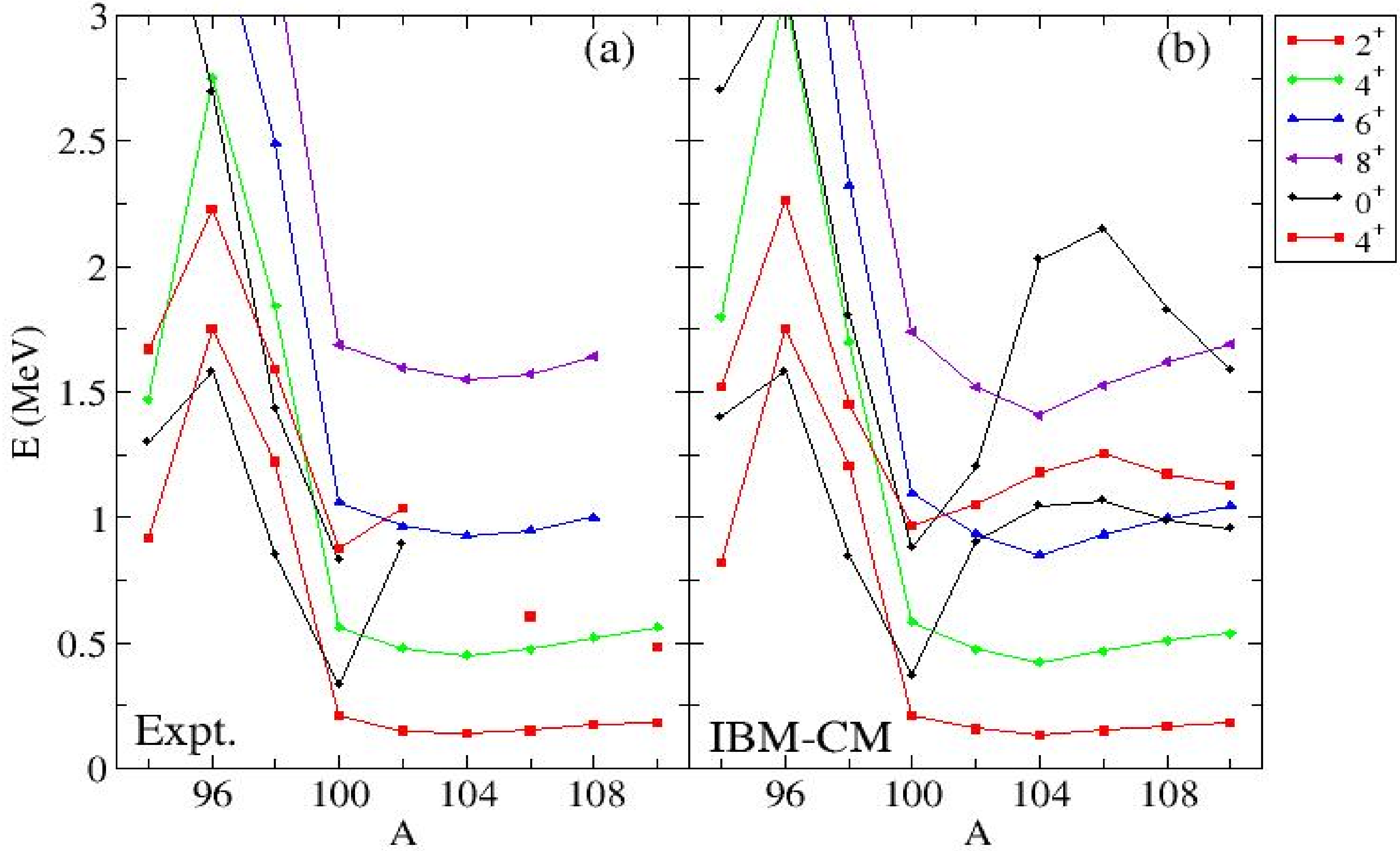
Interacting Boson Model

(configuration mixing)

$$\hat{H} = \hat{P}_N^\dagger \hat{H}_{\rm ECQF}^N \hat{P}_N + \hat{P}_{N+2}^\dagger \left(\hat{H}_{\rm ECQF}^{N+2} + \Delta^{N+2}\right) \hat{P}_{N+2} + \hat{V}_{\rm mix}^{N,N+2},$$



IBM-CM vs experimental data (Zr)



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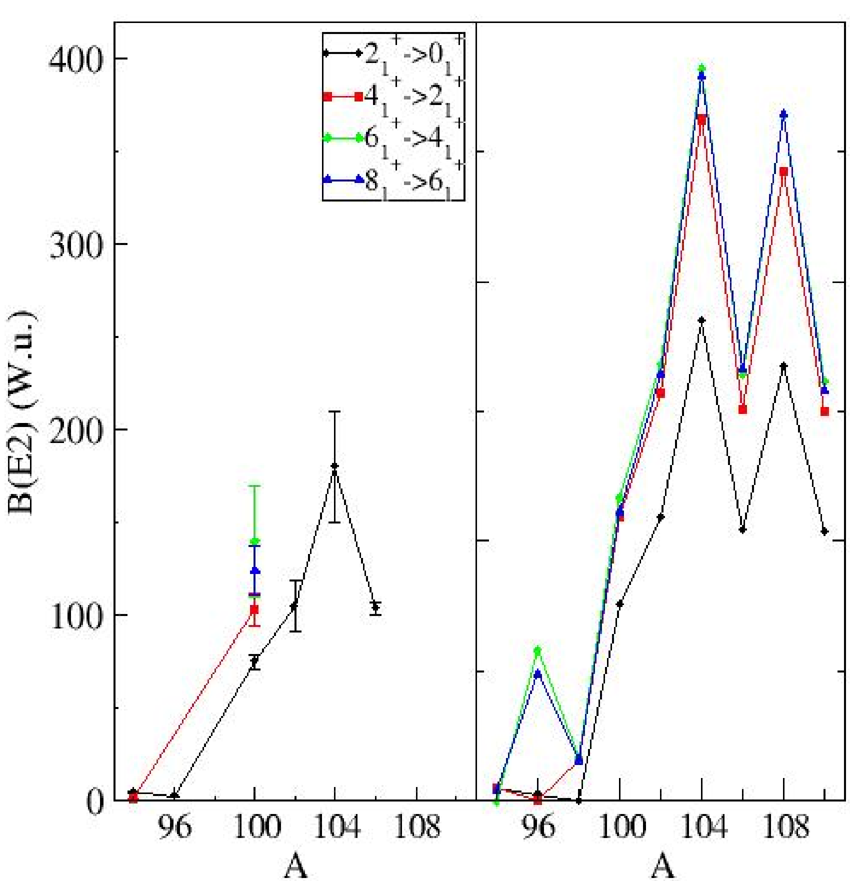
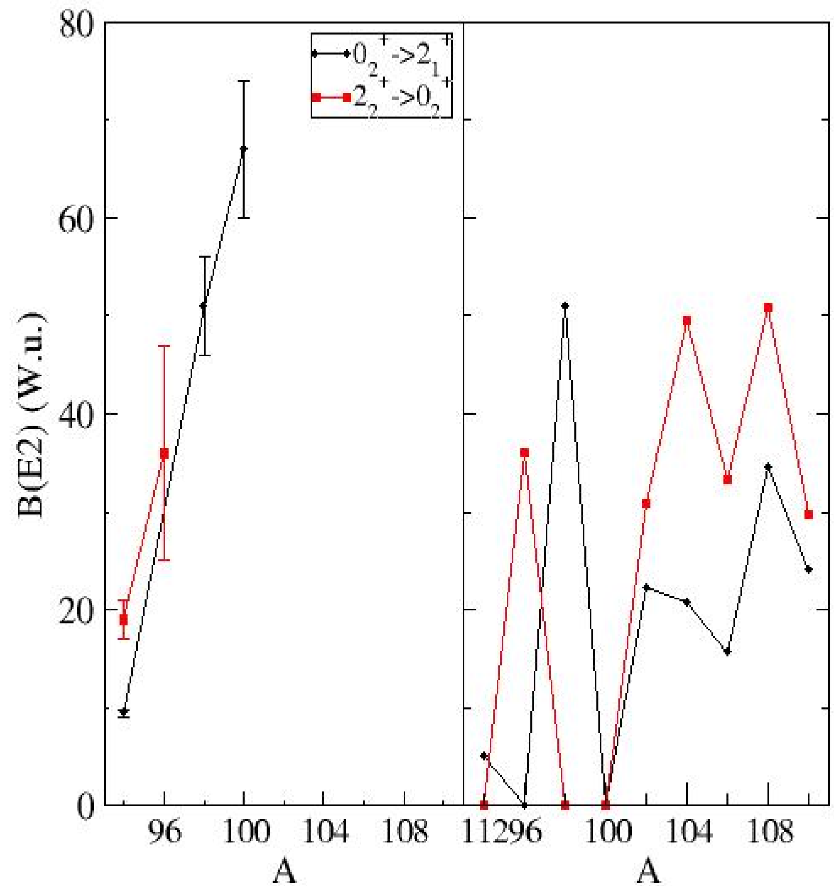
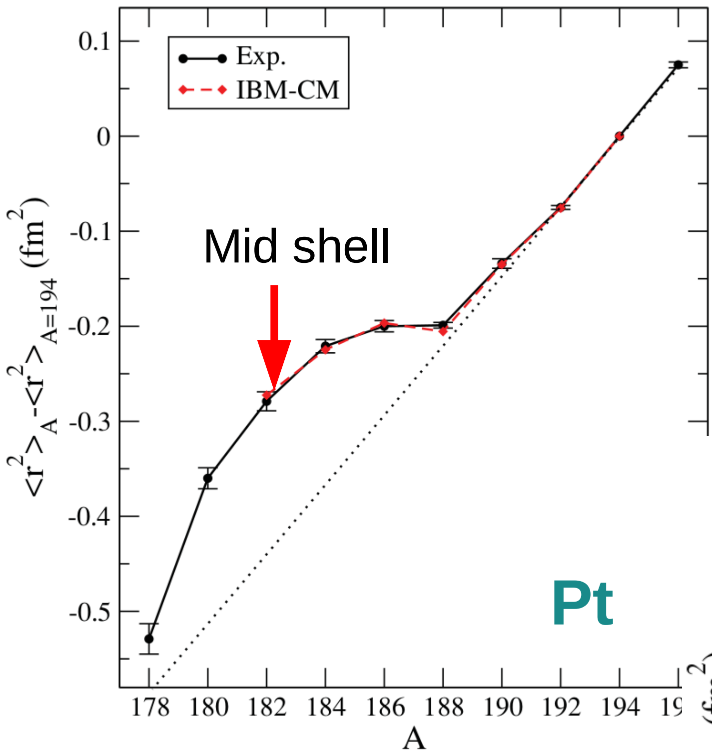
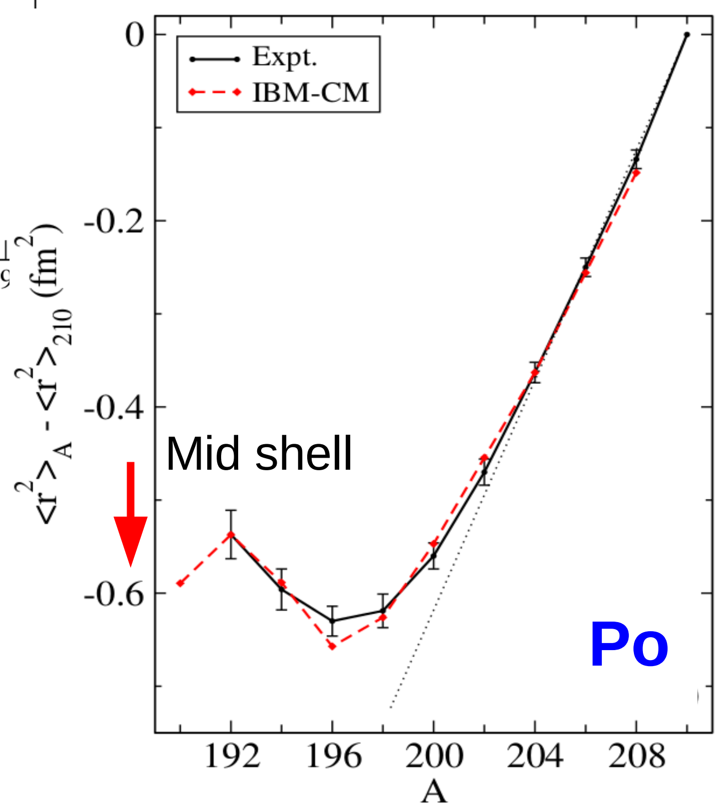
IBM-CM vs experimental data (Zr)

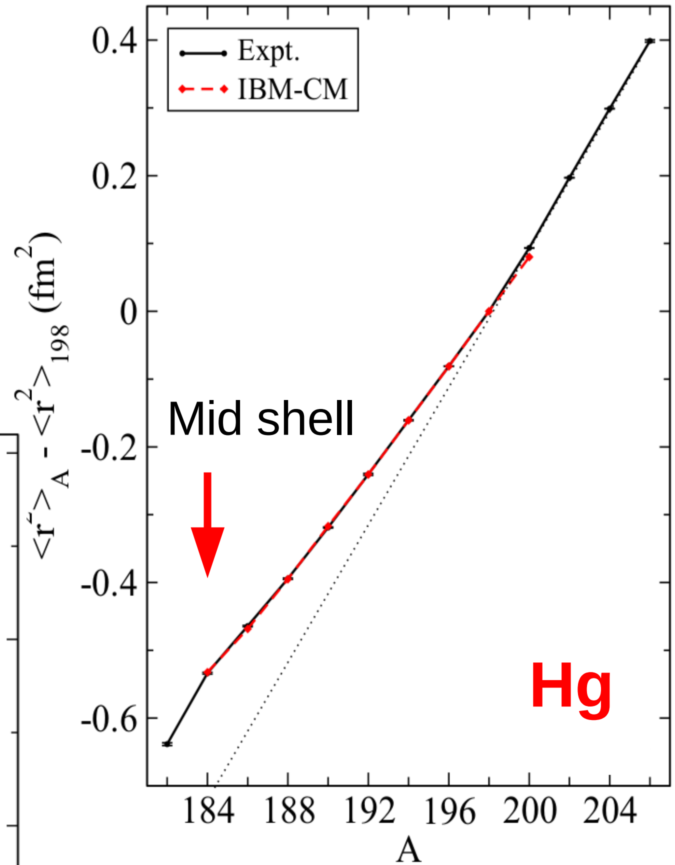




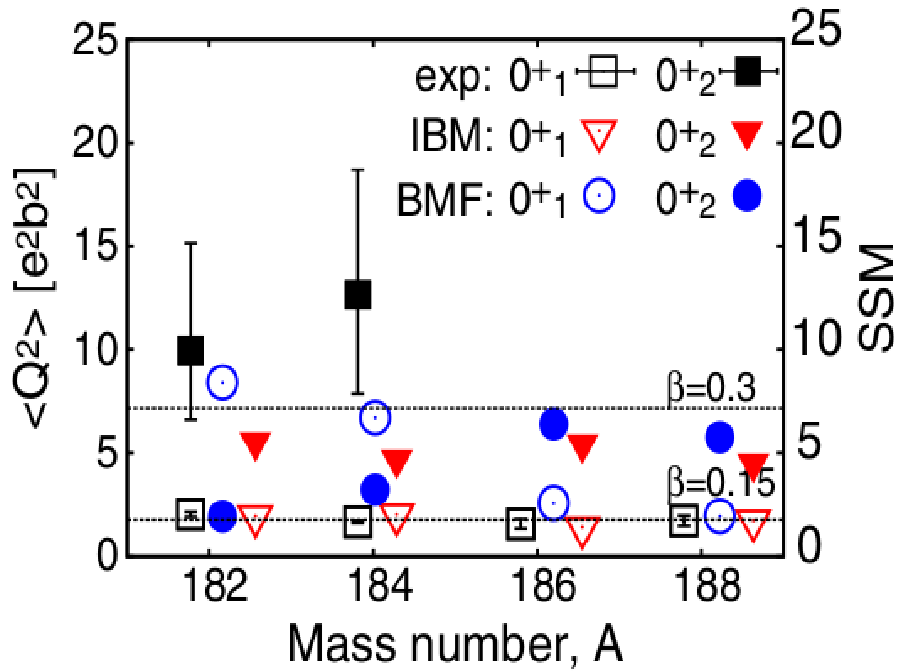
Radii

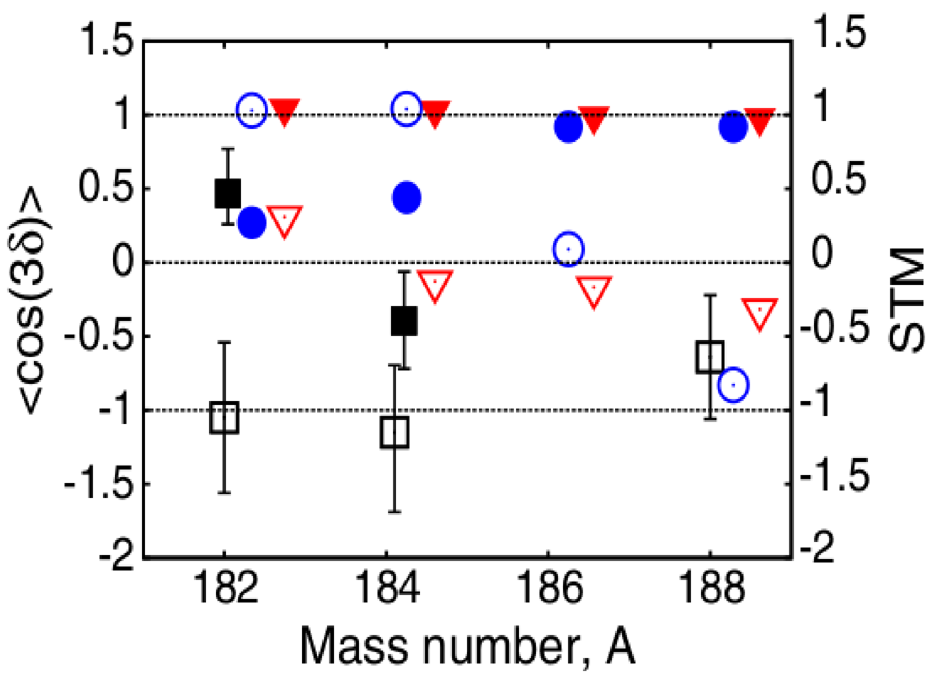

Exp.
IBM-CM
Mid shell
Pt
$<r^2>_A - <r^2>_{A=194}$ (fm^2)
A
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
178
180
182
184
186
188
190
192
194


Expt.
IBM-CM
Mid shell
Po
$<r^2>_A - <r^2>_{210}$ (fm^2)
A
0
-0.2
-0.4
-0.6
192
196
200
204
208


Expt.
IBM-CM
Mid shell
Hg
$<r^2>_A - <r^2>_{198}$ (fm^2)
A
0.4
0.2
0
-0.2
-0.4
-0.6
184
188
192
196
200
204

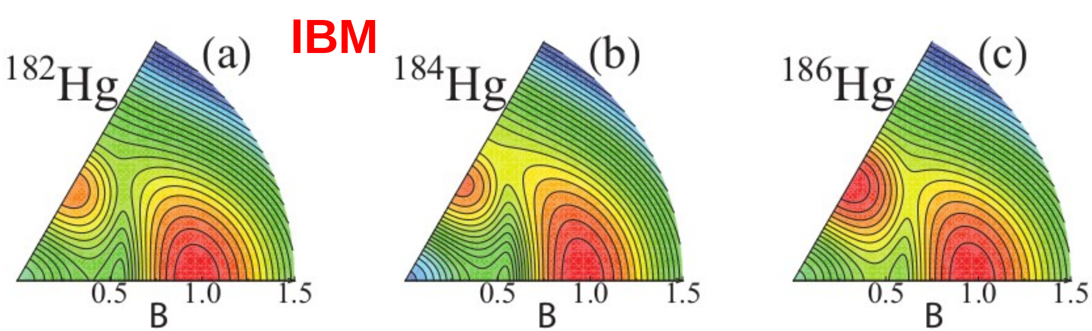
Shapes from COULEX





N. Bree et al, PRL112, 162701 (2014)

Note that, though, at the mean-field level the prolate minimum is the lowest one, in the lab-frame description the oblate is the lowest one.



JEGR and K. Heyde, PRC 89, 014306 (2014)